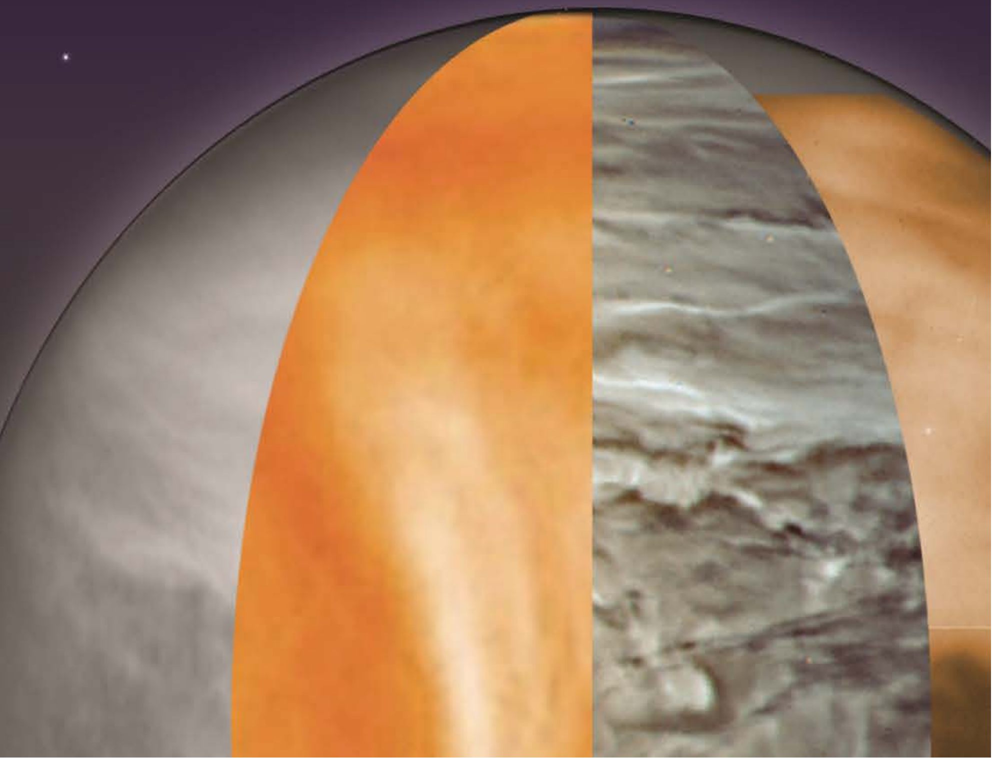
The 74th Fujihara Seminar
"Akatsuki" Novel Development of Venus Science
International Venus Conference 2019

May 31 (Fri.) - June 3 (Mon.), 2019
Hilton Niseko Village, Hokkaido, Japan

第74回藤原セミナー
「あかつき」がもたらす金星科学の新展開
国際金星会議2019

2019年 5月31日(金) - 6月3日(月)
ヒルトンニセコビレッジ



ABSTRACTS

Program

The 74 th Fujihara Seminar / International Venus Conference 2019 (Niseko, Hokkaido, Japan)

	31-May-2019 Day 1	1-Jun-2019 Day 2	2-Jun-2019 Day 3	3-Jun-2019 Day 4	4-Jun-2019 Day 5
AM1	Arrivals to Niseko (transfer service from New Chitose Airport)	**03: Clouds and Chemistry (1)** (8:30-10:10)	**07: Clouds and Chemistry (2)** (8:30-10:05)	**09: Atmospheric Structure** (8:30-10:15)	All your own!
		Coffee	Coffee	Coffee	
AM2		**04: Atmospheric Dynamics (1)** (10:30-12:15)	**08: Poster (2)** (10:30-12:30)	**10: Atmospheric Dynamics (2)** (10:50-12:15)	
Lunch	Lunch (11:30-13:30) **Opening** (13:30-14:00)	Lunch (12:30-14:00)	Lunch (12:30-14:00)	Lunch (12:30-14:00)	
PM1	**01: Geology: Observations and Lab Measurements** (14:00-15:40)	**05: Future Missions** (14:00-16:05)	**Excursion** (13:30-)	**11: Atmospheric Dynamics (3)** (14:00-15:20)	
	Coffee	Coffee		Coffee	
PM2	**02: Geology and Evolution** (16:10-17:45)	**06: Poster (1)** (16:30-18:30)		**12: Aeronomy and Plasma Environment** (15:50-18:00)	
	Welcome Dinner (19:00-21:00)			**Banquet** (19:30-21:30)	*revised on May 29*

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Program No.	ho	End time	Name	Organization (abbreviated)	Title	Registration No	Remarks
31-May-2019 Day1							
	(11:30-13:30)		*Lunch*				
Session00 Opening							
	13:30	13:50	Hironori Iwase	The Fujihara Foundation of Science	Profile of The Fujihara Foundation of Science		
	13:50	14:00	Makoto Kobayashi	KEK	Opening Address		
Session 01 Geology: Observations and Lab Measurements (Masaki Ogawa, Martha Gilmore)							
01-1INVITE	14:00	14:20	Smrekar Suzanne	Jet Prop Lab/Caltech	VENUS INTERIOR AND SURFACE TODAY	IVC2019-0124	
01-2	14:20	14:35	Martha Gilmore	Wesleyan Univ.	CONTRASTS BETWEEN LOW EMISSIVITY TESSERA AND PLAINS MATERIALS ON VENUS MOUNTAINTOPS.	IVC2019-0119	
01-3INVITE	14:35	14:55	Helbert Jorn	DLR	The Spectroscopy of the surface of Venus - in the laboratory and from orbit	IVC2019-0122	by Smrekar Suzanne
01-4	14:55	15:10	Erika Kohler	NASA Goddard Space Flight Center	Measuring spectral properties of candidate minerals: Applications to the Venus radar anomalies	IVC2019-0001	
01-5	15:10	15:25	Sara Taeko Port	University of Arkansas	Lead Minerals under Simulated Venus Conditions	IVC2019-0020	
01-6	15:25	15:40	Joseph G O'Rourke	ASU	Detectability and Scientific Implications of Crustal Remanent Magnetism on Venus	IVC2019-0098	
	(15:40-16:10)		*Coffee*				
Session 02 Geology and Evolution (David Grinspoon, Smrekar Suzanne)							
02-1	16:10	16:25	Abhinav Jindal	Cornell University	Unveiling the Interior of Venus: Using tectonic deformations along canali to constrain lithospheric structure & mantle convection	IVC2019-0083	
02-2INVITE	16:25	16:45	Masaki Ogawa	Univ. of Tokyo at Komaba	A two-stage evolution model of Venusian mantle and its implications for the Earth	IVC2019-0002	
02-4INVITE	16:45	17:05	Cedric Gillmann	ULB	The early and long term evolution of Venus and its atmosphere	IVC2019-0021	
02-5INVITE	17:05	17:25	Michael Way	NASA/GISS	Modeling Venus-like Worlds Through Time: The habitable zone, and the evolution of Venus' atmosphere.	IVC2019-0015	
02-6INVITE	17:25	17:45	David Grinspoon	Planetary Science Institute	The Evolution of Climate and a Possible Biosphere on Venus	IVC2019-0012	
			Group Photo				
	(19:00-21:00)		*Welcome Dinner*				
1-Jun-2019 Day2							
AM1: Session 03 Clouds and Chemistry (1) (Franklin Mills, Kevin McGouldrick)							
03-1	8:30	8:45	Satoshi Sasaki	Tokyo University of Technology	Microscope for Life Detection in Venus Clouds	IVC2019-0061	
03-2INVITE	8:45	9:05	Emmanuel Marcq	LATMOS / UVSQ	SPICAV-UV/VEx nadir observations: SO2, O3 and UV absorber	IVC2019-0062	
03-3	9:05	9:20	Michael Radke	Johns Hopkins University	Optical Properties of Venus Aerosol Analogues	IVC2019-0052	
03-4	9:20	9:35	Pushkar Kopparla	U Tokyo	Principal Components of UV Albedo Variability in Venus' Atmosphere as seen at 283 nm	IVC2019-0013	
03-5INVITE	9:35	9:55	Yeon Joo Lee	TUB	Long-term variations of Venus' 365-nm albedo observed by Venus Express, Akatsuki, MESSENGER, and Hubble Space Telescope	IVC2019-0038	
03-6	9:55	10:10	Takao Sato	HIU	Mapping of Venus' cloud top altitude from Akatsuki/IR2 dayside images	IVC2019-0109	
	(10:10-10:30)		*Coffee*				
AM2: Session 04 Atmospheric Dynamics (1) (Masahiro Takagi, Sebastien Lebonnois)							
04-1INVITE	10:30	10:50	Peter Read	University of Oxford	Venus in context : exploring atmospheric circulation regimes for slow (and fast) rotators	IVC2019-0027	
04-2	10:50	11:05	Masaru Yamamoto	Kyushu Univ.	Atmospheric simulations using Venus AORI general circulation models	IVC2019-0029	
04-3INVITE	11:05	11:25	Takeshi Imamura	The University of Tokyo	Localtime-dependent structures in the Venusian atmosphere revealed by Akatsuki radio occultation measurements	IVC2019-0073	
04-4	11:25	11:40	Masataka Imai	AIST	Continuous monitoring of planetary-scale waves in the Venus cloud top	IVC2019-0057	
04-5	11:40	11:55	Hiroki Kashimura	Kobe University	Planetary-scale streak structure reproduced in high-resolution simulations of the Venus atmosphere with a low-stability layer	IVC2019-0094	
04-6INVITE	11:55	12:15	Javier Peralta	ISAS (JAXA)	The complex features and dynamics of the nightside clouds of Venus as revealed by Akatsuki and Venus Express	IVC2019-0093	
	(12:30-14:00)		*Lunch*				
PM1: Session 05 Future Mission+A69s (Colin Wilson, Takehiko Satoh)							
05-2	14:00	14:15	Jonathan Grandidier	NASA - JPL	Solar Spectrum and Intensity Analysis Under Venus Atmosphere Conditions for Photovoltaics Operation	IVC2019-0006	
05-3	14:15	14:30	Armin Kleinboehl	JPL	Venus Climate Sounder - A Limb Infrared Radiometer for the Middle Atmosphere of Venus	IVC2019-0060	
05-4INVITE	14:30	14:50	Lori S Glaze	NASA Goddard Space Flight Center	NASA Planetary Portfolio: Present and Future Plans	IVC2019-0131	
05-5	14:50	15:05	Nicolas Rambaux	IMCCE - Obs. Paris	Rotational motion of Venus and Envision determination	IVC2019-0063	
05-6	15:05	15:20	Colin F Wilson	Oxford University	Envision M5 Venus Orbiter: Status And Opportunities	IVC2019-0086	
05-7	15:20	15:35	Pascal Rosenblatt	Geoazur	Gravity and ephemeris experiment with EnVision	IVC2019-0115	
05-8	15:35	16:50	Ludmira Zasova	Space Research Institute (IKI RAS)	VENERA-D: Mission for long-term study of the atmosphere, surface, interior structure and solar wind interaction	IVC2019-0126	by Sanjay Shridhar Limaye
05-9	15:50	16:05	Thomas F Bristow	NASA	CheMin-V: A Definitive Mineralogy Instrument for the Venera-D Mission	IVC2019-0117	
	(16:05-16:30)		*Coffee*				
PM2: Session 06 Posters (1) (Takeshi Horinouchi)							
	16:30	17:15	Poster Short Presentations (P01, P03, ···, odd number posters, one minute for each)				
	17:15	18:30	Core Time				

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Program No.	ho	End time	Name	Organization (abbreviated)	Title	Registration No	Remarks
2-Jun-2019 Day3							
AM1: Session 07 Clouds and Chemistry (2)							
(Emmanuel Marcq, Takao Sato)							
07-1	8:30	8:45	Kevin McGouldrick	CU/LASP	Cytherometeorology	IVC2019-0092	
07-2INVITE	8:45	9:05	George L. HASHIMOTO	Okayama Univ.	Climate control on Venus: Connections among clouds, UV absorber, surface chemical reaction, and atmospheric circulation	IVC2019-0085	
07-3	9:05	9:20	Takeshi Kuroda	Tohoku Univ.	Maintenances of Venusian Sulfuric Acid Clouds due to Chemistry and Dynamics Simulated by a General Circulation Model	IVC2019-0075	
07-4	9:20	9:35	Franklin Mills	ANU and SSI	Modeling the Distribution of Sulfur Species in the Atmosphere of Venus	IVC2019-0055	
07-5	9:35	9:50	Sanjay Shridhar Limaye	University of Wisconsin	Puzzling Cloud Cover of Venus	IVC2019-0077	
07-6	9:50	10:05	Eliot Young	SWRI	Spectral Properties of Unusual Nightside Cloud Features on Venus	IVC2019-0097	
	(10:05-10:30)		*Coffee*				
AM2: Session 08 Posters (2)							
(Makoto Taguchi)							
	10:30	11:15	Poster Short Presentations (P02, P04, ···, even number posters, one minute for each)				
	11:15	12:30	Core Time				
	(12:30-14:00)		*Lunch*				
	13:30		*Excursion*				
3-Jun-2019 Day4							
AM1: Session 09 Atmospheric Structure							
(Takeshi Imamura, Yeon Joo Lee)							
05-1	8:30	8:45	Tibor Kremic	NASA	Preparing for Venus Surface Exploration	IVC2019-0011	
09-1	8:45	9:00	Carver Jay Bierson	UCSC	A fully coupled photochemical-condensation model of the Venus atmosphere from the ground to 110 km	IVC2019-0026	
09-2	9:00	9:15	Ralph Lorenz	APL	The Dust Cycle on Venus	IVC2019-0031	
09-4	9:15	9:30	Christopher Dennis Parkinson	University of Michigan	Modeling of Observations of the OH Nightglow in the Venusian Mesosphere	IVC2019-0102	
09-5	9:30	9:45	Gourav Mahapatra	TU Delft	Studying the polarization in CO2 absorption bands of Venus atmosphere	IVC2019-0108	
09-6	9:45	10:00	Daria Evdokimova	IKI RAS, LATMOS	Variations of lower clouds and water vapor amount in deep Venus atmosphere based on night windows observations by the SPICAV-IR/Venus-Express	IVC2019-0112	
09-7	10:00	10:15	Mikhail Luginin	Space Research Institute (IKI), Moscow	Retrieval of upper haze aerosol properties from SPICAV-UV and -IR data	IVC2019-0045	
	(10:15-10:50)		*Coffee*				
AM2: Session 10 Atmospheric Dynamics (2)							
(Aymeric Spiga, Toru Kouyama)							
10-1	10:50	11:05	LEFEVRE Maxence	AOPP, Oxford	Organization of the convection in the Venusian cloud layer	IVC2019-0008	
10-2	11:05	11:20	Shinichiro Kawase	Rikkyo University	Comparison of horizontal distributions of temperature and UV absorbers at the Venus cloud-tops	IVC2019-0033	
10-3	11:20	11:35	Ehouarn Millour	LMD	Towards a (GCM-based) Venus Climate Database	IVC2019-0051	
10-4INVITE	11:35	11:55	Masahiro Takagi	KSU	Numerical modeling of the Venus atmosphere	IVC2019-0076	
10-5INVITE	11:55	12:15	Sebastien Lebonnois	LMD/IPSL, CNRS	Investigations below the clouds of Venus with the IPSL Venus GCM	IVC2019-0048	
	(12:30-14:00)		*Lunch*				
PM1: Session 11 Atmospheric Dynamics (3)							
(Helen Parish, Javier Peralta)							
11-1	14:00	14:15	Toru Kouyama	AIST	Detection of large stationary gravity waves over ten Venusian solar days seen in LIR images	IVC2019-0070	
11-2	14:15	14:30	Aymeric Spiga	Sorbonne Université / LMD	A new mesoscale model for Venus' atmosphere and its application to the bow-shaped structures discovered by Akatsuki	IVC2019-0014	
11-3INVITE	14:30	14:50	Takeshi Horinouchi	Hokkaido Univ	Venus atmosphere dynamics revealed by cloud tracking using images from Akatsuki	IVC2019-0079	
11-4	14:50	15:05	Ruben Gonçalves	IA, Portugal	Akatsuki (cloud-tracking) and TNG/HARPS-N (Doppler velocimetry) coordinated wind measurements of cloud top Venus atmosphere.	IVC2019-0007	
11-5	15:05	15:20	Machado Pedro	I. Astrophysics and Space Sciences	Meridional and Zonal winds at Venus atmosphere from Cloud tracking, Doppler techniques and comparison with modelling	IVC2019-0009	
	(15:20-15:50)		*Coffee + Poster Removal*				
PM2: Session 12 Aeronomy and Plasma Environment							
(Masato Nakamura, Amanda Susanne Brecht)							
12-2INVITE	15:50	16:05	Amanda Susanne Brecht	NASA	Understanding the Impact of Waves on Venus' Upper Atmosphere through General Circulation Model Simulations	IVC2019-0066	
12-3	16:05	16:25	Martin Paetzold	RIU-Planetary Research	The Venus Ionosphere as seen by the Akatsuki Radio Science Experiment	IVC2019-0035	
12-4INVITE	16:25	16:40	Yoshifumi Futaana	Swedish Institute of Space Physics (IRF)	Upper atmosphere of Venus and impact from solar wind plasma: What we have learned from Venus Express	IVC2019-0005	
12-5	16:40	17:00	Dmitry Gorinov	Space Research Institute (IKI)	Circulation of Venusian atmosphere at 90-110 km based on apparent motions of the O2 1.27 um nightglow from VIRTIS-M (Venus Express) data	IVC2019-0040	
12-6	17:00	17:15	Stephen W Bougher	U of Michigan	An Investigation of the Solar Wind Influence on the Venus Upper Atmosphere Structure and Dynamics	IVC2019-0084	
12-7	17:15	17:30	Moa Persson	IRF Kiruna	H+/O+ escape rates in the Venusian magnetotail and their dependence on upstream conditions	IVC2019-0037	
12-8	17:30	17:45	Candace Leah Gray	Apache Point Observatory	Variability of the Venusian and Martian nightside ionosphere after solar storms	IVC2019-0047	
12-9	17:45	18:00	Kerstin S. Peter	RIU Cologne, Planetary Research	Small-scale disturbances in the lower dayside ionosphere of Venus	IVC2019-0023	
	(19:30-21:30)		*Banquet*				

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Program No.	ho	End time	Name	Organization (abbreviated)	Title	Registration No	Remarks
Poster	Session 06 (Day2 PM2, odd numbers) and Session 08(Day3 AM2, even numbers)						
P01			Gilles BERGER	IRAP, CNRS-OMP, Toulouse	Experimental investigation of wet atmosphere-surface interaction at the conditions of Venus surface: an example for early terrestrial planets	IVC2019-0004	
P02			Martha Gilmore	Wesleyan Univ.	THIRTY DAYS ON VENUS: CHEMICAL AND ELECTRICAL CHANGES MINERALS EXPOSED TO THE GLENN EXTREME ENVIRONMENT RIG (GEER).	IVC2019-0116	
P03			Jeremy Brossier	Wesleyan University	Low radar emissivity signatures on coronae	IVC2019-0030	
P04			Cayman Thomas Unterborn	Arizona State University	Self-Consistent Reference Seismological Models for Determining Venus's Interior Composition	IVC2019-0003	cancelled
P05			Saman Karimi	Johns Hopkins University	Crater Relaxation on Venus: Implications for Geologic and Thermal History	IVC2019-0087	cancelled
P06			Sara Taeko Port	University of Arkansas	The Emissivity of Pyrrhotite/Basalt Mixtures at Venusian Temperatures	IVC2019-0067	
P07			Moa Persson	IRF Kiruna	Heavy ion flows in the upper ionosphere of the Venusian North Pole	IVC2019-0036	
P08			Masataka Imai	AIST	Cosmic rays detected by LAC on board Akatsuki	IVC2019-0056	
P09			Martin Paetzold	RIU-Planetary Research	Eight years of VEX-VeRa radio sounding of the Venus ionosphere	IVC2019-0041	
P10			Adhithiyan Neduncheran	UPES, India	A review of photochemical reactions and electrical discharge in the atmosphere of Venus with special focus on lightning in the cloud region	IVC2019-0082	
P11			Stephen A Ledvina	Space Sciences Lab, UC Berkeley	Simulations of Ion Flow and Energy Transfer in the Venus Environment	IVC2019-0096	
P12			Chuanfei Dong	Princeton University	Role of a Weak Planetary Dipole Moment on Venusian Upper Atmosphere and Near Space Environment	IVC2019-0121	
P13			Valeriy Tenishev	University of Michigan	Toward Development of Coupled Kinetic-Fluid Model of Venus Thermosphere-Exosphere System Interacting with the Ambient Solar Wind	IVC2019-0065	
P14			Yukihiro Takahashi	Hokkaido Univ.	Search for lightning discharge in Venus with Akatsuki/LAC and Pirka telescope	IVC2019-0088	
P15			Christopher Dennis Parkinson	University of Michigan	The Impact of Venus Middle Atmosphere Aerosol Heating upon SO2 and CO Density Distributions through GCM Model Simulations	IVC2019-0111	
P16			Franklin Mills	ANU and SSI	Simulations of Vertical Profiles of Sulfur Oxides in Venus' Mesosphere	IVC2019-0054	
P17			Seiko Takagi	Hokkaido Univ.	The global variation of Venus cloud investigated from IR1 onboard AKATSUKI	IVC2019-0072	
P18			Christopher Dennis Parkinson	University of Michigan	Photochemical Control of the Distribution of Venusian Water and and Sulphuric Acid Aerosols in the Clouds and Upper Haze of Venus	IVC2019-0105	
P19			Kensuke Nakajima	Kyushu Univ.	Development of a Venus' cloud formation scheme for a convection resolving model	IVC2019-0078	
P20			Kandis-Lea Jessup	Southwest Research Institute	Venus Cloud Top Chemistry, Convective Activity and Topography: A Perspective from HST	IVC2019-0104	by Emmanuel Marcq
P21			Hiroki Andou	Kyoto Sangyo University	Venusian cloud physics investigated by a general circulation model	IVC2019-0016	
P22			naomoto iwagami	none	Cloud morphology and wind measurements by the Akatsuki 1-micrometer camera	IVC2019-0010	
P23			Sebastien Lebonnois	LMD/IPSL, CNRS	Composition and clouds, some insights and questions from the coupled IPSL Venus GCM	IVC2019-0050	
P24			Takehiko Satoh	ISAS/JAXA	Enormous cloud cover as seen by Akatsuki/IR2 on the night-side disk of Venus	IVC2019-0068	
P25			Sebastien Lebonnois	LMD/IPSL, CNRS	Interactions between the topography and the atmosphere on Venus	IVC2019-0101	
P26			Takeshi Horinouchi	Hokkaido Univ	Understanding the formation of super-rotation under zonally symmetric thermal forcing	IVC2019-0081	
P27			Kosuke Takami	PAT	Temperature and wind variations in Venusian mesosphere and lower thermosphere by mid-infrared heterodyne spectrometer in 2018	IVC2019-0091	cancelled
P28			Norihiko Sugimoto	Keio Univ.	The Venus AFES LETKF Data Assimilation System (VALEDAS)	IVC2019-0018	
P29			Asako Hosono	Toshimagaoka Women High School	The study on the reproducibility of cold collar assuming radio occultation measurement by small satellites	IVC2019-0043	
P30			Thomas Widemann	Paris Observatory	Clouds Top Wind Measurements and Thermal Properties near Beta Regio (25N, 283E)	IVC2019-0089	
P31			Kosuke Takami	PAT	Temperature and wind variations in Venusian mesosphere and lower thermosphere by mid-infrared heterodyne spectrometer in 2018	IVC2019-0091	
P32			Yusuke Nara	Univ. Tokyo	Structures of planetary-scale waves at Venusian cloud top revealed by an improved cloud-tracking method tolerant to streaky features	IVC2019-0095	
P33			Hideo Sagawa	Kyoto Sangyo Univ.	Doppler-wind observations of Venus mesosphere: Comparison with new GCM experiments	IVC2019-0114	
P34			Ryota Mori	The University of Tokyo	Gravity wave packets detected in radio occultation temperature profiles of the Venus atmosphere	IVC2019-0058	
P35			Neil Tamas Lewis	University of Oxford	What controls the strength of super-rotation in terrestrial atmospheres?	IVC2019-0132	
P36			Marina Patsaeva	IKI RAS	Solar related variations of the cloud top circulation above Aphrodite Terra from VMC/Venus Express wind fields. Comparison with Akatsuki (first results)	IVC2019-0059	
P37			Kunio M Sayanagi	Hampton University	The relationship between wind shear and eddy momentum forcing in the Venusian atmospheric super-rotation	IVC2019-0100	
P38			Toru Kouyama	AIST	Venusian yearly-scale variation of super rotation seen in Akatsuki observations	IVC2019-0064	
P39			Takeshi Horinouchi	Hokkaido Univ	A novel cloud tracking method and results from Akatsuki	IVC2019-0080	
P40			Helen F. Parish	UCLA	Investigating the Influence of Wave Variations on Venus' Cloud-level Atmosphere using a Middle Atmosphere Model	IVC2019-0019	
P41			Tetsuya Fukuhara	Rikkyo University, Tokyo	Local-time variation of the zonal wave number spectra derived from the Venus cloud-top Temperature observed by Akatsuki LIR	IVC2019-0017	
P42			Silvia A. Tellmann	RIU Cologne, Germany	Eight years of VEX-VeRa radio sounding of the Venus atmosphere	IVC2019-0039	
P43			Ryan Matthew McCabe	Hampton University	Tracking the Venus Y-Feature During Venus Express and Ground-based Observing	IVC2019-0071	
P44			Janusz Oschlisniok	RIU Cologne, GER	Sulfuric acid vapor in the atmosphere of Venus as observed by the Venus Express Radio Science Experiment VeRa	IVC2019-0025	
P45			Tatiana M Bocanegra Bahamon	NASA JPL	Radio-holographic methods for inversion of radio occultation experiments of past Venus' spacecraft	IVC2019-0090	
P46			Choon Wei Vun	SOKENDAI	Akatsuki's IR2 Nightside Photometry Restoration by Deconvolution in 2.26um and 1.735um filters	IVC2019-0118	
P47			Grzegorz Slowik	University of Zielona Gora	Measuring the properties of acidophilic bacteria under Venus cloud conditions	IVC2019-0042	
P48			Sebastien Lebonnois	LMD/IPSL, CNRS	An experiment to investigate Venus's deep atmosphere	IVC2019-0049	
P49			Alexander B. Akins	Georgia Tech	Ka Band Opacity of Sulfuric Acid Vapor at Venus: Initial Results	IVC2019-0046	
P50			Kiichi Fukuya	The University of Tokyo	Stationary wavy features and Banded structures at Venusian cloud top extracted by averaging multiple LIR images	IVC2019-0123	
P51			Jeffrey Balcerski	Ohio Aerospace Institute (OAI)	LEAVES - A swarm probe mission concept to Venus' clouds	IVC2019-0113	cancelled
P52			Adhithiyan Neduncheran	UPES, India	Remote sensing studies of our sister planet: Exploring Venus using planetary glider and CubeSat constellation	IVC2019-0032	
P53			Silvia A. Tellmann	RIU Cologne, Germany	Radio Sounding of the Venusian Atmosphere and Ionosphere with EnVision	IVC2019-0107	
P54			Yoshiyuki O. Takahashi	Kobe University	Zonal mean structure of Venus atmosphere observed in a Venus general circulation model, DCPAM, with explicit radiative transfer calculation	IVC2019-0022	by Yoshi-Yuki Hayashi
P55			Kosenkova Anastasia	Lavochkin Association	DEVELOPMENT OF THE VENERA-D SPACECRAFT DESIGN	IVC2019-0044	
P56			Eliot Young	SWRI	Observing Venus with NASA's Terrestrial Balloon Program	IVC2019-0099	
P57			Makoto Taguchi	Rikkyo University	Spectroscopic observation of the Venus atmosphere by a circumpolar stratospheric telescope FUJIN	IVC2019-0053	
P58			Ralph Lorenz	APL	A Lightweight Imaging/Altimeter Radar for Venus Exploration	IVC2019-0120	
P59			Smrekar Suzanne	Jet Prop Lab/Caltech	VERITAS (VENUS EMISSIVITY, RADIO SCIENCE, INSAR, TOPOGRAPHY AND SPECTROSCOPY): A PROPOSED DISCOVERY MISSION.	IVC2019-0125	
P60			Masahiro Akiba	Rikkyo graduate school	3-D structure of a thermal tide in the Venus atmosphere	IVC2019-0127	
P61			James Alfred Cutts	Jet Propulsion Laboratory	Exploration of Venus with Aerial Platforms	IVC2019-0128	
P62			James Alfred Cutts	Jet Propulsion Laboratory	Prospects for the Investigation of Venus using Infrasound	IVC2019-0129	S. Krishnamoorthy

Session 01

Geology: Observations and Lab Measurements

Session Chair: Masaki Ogawa
Session Chair: Martha Gilmore

VENUS INTERIOR AND SURFACE TODAY

S. Smrekar[1], A. Davaille[2], and N. Mueller[3], (1) Jet Propulsion Laboratory/Caltech, 4800 Oak Grove Dr., Pasadena CA, 91109 USA (ssmrekar@jpl.nasa.gov); (2) Laboratoire FAST, CNRS / Univ. Paris-Sud, Orsay, France; (2) Inst for Planetary Research, DLR, Rutherfordstrasse 2, 12489 Berlin, Germany.

Introduction: Some of the key questions for understanding the evolution of Venus are: Why does Venus lack plate tectonics? How does it lose heat? Did it resurface catastrophically? How are the interior, surface, and atmosphere coupled? What geologic processes are active today? We discuss these questions in light of VIRTIS surface emissivity studies of coronae, hotspots, proposed subduction zones, as well as resurfacing studies. We propose that Venus has local, ongoing resurfacing via processes such as hotspot volcanism, subduction and delamination.

Resurfacing: Constraining the resurfacing history of Venus is challenging due to the limited number (~1000) of impact craters. Combining additional constraints from observations of dark floored craters [1,2] or removal of extended ejecta [3] argues for ongoing, equilibrium rather than catastrophic resurfacing at the scale of 100s to 1000s of km.

Subduction & Plate Tectonics: Subduction is the necessary first step in initiating plate tectonics. Subduction was proposed to occur on Venus [4-6], but the presence of features produced by mantle plume at many of the sites brought this interpretation into question [7]. More recently plume-induced subduction has emerged as a key hypothesis for initiating terrestrial plate tectonics [e.g. 8]. Recent laboratory experiments have demonstrated how plume-induced subduction operates on planets; the predicted characteristics match many subduction features on Venus remarkably well [9]. Further, this process acts to recycle the entire lithosphere and resurface local areas on the scale of 100s to 1000s of km.

Yet subduction has not produced plate tectonics on Venus. Many have proposed that the interior of Venus is dry, and that this makes the lithosphere too strong to break [e.g. 10 & refs]. However, this hypothesis needs to be reexamined, given evidence that planets form wet [11], as well as evidence for at least locally weak lithosphere [e.g. 12] and limited volatile loss [e.g. 13]. Alternatively, hot lithosphere may allow the lithospheric scale faults produced by subduction to anneal overtime [14]. If faults that break the entire lithosphere cannot be maintained, they cannot lead to the network lithospheric-scale faults needed for plate tectonics.

Emissivity: The VIRTIS instrument on Venus Express measured the surface brightness temperature at 1.02 um for much of the s. hemisphere, from which emissivity can be derived [15]. Areas of high emissivity have been interpreted as evidence of recent, unweathered basalt, implying geologically recent activity [16]. Such areas are in locations previously interpreted as underlain by a mantle plume based on the geology, topography, and gravity data [e.g. 17], corroborating the interpretation of recent volcanism. At least one of these sites has evidence of plume-induced subduction [9].

Venus Today: Surface emissivity provides evidence of recent volcanism. Changing levels of SO_2 in the atmosphere may reflect volcanic outgassing [18]. These volcanic sites are directly linked to the interior, as the volcanism occurs at sites of mantle upwelling, with at least one showing evidence of subduction. These observations suggest gases are currently being released from the in the interior and possibly recycled back into the interior. Volcanism is still actively resurfacing Venus, consistent with equilibrium resurfacing. Thus Venus is best characterized as in a sluggish convective regime. Further, early Earth, with its hot lithosphere, may well have experienced a similar state before the start of plate tectonics [9].

Major progress on understanding the evolution of Venus would be enabled by high resolution topography, radar imaging, interferometry to look for active deformation and near infrared spectroscopy. These measurements would resolve the processes modifying craters, resurfacing the planet, and driving activity today.

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CONTRASTS BETWEEN LOW EMISSIVITY TESSERA AND PLAINS MATERIALS ON VENUS MOUNTAINTOPS. M. S. Gilmore, J. F. Brossier, N. Zalewski and A. J. Stein, Wesleyan University, 265 Church St., Middletown CT, 06459 USA mgilmore@wesleyan.edu

Previous work attempting to model the causes in Magellan 12.6 cm radar properties at high elevations have considered the cumulative emissivity of all surfaces [1-7], without exploring potential differences in the emissivity of geologic units. In this study, we leverage bedrock and impact crater ejecta of known relative age to estimate the rate and style of the weathering reactions at the summits of the 40 largest tessera occurrences on Venus. Tessera terrain is a heavily tectonized morphologic unit that comprises 8% of the Venus surface [8]. Tessera terrain is stratigraphically older than the volcanic plains and edifices that cover the remainder of the planet [8]. Surface-atmosphere reactions offer the opportunity to constrain the composition of Venus surface materials, particularly in the highland tessera terrain whose composition is inadequately known [9,10].

We measured the pattern of emissivity and elevation for 40 tesserae on Venus. Sixteen of the 40 show a decrease in emissivity at elevations > 6053 km. Eight have a trend like Ovda, which has an emissivity pattern (gradual decrease of emissivity and sharp return to high emissivity with altitude) we interpret as did [2,7] to be indicative of the presence of a ferroelectric mineral. At or near the Curie-Weiss temperature the dielectric constant increases significantly, followed by a gradual decline in dielectric constant with increasing temperature. The low emissivity excursion at ~6056 km corresponds to a Curie temp of 705K [11]. This pattern is present in tessera in Aphrodite, Beta and Phoebe Regio, requiring that this ferroelectric is widespread. We relate differences magnitude of this excursion to differences in the volume of the ferroelectric [7]. That there is a difference between Ovda and adjoining Manatun and Thetis and adjoining Haasttse-baad suggests that the weathering process has been lessened by a lower volume and/or exposure of the reactants that form the ferroelectric mineral, or a younger age for these tessera surfaces, where the reaction has not had time to go to completion.

The lower elevation trend tessera have a peak emissivity excursion at ~6054 km, coinciding with a Curie temperature of 720 K if due to ferroelectric minerals. This suggests that these tesserae in Aphrodite and Phoebe have a slightly different mineralogy than the Ovda class due to rock type and/or local atmospheric conditions.

The Fortuna group is fundamentally different. The tesserae in this category do not change emissivity until altitudes >6056 km and then only slightly. The elevation trend overlaps that of Maxwell which has been interpreted to be consistent with the presence of a semiconductor material there not seen in Ovda [7]. Treiman et al. [7] further posits this difference can be attributed to differences in rock type or atmosphere. That all of the materials in the Ishtar region: tesserae, mountains and volcanoes [12] have similar emissivity patterns requires that this reaction is common to this location on the planet. Are the rocks of the volcanoes in Ishtar unique amongst the volcanoes? Does the composition of the atmosphere in the northern latitudes differ than the mid latitudes over a time scale to produce semiconductor materials?

Conversion of emissivity to permittivity shows that the tesserae have greater permittivity than do plains materials. We hypothesize that each case under study has different abundances of ferroelectric and/or semiconductor materials, where these minerals are more concentrated in tesserae than in plains materials. Ferroelectric minerals are comprised of incompatible elements that are expected to be more common in felsic rocks relative to basalts.

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The Spectroscopy of the surface of Venus –in the laboratory and from orbit. J. Helbert[1], M. D. Dyar[2,3], A. Maturilli[1], T. Widemann[4], E. Marcq[5], D. Wendler[1], I. Walter[6], M. D'Amore[1], S. Ferrari[7,1], N. Müller[8], S. Smrekar[8], [1]Inst. for Planetary Research, DLR, Berlin, Germany (joern.helbert@dlr.de), [2] Planetary Science Institute, Tucson, AZ, USA, [3]Dept. of Astronomy, Mount Holyoke College, South Hadley, MA USA, [4]LESIA, Observatoire de Paris, France [5]LATMOS, Université Paris-Saclay, France, [6]Institute for Optical Sensor Systems, DLR, Berlin, Germany, 7University of Padova, Padova, Italy, [8]Jet Propulsion Laboratory, Pasadena CA, USA.

Introduction: Many efforts have been made since the landing of Venera 9 and 10 [1] to obtain optical spectra of Venus analog materials at relevant temperatures. [2] provided a first set of reflectance measurements of basaltic materials in the spectral range from 0.4 to 0.8 µm. Since then, all efforts to extend these measurements to longer wavelengths have stalled.

It was commonly accepted that compositional data could only be obtained by landed missions because Venus' permanent cloud cover prohibits observation of the surface with traditional imaging techniques over most of the visible spectral range. Fortuitously, Venus' CO_2 atmosphere is actually partly transparent in small spectral windows near 1 µm. These windows have been used to obtain limited spectra of Venus' surface by ground observers, during a flyby of the Galileo mission at Jupiter, and from the VMC and VIRTIS instruments on the ESA VenusExpress spacecraft. In particular, the latter observations have revealed compositional variations correlated with geological features [3-8].

These observations challenge the notion that landed missions are needed to obtain mineralogical information. However, any interpretation in terms of mineralogy of VNIR spectroscopy data from orbiters requires spectral libraries acquired under conditions matching those on the surfaces being studied.

Venus facility at PSL: The Planetary Spectroscopy Laboratory (PSL) at DLR took up this challenge, building on nearly a decade of experience in high temperature emission spectroscopy in the mid-infrared [9-11]. After several years of development and extensive testing, PSL is now in routine operation for Venus-analog emissivity measurements from 0.7 to 1.5 µm over the whole Venus surface temperature range.

PSL has started a database of Venus analog spectra including measurements of rock and mineral samples covering a range from felsic to mafic rock and mineral samples [12]. This first set already shows the potential for mapping of Venus mineralogy and chemistry *in situ* from orbit with six-window VNIR spectroscopy [13-15].

The Venus facility at PSL is open to the community through the Europlanet Research Infrastructure (http://www.europlanet-2020-ri.eu/).

Venus Emissivity Mapper (VEM): VEM builds on these recent advances in the laboratory. It is the first flight instrument specially designed to focus on mapping the surface of Venus using the atmospheric windows around 1 µm. By observing through all five windows with six narrow band filters, ranging from 0.86 to 1.18 µm, VEM will provide a global map of surface composition as well as redox state of the surface. Continuous observation of Venus' thermal emission will place tight constraints on current day volcanic activity. Eight additional channels measure atmospheric water vapor abundance as well as cloud microphysics and dynamics and will permit accurate correction of atmospheric interference on the surface data.

Conclusion: Interpretation of mineralogy using VNIR spectroscopy data from orbiters [14,15] requires spectral libraries acquired under conditions matching those on the surfaces being studied. Recent advances in high-temperature laboratory spectroscopy at the Planetary Spectroscopy Laboratory at DLR provide the necessary data and enable novel instruments like the Venus Emissvity Mapper.

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Measuring spectral properties of candidate minerals: Applications to the Venus radar anomalies

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Radar mapping of the surface of Venus shows areas of high reflectivity (low emissivity) in the Venusian highlands at altitudes between 2.5-4.75 kilometers. The origin of the radar anomalies found in the highlands remains unclear. Previous, and ongoing experimental research investigated possible materials under simulated Venusian atmospheric and surface conditions, with special emphasis on the combined effect of pressure and temperature, and chemical composition. The results of these studies identified candidate source materials for the radar anomalies. In order to fully be considered a true source candidate the material must have spectroscopic measurements comparable to those measured on the surface of Venus where the high temperature affects spectral characteristics of minerals. Spectroscopic measurements of previously identified candidate minerals were made at the Planetary Spectroscopy Laboratory (PSL) of DLR in Berlin in an effort to identify the anomaly source.

The spectroscopic measurements were made with a FTIR Bruker Vertex 80V evacuated to ~.1 mbar and using several pairings of detector+beamsplitter to cover the spectral range from 0.2 to 20 μm. Each sample was poured in a stainless steel reflectance cup and measured fresh. Successively each cup was heated (via an induction system) in vacuum (0.07 mbar) at 400°C for 8 hours and measured again in the UV+VIS+MIR spectral range. Three consecutive cycles of heating and measuring reflectance were performed to account for spectral variations arising from the thermal processing of the samples. Heating the samples directly inside the reflectance cups allows to measure every time exactly the same surface, exposed to increasing levels of thermal processing.

Results from this study are expected to further constrain the source of the Venus radar anomalies.

Lead Minerals under Simulated Venus Conditions

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Introduction: Many researchers have undertaken the investigation into the origin of the radar reflective highlands on Venus [1-4]. Several theories have been postulated, including the deposition of a mineral onto the highlands [5-8]. Lead minerals are found near fumaroles and in eruption plumes on Earth [9], a phenomenon that if not present today, once existed on Venus. Many lead minerals also high dielectric constants [10]. Lead has been identified in surface rocks by Vega 2, which detected <0.3 mass % of lead in its landing site [11]. Due to the abundance of various carbon, oxygen, and sulfur bearing gases various lead minerals such as PbO, $PbSO_4$, and $PbCO_3$ may be present on Venus and could explain the radar reflective signal in the highlands.

Methods: Experiments were completed using powdered Pb, PbO, $PbSO_4$, and PbS. The samples were exposed to the temperature and pressure found in the lowlands (460°C/95 bar) and at the top of Maxwell Montes (380°C/45 bar) in the Venus simulation chamber at the University of Arkansas. The experiments were completed in one of three different gases representing a simplified version of the environment found on Venus. These gases were 99.999% CO_2, 100ppm SO_2 in CO_2, and 100ppm COS in CO_2. Samples were tested for 24 hours and then analyzed via XRD and XPS to determine any changes to the structure and elemental composition. Several samples are currently being analyzed with a LIBS at LANL.

Results: The experiments completed with Pb, PbS, and $PbSO_4$ in CO_2 exhibited no changes in either temperature regime. Though PbO was stable in the lowland conditions in CO_2, it formed various carbon bearing minerals such as shannonite (Pb_2OCO_3) in the highlands. There was no evidence of the formation of $PbCO_3$. PbS was heated in the highland conditions in CO_2/SO_2 and in CO_2/COS, but there was no evidence of any change to the sample. Pb has also been tested in the chamber and when exposed to CO_2/SO_2 in the highlands it produced lanarkite (PbO-$PbSO_4$). When Pb was tested in CO_2/COS it produced another mineral that we are currently confirming through the use of the XPS and LIBS.

Discussion: PbS was found to be stable at all conditions. To confirm its stability, we tested PbS in the lowland conditions in CO_2 for 75 hours and the sample still exhibited no change when analyzed with an XRD. Thus if it is the source there must be a mechanism for its formation in the highlands but not the lowlands. Though there is no evidence of a reaction between Pb and CO_2, it seems to react with SO_2 and COS. Due to the contamination of Pb with PbO (25%) it is difficult to ascertain if the gas is directly interacting with Pb or PbO. Future experiments and thermodynamic calculations will be used to help clarify this issue. Additionally PbO experiments will be completed in the mixed gases to better understand the reactions taking place in the Pb experiments.

Conclusion: If PbS forms on Venus it would be stable in both highland and lowland conditions. Pb did not react to CO_2 but reacts with SO_2 and COS. Venus's atmosphere contains more SO_2 than our experiments, so sulfur bearing minerals, at least PbO-$PbSO_4$, are likely to form on Venus. Unlike Pb, PbO reacts with CO_2 to form minerals (Pb_2OCO_3 and $Pb_3O_2CO_3$). In the future we will also study the stability of PbO and $PbSO_4$ in the mixed gases.

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Detectability and Scientific Implications of Crustal Remanent Magnetism on Venus

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Venus lacks an internally generated magnetic field today. Whether one existed in the past is unknown, yet key to models of long-term evolution and comparative planetology. Canonical models assume the core of Venus has Earth-like structure and composition but is cooling too slowly for convection and thus a dynamo to operate in the core today. However, recent studies of impact craters and other surface features support more steady heat loss over geologic time. Precipitation of MgO from the core and solidification of an inner core over time can also drive compositional convection and a dynamo even if the core cools slowly. Here we present numerical simulations of the coupled atmosphere-surface-mantle-core evolution. Any simulation initialized with an "Earth-like" core (i.e., chemically homogeneous, liquid, and hot initially) predicts a global magnetic field with Earth-like surface strength for >2 to 3 billion years after accretion. Dynamo activity is suppressed today if the thermal conductivity is higher than the lower limit to the modern range of uncertainty. Sporadic dynamo activity is predicted also within the surface age while surface temperatures remain below the Curie point of magnetite. If Venus accreted under relatively cold conditions, in contrast, then chemical stratification in the core could always preclude a dynamo. Any detection of remanent magnetism would thus provide vital constraints on the accretion, evolution, and recent climate history of Venus.

Prior studies downplayed the prospect of obtaining useful results from a new search for crustal remanent magnetism on Venus. However, past measurements from spacecraft only exclude crustal magnetization near the Venera 4 landing site and northward of 50º South latitude (i.e., the periapsis latitudes for Venus Express and Pioneer Venus Orbiter) for >150 km coherence scales and strong magnetization intensities. Venusian rocks could acquire thermoremanent magnetism (TRM) if an ambient field exists when they cool below the Curie temperature(s) for their magnetic carrier(s). Venus has the hottest surface in the Solar System—but the average temperature (~737 K) is still ~100 and 200 K below the Curie points of magnetite (~858 K) and hematite (~948 K), respectively.

Decades of results from terrestrial paleomagnetic studies indicate that magnetite and hematite can retrain TRM for billions of years at near-surface conditions on Venus. Plausible depths to the Curie temperature of magnetite across the surface are >5–10 km and potentially >20 km at regions with below-average heat flow. Based on the iron content measured at landing sites on the volcanic plains, potential magnetization intensities mostly exceed the lower limits for detection by measurements above regions where the horizontal coherence scale of magnetization is greater than the observational altitude. Aerial platforms operating in clement regions of the atmosphere are ~27 times more sensitive than orbiters to small-scale magnetization. Strong crustal magnetization at wavelengths significantly less than 150 km and weak magnetization at longer wavelengths may still await detection almost anywhere on the planet. Future missions thus offer new hope for unveiling the mysterious magnetic history of Venus with implications for our Solar System and beyond.

Associated publications:

[1] O'Rourke, J. G., Gillmann, C., Tackley, P., *2018*. Prospects for an ancient dynamo and modern crustal remanent magnetism on Venus. Earth and Planetary Science Letters 502, 46–56.

[2] O'Rourke, J. G., Buz, J., Fu, R. R., and Lillis, R. J. *2019*. Detectability of remanent magnetism in the crust of Venus. Submitted.

Session 02

Geology and Evolution

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UNVEILING THE INTERIOR OF VENUS: USING TECTONIC DEFORMATIONS ALONG CANALI TO CONSTRAIN LITHOSPHERIC STRUCTURE & MANTLE CONVECTION.

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Venus is Earth's "sister planet", having nearly identical size and density to our home. Despite these similarities, however, its surface and atmosphere took a very different evolutionary path from Earth. Studying the interior of Venus can help us understand when the evolutionary paths of Earth & Venus diverged and what caused this divergence. With the massive interest in the search for life beyond Earth, understanding the evolution of Venus will also contribute towards answering the timely and provocative question of what makes a planet habitable.

Deformational features of various varieties and styles are ubiquitous on the surface of Venus, and many of these display characteristic scales (widths or spacings) of deformation that fall into distinct size classes. We will study the mantle convection and lithospheric structure of Venus by analyzing tectonic deformation features along canali. Canali-type channels are long lava channels with almost constant widths found in the Venusian plains. Stratigraphic evidence points towards the canali being old features on the plains that formed with the last phases of extensive plains volcanism possibly induced by a global resurfacing event 300 Myr ago [1,2]. When these channels were emplaced, they must have followed shallow downhill gradients. Post-depositional tectonic deformations in the Venusian lithosphere, however, have caused the topography of modern canali to be interspersed with various scales of periodic relief [3]. The dominant length scales associated with these periodic deformation features can inform lithospheric structure. The largest scale deformation may provide evidence for mantle convection.

We have mapped all major (longer than 300 km) canali on Venus and obtained their topographic profiles. Within these profiles, we have found several characteristic length scales that show some regional correlation. While most terrain contains characteristic length scales between 100-125 kms, some areas also exhibit longer length scales between 300-400 kms. During the next stage of our project, we will use the discovered length scales to build on crustal-thickness models [4] and plume models [5] and link the observed length scales to the lithospheric structure and mantle convection of Venus.

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A two-stage evolution model of Venus' mantle and its implications for the Earth

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We developed a series of numerical models of magmatism in a convecting mantle with a stagnant lithosphere to understand the evolution of Venus' interior. Magmatism occurs as a permeable flow of basaltic magma generated by decompression melting through the solid mantle, and the solid-state convection of the mantle with temperature-dependent Newtonian rheology is affected by the garnet-perovskite transition and the post-spinel transition. In our preferred models, the mantle evolves in two stages: On the earlier stage, the solid-state convection occurs as a layered convection punctuated by repeated bursts of hot materials from the lower mantle to the surface. The bursts induce vigorous magmatism that forms the basaltic crust, enriched in heat-producing elements (HPEs). A part of the basaltic crust recycles into the mantle and accumulates along the post-spinel boundary to form a barrier to the convective flow; the barrier occasionally collapses to cause the bursts. On the later stage when the HPEs have already decayed, in contrast, the basalt barrier disappears and whole-mantle convection occurs more steadily. Mild magmatism is induced by small-scale partial melting at the base of the crust and hot plumes from the deep mantle. The internal heating by the HPEs that recycled into the mantle in the earlier stage allows the magmatism of the later stage to continue throughout the calculated history of mantle evolution. The two-stage evolution model meshes with the observed history of magmatism and the lithosphere on Venus. By implementing a model of tectonic plates to this model of Venus, I also obtained a two-stage evolution model of the Earth's mantle that meshes with observed features of the Earth's history. On the earlier stage that continues for 1-2 billion years, tectonic plates move chaotically due to repeated bursts of hot materials from the lower mantle. On the later stage, however, plate motion becomes steadier, as mantle bursts subside.

The early and long term evolution of Venus and its atmosphere.

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Venus shares some striking similarities with Earth; at the same time, it exhibits characteristics that are widely different from that of our own planet. Indeed, it is an example of an active planet that followed a radically different evolutionary pathway despite the similar mechanisms at work and probably comparable initial conditions. Understanding Venus' evolution might be a key to our comprehension of how a planet can become or cease to be habitable.

We have been developing a coupled numerical simulation of the evolution of Venus, striving to identify and model mechanisms that are important to the behaviour of the planet and its surface conditions. Currently the simulations include modelling of mantle dynamics, core evolution (magnetic field generation), volcanism, atmospheric escape (both hydrodynamic and non-thermal), evolution of atmosphere composition, and evolution of surface conditions (greenhouse effect) and the coupling between interior and atmosphere of the planet. We have also modelled the effects of large meteoritic impacts on long term evolution through three aspects: atmosphere erosion, volatile delivery and mantle dynamics perturbation due to energy deposition.

Volatile fluxes between the different layers of the planet seem critical to estimate how Venus changed over time. This is especially important as we have highlighted the strong role played by mantle/atmosphere coupling in regulating both mantle dynamics and surface conditions through surface temperature evolution. Mantle convection regime evolves with time and depends on surface conditions. We produce scenarios that fit present-day conditions and feature both early mobile lid regime (akin to plate tectonics) as well as late episodic lid regime with resurfacing events. The early history of Venus, in particular, seems to have large repercussions on its long term evolution and present-day state, as it determines volatile inventories and repartition.

Large impacts also affect significantly the evolution of Venus during the Late Veneer era. While the atmosphere erosion they generate is only moderate and doesn't deplete the atmosphere as much as swarms of smaller bodies, they act as a significant source of volatiles. Indeed, if Late Veneer is mainly composed of volatile-rich bodies, it is very difficult to reach the observed present-day state of Venus; instead the atmosphere may become too wet. Large impacts also affect mantle convection, modifying convection patterns for millions of years. Finally, the more energetic collisions (impactors with radii in the 100s of km, high velocity) generate massive melting events near impact location, associated with large scale degassing of the mantle. This leads to mantle depletion and can potentially leave (at least) the upper mantle of the planet dry, with strong consequences for later evolution. Therefore, in the absence of remixing mechanism, large impacts move water from the mantle to the atmosphere and are difficult to reconcile with present-day observation.

Modeling Venus-like Worlds Through Time: The habitable zone, and the evolution of Venus' atmosphere.

Michael J. Way & Anthony D. Del Genio
NASA Goddard Institute for Space Studies

Using a modern three-dimensional general circulation coupled atmosphere/ocean model [1] we recently demonstrated [2] that climatic conditions may have permitted liquid water on Venus' surface for ~2 billion years in its early history. Similar such conditions on Earth are believed amenable to the rise of life. Several assumptions were made based on what little data we have for early Venus such as; the type of solar spectrum extant at that time, orbital parameters, estimates of a shallow ocean from Pioneer Venus D/H ratios, and topography from the Magellan Mission. We also assumed that it would have had an atmosphere similar to modern day Earth: 1 bar N_2, 400ppmv CO_2, 1ppmv CH_4. I will discuss the motivations behind these assumptions and additional parameter space studies with direct relevance to hypothetical exoplanetary Venus-like worlds found at the inner edge of the liquid water habitable zone. Finally, I will show how our studies demonstrate that the reason for Venus' present climatic state is unlikely to be related to the gradual warming of our sun over the past 4Gyr as is commonly believed.

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The Evolution of Climate and a Possible Biosphere on Venus

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Of the three local terrestrial planets, two have lost their oceans either to a subsurface cryosphere or to space, and one has had liquid oceans for most of its history. It is likely that planetary desiccation in one form or another is common among extrasolar terrestrial planets near the edges of their habitable zones. As our understanding of terrestrial planet evolution has increased, the importance of water abundance as a substance controlling many evolutionary factors has become increasingly clear. This is true of biological evolution, as wel as geological and climatic evolution. Water is among the most important climatically active atmospheric gasses on the terrestrial planets. It is also a controlling variable for tectonic style and geologic processes, as well as a mediator of surface-atmosphere chemical reactions. Thus, understanding the sources and sinks for surface water and characterizing the longevity of oceans and the magnitude of loss mechanisms on terrestrial planets of differing size, composition and proximity to stars of various stellar types, and the range of physical parameters which facilitates plate tectonics is key to defining stellar habitable zones.

Venus almost surely experienced a transition, early in its history, from a wet, more Earth-like environment to its current hot and highly desiccated state. The timescale is disputed, but recent results using 3D GCM's suggest that, depending on ancient rotation rate and topography, an ancient ocean may have persisted for ~ 2 GY.

A more recent global transition is indicated by the sparse, randomly distributed and relatively pristine crater population, which implies a decrease in volcanic resurfacing rate between 300 and 1000 Myr ago. The accompanying decline in outgassing rate may have caused large climate change. Geological evidence for dramatic changes in resurfacing rate implies large amplitude climate changes which may have left a record of synchronous global deformations and other climatically forced geological signatures. These two transitions may have been causally related if the loss of atmospheric and interior water caused the transition from plate tectonics to single plate behavior.

Today ongoing volcanism most likely provides the ingredients for the global sulfuric acid cloud decks. Rapid loss of SO_2 to carbonates at the surface and H_2O to space strongly implies an active source for these gases on the scale of 10's of MY, a result consistent with surface data suggesting the presence of active volcanism. The stability of Venus' climate is therefore likely dependent upon active volcanism and the sulfur cycle.

For much of solar system history Earth may have had a neighboring planet with life-supporting oceans. During this time the terrestrial planets were not isolated. Rather, due to frequent impact transport, they represented a continuous environment for early microbial life. Life, once established in the early oceans of Venus, may have migrated to the clouds which, on present day Venus, may represent a habitable niche. Though highly acidic, this aqueous environment enjoys moderate temperatures, surroundings far from chemical equilibrium, and potentially useful radiation fluxes. Observations of unusual chemistry in the clouds, puzzling patterns of unidentified solar absorbers, and particle populations that are not well characterized, suggest that this environment must be explored much more fully before biology can be ruled out. A sulfur-based metabolism for cloud-based life on Venus has been proposed. While speculative, these arguments, along with the discovery of terrestrial extremophile organisms that might survive in the Venusian clouds, establish the credibility of astrobiological exploration of Venus.

Session 03

Clouds and Chemistry (1)

Session Chair: Franklin Mills
Session Chair: Kevin McGouldrick

Microscope for Life Detection in Venus Clouds.

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Introduction: Although Venus clouds consist of droplets of 75-85% sulfuric acidic-water, sulfuric acid is not sufficient to explain the observed cloud contrasts and albedo of the planet [1]. Contribution of other chemical species involved in the absorption has been discussed so far [2]. Based on the presence of active volcanos suggested on Venus [3] and the possible existence of the past liquid water, emergence and evolution of sulfur-metabolizing or thermophilic bacteria have been discussed [4]. Although surface of current Venus is too severe for organic compound and living organism to survive, altitudes with moderate temperature and pressure exists several tens km above surface on Venus. Presence of microorganisms in the clouds [4] that might contribute to the spectroscopic characteristics is premised. Life detection instruments will be useful to distinguish biological aerosols from abiotic ones [4], for the aerial platform based astrobiological missions.

Our Approach: We propose a Life Detection Microscope (LDM) as a good candidate for this purpose. LDM has been designed to obtain visible images of particles to search for possible "cells" in the samples with the resolution (1 μm/pixel) needed to observe most of terrestrial microbes. Pigment system has also been designed to distinguish biotic organic compounds from abiotic ones. Cells are represented as ones with biological organic compounds surrounded by membrane, and are also observed by the system [5]. The LDM detects life as particles having the organic compounds and characteristics of life on earth as following. Terrestrial life is sustained by organic compounds. The compounds are separated from their environment by an envelope structure called membrane, so that variations in the external environment would have small effect on the cell homeostasis. The "cell" structure with organic compounds surrounded by the membrane is the fundamental framework for terrestrial life. In order to produce free energy for sustaining life, organic compounds in a cell possess the catalytic activities. Although we do not know yet what life on Venus clouds looks like, as our biology stands on the principle that all the terrestrial life has cells as the building block, it is reasonable to use the same approach for detecting Venus life. Based on such postulation, LDM is capable of characterizing and detecting organic compounds with a combination of widely used fluorescent dyes. In biology, combination of fluorescent dyes are frequently employed for facilitating the detection of various compounds: biotic organic compound seen inside cells such as DNA, RNA and proteins, biotic organic compound surrounded by membrane, and those of abiotic origin such as polycyclic aromatic hydrocarbon (PAH). Additionally, the product of biochemical catalytic activity, (so-called enzymatic activity), can also be detected. Organic compounds surrounded by membrane having catalytic activity, which is equivalent to the fundamental factors that we think for a cell to maintain life, i.e., can be imaged by our microscope. Specifically, "cells" can be detected using fluorescence dyes named SYPRO Red, SYTO 24, propidium iodide and CFDA-AM. PAH and proteinoid are stained by SYPRO Red. Organic molecules inside cells are stained by SYTO 24 regardless of their state, dead or alive. Propidium iodide, on the other side, stains only the dead cells. Accordingly, the combination of propidium iodide and SYTO 24 is effective to distinguish living cells from dead cells. CFDA-AM will yield fluorescent compound through the most commonly found reaction in terrestrial life, i.e., one catalyzed by esterase. [6] All these piments are now being examined if they have desired function in acidic condition, and a part of them seems positively working. Aerial platforms such as Venus Atmospheric Mobile Platform can be a vehicle for LDM [7] to analyze aerosol collected in the Venus clouds.

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SPICAV-UV/VEx: SO_2, O_3 and UV absorber

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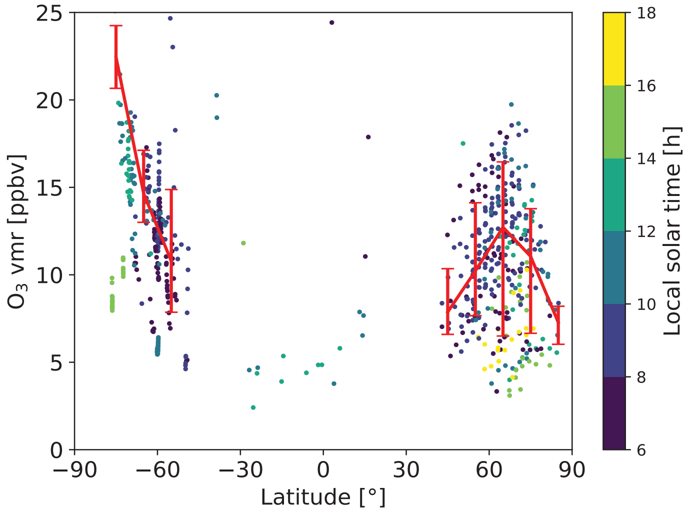
SPICAV [Bertaux et al., 2007] was a UV and IR spectrometer on board Venus Express, ESA's first mission in orbit around Venus (2006−2014). Observations of the reflected UV sunlight (170 to 320 nm, R ∼ 200) by SPICAV during the whole mission were sensitive to many variable quantities near Venus' day side cloud top (65 − 75 km): (1) gaseous constituents such as SO_2 [Marcq et al., 2011, 2013] and (2) O_3, (3) UV absorption caused by a yet unknown UV absorber within submicron particles, and marginally (4) cloud top altitude (via differential CO_2 absorption).

Here we present the first full analysis of the complete SPICAV-UV nadir data set. First findings include: (i) detection of ∼ 10 ppb cloud top O_3 at latitudes higher than 50° [Marcq et al., 2019] (ii) confirmation of most of the spatial and temporal trends of SO_2 climatology as described by Marcq et al. (2013, 2011) and other observers [Jessup et al., 2015; Encrenaz et al., 2012, 2013, 2016, submitted; Marcq et al., submitted]: short-lived bursts of SO_2 at lower latitudes, happening more often in the 2006-2009 epoch; (iii) possible enhancement of SO_2 over the western slope of Aphrodite Terra; and (iv) spatial and temporal variations of the UV absorber embedded in mode 1 particles, with darker lower latitudes and a possible secular darkening in the 2006-2010 epoch.



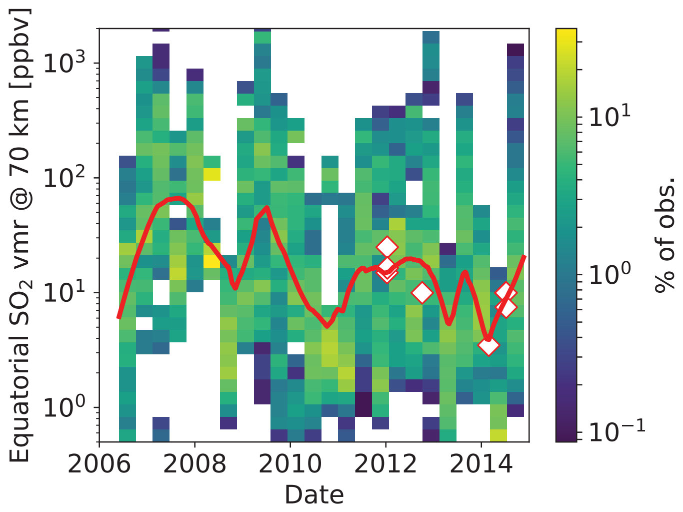


Fig. 1 (left) *cloud top (55-70 km) O_3 measurements in 2006-2014 using SPICAV/Venus Express*
Fig. 2 (right) *Moving median (solid red) SO_2 mixing ratio as measured by SPICAV/Venus Express, and TEXES measurements from Encrenaz et al. (white diamonds).*

OPTICAL PROPERTIES OF VENUS AEROSOL ANALOGUES. Michael J. Radke[1], S. M. Hörst, C. He[1], and M. H. Yant[1]
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Introduction: The Venusian cloud deck is a 20-km-thick global layer of sulfuric acid droplets with other trace components. This cloud layer absorbs fully half the incident solar radiation and is important for understanding the thermal balance, composition, and chemistry of the Venusian atmosphere [1,2]. A complex sulfur cycle sustains the extensive cloud layer, which includes particles of sulfuric acid, elemental sulfur, and an unidentified ultraviolet absorbing species [3]. The wealth of new ground-based and spacecraft data in recent years has transformed our understanding of the Venusian clouds and their temporal and spatial variability.

A variety of measurements have converged on a trimodal (or bimodal) model for Venus' clouds [e.g. 4–7]. Reflected light phase curves as measured by spacecraft and ground-based telescopes are strongly sensitive to variations in particle size and refractive index. Many retrievals find a refractive index that is higher than possible for aqueous sulfuric acid [e.g. 7–9], suggesting that a higher refractive index component must be present in the clouds. It has long been suggested that other, non-sulfuric-acid, components are present in the clouds: elemental sulfur [10,11], sulfur oxides [12], iron chloride [13,14], and phosphoric acid [14], among others. However, most of these proposed "contaminants" lack refractive index measurements over the full range of wavelengths for which phase curves and/or polarimetry are available. Additionally, the wealth of new ground-based and spacecraft observations of Venus in recent years has revealed that both cloud particle size and refractive index are variable in time and location [9,15–18]. These factors, combined with the inherent degeneracies within Mie scattering models, can result a wide range of retrieved cloud parameters from remote sensing observations that cannot be used to effectively interpret cloud composition and chemistry.

Methods: In order to address this issue we have measured the optical properties of a variety of Venus aerosol analogues—both as pure substances and as mixtures with sulfuric acid. Imaginary refractive indices ($n + ik$) of pure solids were measured from 0.2 – 28.0 µm, and liquids and mixtures from 0.2 – 5.0 µm, using FTIR and UV-Vis spectroscopy.

We also investigated the production and chemistry of additional possible cloud components by performing photochemistry experiments with Venus atmospheric gases in the lab. Laboratory experiments of sulfate aerosol formation have been performed with Earth-like atmospheres [19,20], but similar investigations have, until now, not been performed for strongly oxidized Venus-like atmospheres. In our new experiments, Venus analogue atmospheres composed of CO_2 and SO_2 to an energy source (UV lamp or cold plasma) to initiate photochemical reactions. Conditions of these experiments (295K to 180 K and ~10 mbar) were most similar to about 80 km altitude on Venus, well above the main cloud layer. Our experiments generated both gaseous and solid products, which were collected for analysis with mass spectrometry and optical spectroscopy.

Experimental SO_2 mixing ratios were varied from parts-per-million to several percent, in order to encompass the full range of possible mixing ratios on Venus—from the SO_2-poor upper atmosphere to SO_2-rich volcanic gases—in order to investigate the effects of SO_2 on aerosol formation.

Results: Preliminary photochemistry experiments performed with mixtures of SO_2 and CO_2 generated micron to millimeter size particles of yet unknown composition. Analysis of these particles is difficult due to their low abundance and quick reaction with terrestrial atmospheric gases.

Complex refractive indices were measured for possible Venus cloud species (and mixtures with sulfuric acid). These refractive indices can be used in Mie scattering models of Venus' clouds to help understand compositional changes in the clouds.

Future work may include measurement of optical constants at low temperature, spectroscopy of other possible Venus lower cloud components, and photochemistry experiments with additional trace gases.

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Principal Components of UV Albedo Variability in Venus' Atmosphere as seen at 283 nm

Pushkar Kopparla, Yeon Joo Lee, Takeshi Imamura, Atsushi Yamazaki

We explore the dominant modes of variability in the observed albedo at the cloud tops of Venus using the Akatsuki UVI 283 nm observations over the period Dec 2016 to May 2018. The observations consist of images of the dayside of Venus, most often observed at intervals of 2 hours, but interspersed with longer gaps. The orbit of the spacecraft does not allow for continuous observation of the full dayside, and the unobserved regions cause significant gaps in the dataset. The missing data are interpolated and the dataset is then subjected to a principal component analysis (PCA) to find six oscillating patterns in the albedo. Some of the spatial patterns and the time scales of these modes correspond to well known physical processes in the atmosphere of Venus such as short period atmospheric waves and the overturning circulation, while others defy a simple explanation. We also a find a hemispheric mode that has not been identified before and discuss its implications.

Title:
Intense Decadal Variation of Venus' UV Albedo and its Impacts on the Atmosphere

Authors:
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Abstract:

Around 70 km altitude from the surface, Venus' an unidentified absorber creates broad absorption spectrum in the UV-to-visible wavelength range that peaks around 340-380 nm. Recent efforts to identify this unknown absorber suggest several candidates, e.g., OSSO, S_2O, S_x, $FeCl_3$, by fitting observed spectra or through chemical modeling. However, the chemical composition of this absorber is yet an unsolved question, and even iron-bearing microorganism has been suggested. Regardless on its identity, it is known that it absorbs about half of the solar energy deposited in the atmosphere according to several model calculations. As a result, the unidentified absorber plays a critical role in the atmospheric energy balance.

Here we report the first quantitative study on the variability of the cloud albedo at 365 nm and its impact on Venus' solar heating rates based on an analysis of Venus Express (2006-2014) and Akatsuki (December 2015-May 2017) UV images, and MESSENGER (June 2007) and Hubble Space Telescope (January 2011) UV spectral data. These results show that the 365-nm albedo varied by a factor of 2 from 2006 to 2017 at both high and low latitudes. This is the largest level of decadal variations compared to the other bodies in the Solar System.

We take into account this observed range of 365-nm albedo variations in our radiative transfer calculations, fitting the observed albedo by multiplying factors to the mode-1's assumed absorption coefficient for the unknown absorber in the spectral range of 310-780 nm (Crisp 1986). The results show that the observed albedo variance can produce a -25~+40% variance in the low latitudinal local noon time solar heating rate. This means that the cloud top level atmosphere should have experienced considerable solar heating variations over a decade.

We suggest that this variable solar heating would drive dynamical changes like the reported Venus' zonal wind variations from 2006 to 2017. The solar heating rate variances may also provide the first evidence of climate change on Venus due to the clouds, a phenomenon distinct from other terrestrial clouds which buffer against climate change.

Mapping of Venus' cloud top altitude from Akatsuki/IR2 dayside images

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7. Tohoku University
8. Chiba Institute of Technology

We present the cloud top structure of Venus retrieved from a total of 93 dayside images acquired at a wide variety of solar phase angles (0-120˚) by the 2.02-μm channel of the 2-μm Camera (IR2) onboard Venus orbiter, Akatsuki, during the period from April 4 to May 25, 2016. Since the 2.02-μm channel locates in a CO_2 absorption band, the sunlight reflected from Venus allows us to determine the cloud top altitude (unit aerosol optical depth at 2.02 μm) with radiative transfer calculation. Firstly, the observed solar phase angle dependence and zonal variation of the reflected sunlight in the equatorial region were used to construct the averaged cloud top structure characterized by cloud top altitude z_c, Mode 2 radius $r_{g,2}$, and cloud scale height H which are 70.287 km, 1.26 μm and 5.1 km, respectively. Secondly, individual cloud top altitudes were retrieved with the assumption that the last two values described above are valid for the entire planet. The latitudinal structure of cloud top altitude is symmetrical with respect to the equator: the averaged cloud top locates at altitudes of 68-70 km equatorward of ±45˚ but rapidly drops in latitudes of 50-60˚ (-50--60˚) and reaches 61 km poleward of ±70˚. The averaged cloud top in the equatorial region indicates the tendency to increase from early morning (~7 h) and reach a maximum near early afternoon (~14 h) and decrease toward late afternoon (~17 h). The magnitude of the change is less than 1 km.

Session 04

Atmospheric Dynamics (1)

Session Chair: Masahiro Takagi
Session Chair: Sebastien Lebonnois

Venus in context : exploring atmospheric circulation regimes for slow (and fast) rotators

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Together with Saturn's moon Titan, its atmosphere and that of Venus represents two of the most extensively studied atmospheres in which the planetary rotation rate is sufficiently slow to be unable to support a circulation in geostrophic balance. Both atmospheres exhibit strong zonal super-rotation, in the sense that the local peak and globally integrated angular momentum far exceeds that of an atmosphere in co-rotation with its underlying planet. Both bodies also exhibit well developed polar vortices and a spectrum of waves and eddies over a range of scales, but the dynamical processes maintaining these circulations appear to be significantly different in each case. Although much can be learnt about these atmospheres by developing sophisticated and comprehensive numerical models of their circulation and climate that are carefully designed to reproduce many features specific to either planetary body, in order to draw more general conclusions it is necessary to explore the simulated circulation and climate obtained in more simplified, prototypical atmospheric models[1,2]. This approach allows us to put atmospheres such as Venus and Titan into a wider context and to begin to understand how the roles of different dynamical processes in the circulation may depend upon key planetary properties and parameters. In this study, we make use of a simplified General Circulation Model (GCM), based on the Portable University Model for the Atmosphere (PUMA) from the University of Hamburg[3]. This uses simplified (linear) boundary layer friction, dry convective adjustment and a Held-Suarez style Newtonian cooling scheme (designated here as PUMA-S)[2] or a simple two-band gray radiation scheme (designated PUMA-G). A series of controlled experiments are conducted by varying planetary rotation rate and other parameters. These defining parameters are further combined with each other into dimensionless forms to establish a generalised parameter space, in which the occurrences of different circulation regimes are mapped and classified. Clear, coherent trends are found when varying planetary rotation rate (thermal Rossby number) and frictional and thermal relaxation timescales. In this contribution we present results from parameter sweeps that embrace conditions relevant to TItan and Venus, both with and without a diurnal cycle, focusing on diagnosing heat transport, super-rotation and turbulent energy cascades. Results confirm, amongst other things, that Venus's realistic super-rotation likely requires a thermal tide or other processes to maintain its observed super-rotation, although Titan's atmosphere does not require this. Heat transport is overwhelmingly dominated by the global Hadley cells at most altitudes, and turbulent kinetic energy cascades are dominated by a strong downscale transfer via a spectrum of divergent inertia-gravity waves in a self-similar spectrum that closely follows the Kolmogorov $k^{-5/3}$ form[4]

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Atmospheric simulations using Venus AORI general circulation models

*Masaru Yamamoto (RIAM, Kyushu Univ.), Kohei Ikeda (NIES), and Masaaki Takahashi (NIES)

Atmospheric dynamics on Venus have been investigated by our simplified GCMs (Yamamoto and Takahashi 2003, 2006, 2009, 2012, 2015, 2018a). At the same time, we have been developing full-physics GCM (Ikeda 2011). In simplified models, the simulated temperature is relaxed to the assumed reference profile by the Newtonian cooling and it is not reproduced by the radiative transfer. However, the simplified GCMs are useful for investigating numerical properties of the dynamical core in the long-term simulation (Yamamoto and Takahashi 2016, 2018b) before applying the dynamical core to the realistic full-physics Venus GCMs. Our recent investigation showed that the super-rotation intensity is sensitive to the horizontal subgrid diffusion. The idealized experiments using the ISSI benchmark show that the strong horizontal subgrid diffusions with the coefficients equal to or larger than that used in Earth's model likely produce fast super-rotation in our model. In the technical view, we need to fully comprehend the effects of the horizontal diffusion on the long-term simulation, in order to check whether the simulation is artificial or physically valid.

Toward full-physics atmospheric modeling, we have been developing Venus GCM at Atmosphere and Ocean Research Institute, Univ. Tokyo (Ikeda 2011), in which both the topographical data and radiative code are incorporated (Yamamoto et al. 2019). We investigated solar-locked and geographical atmospheric structures on Venus and reproduced the wind structure near the subsolar point and the cloud-top slowness of zonal wind over the Aphrodite Terra. The stationary wind slowness corresponds to the negative wind deviation of the topographically forced wave. The incorporation of the radiative code reproduced the heat budget and the static stability similar to the observations. The equatorial super-rotation of ~90 m/s and mid-latitude jet cores of ~120 m/s are simulated around the cloud top. Zonal-mean poleward flow is strong above the cloud layer, where there is a large imbalance between solar and infrared radiative heating. Around the cloud top where the solar radiative heating balances the infrared one, a poleward flow of ~1 m/s is confined within the equatorward flank of the jet core, whereas indirect circulations at high latitudes are formed by the eddy heat fluxes owing to the thermal tide and baroclinic waves. Significant differences between the zonal and dayside averages of the meridional wind and its related fluxes within the cloud layer suggest that we must carefully estimate the zonal-mean Hadley circulation and eddy momentum and heat fluxes from the one-side hemisphere. In this presentation, based on the T21 and T63 models, we discuss the atmospheric structure simulated under the realistic thermal and topographical conditions.

Localtime-dependent structures in the Venusian atmosphere revealed by Akatsuki radio occultation measurements

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As the localtime-dependent structure in the Venusian atmosphere, structures that seem to be thermal tides have been detected in the wind field at the cloud top and in the atmospheric temperature above the cloud layer; however, localtime-dependent structures below the cloud top have been unknown. The cloud-level atmosphere undergoes a periodical change in solar heating with a period of about 4 days due to the super rotation. It is expected that this affects cloud physics through a periodic variation of convection in the cloud layer (Imamura et al. 2016), although it has not been confirmed by observations. Though disordered patterns are known to appear at the cloud top especially in the vicinity of the sub-solar point, what kind of temperature fluctuation causes them is unclear. So that thermal tides contribute to the maintenance of the super rotation, it is particularly important that they propagate downward below the cloud layer to exchange zonal momentum between the upper and the lower atmosphere, but the structure of the waves below the clouds is not known.

Radio obscuration is a powerful technique to capture such atmospheric variations below the cloud top. We have conducted radio occultation measurements from 2016 using Venus orbiter Akatsuki, and have acquired temperature and pressure profile. Since the spacecraft is orbiting the equatorial region, data were obtained especially in the low latitude. According to the initial analysis, the thickness of the neutral layer in the cloud seems to be thicker and more variable on the nightside than on the dayside. This is considered to reflect the variation of the convective activity. Structures depending on the localtime are seen also below the cloud layer; they might be related to thermal tides. Above the cloud layer, we observe structures finer than the wavenumber-1 and 2 components that were conventionally recognized as thermal tides (Ando et al. 2018). We discuss implications of those structures for atmospheric dynamics.

Continuous monitoring of planetary-scale waves at the Venus cloud top

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Introduction

On Venus, two types of planetary-scale waves, ~4-day Kelvin and ~5-day Rossby wave with zonal wavenumber 1, are considered to exist near the 70 km cloud top. Previous explorations by Pioneer Venus and Venus Express revealed that waves changed one to another in every observation season (e.g., Del Genio and Rossow [1990]; Kouyama et al. [2015]). However, the continuous observation for these waves is limited. Considering the importance of planetary-scale waves not only on the momentum transport but also driving the migration of absorbers and forming planetary-scale UV albedo patterns, investigating the long-term continuous changes in wave activities can help to understand the Venus atmospheric dynamics.

Data & Analysis

We conducted time-resolved periodical analysis in 365 nm brightness and cloud tracking wind (measured as the same manner of Horinouchi et al. [2017]) fluctuations obtained by UVI onboard AKATUSKI Japanese Venus Climate Orbiter from January to September 2017. To capture the continuous variability in periodicity, we made sub-dataset with ±14 days shifting window and stepped it with 1-day interval and Lomb-Scargle periodogram analysis was conducted for each sub-dataset. (Fig. 1)

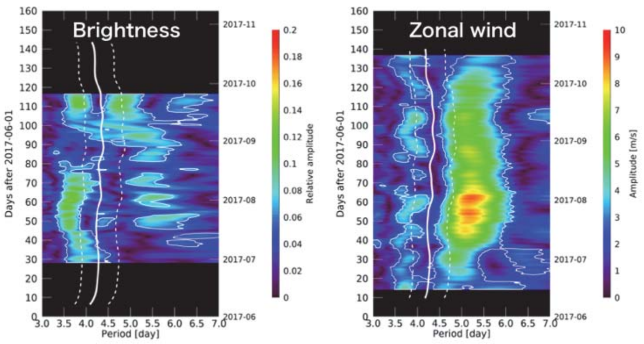

Fig. 1: Temporal changes in periodicities of measured brightness (left) and zonal wind (right) fluctuations at the equatorial region (S10°–N10°)

Results & Discussion

During the observation season, the dramatical evolution of planetary-scale waves and the dynamical connection between wave and planetary-scale UV features. (Fig. 2) We could find prominent ~5-day periodicity in both wind and brightness fluctuations, whose phase velocity was slower than dayside mean zonal winds (or the super-rotation) by > 35 ms^{-1}. We succeeded to reconstruct the horizontal wind field related to the observed 5-day mode Since planetary-scale vortices, whose the center existed ~35° latitudes, having large equatorial symmetric structures in the latitudinal direction were found as reported Imamura (2006), it can be a manifestation of the low frequency equatorial Rossby wave. The observed Rossby wave subjected to temporal changes of enhancing and attenuating in the amplitude of wind fluctuations with ~100-day time scale. According to the temporal evolution of the Rossby wave, white cloud belts in 45° –60° latitudinal regions began rippling synchronously in both hemispheres. Moreover, the Rossby wave deformed the planetary-scale dark UV feature in the equatorial region, and that should be the reason for significant 5.1-day periodicity in brightness variation. Before the Rossby wave enhancement, weak 3.8-day periodical signals can be observed in zonal wind and brightness variations in the equatorial region. This is a suggestive prograde propagating Kelvin wave, and it might be the reason for the origin of dark clusters in the equatorial region.

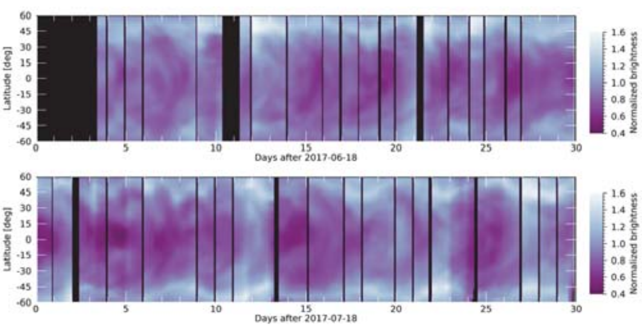

Fig. 2: Reconstructed UV brightness patterns as functions of time and latitude. Time series of brightness data was partitioned with 8-hour interval of observation time. Top and down panels correspond to the Day 31 and 61 of Fig 1.

Planetary-scale streak structure reproduced in high-resolution simulations of the Venus atmosphere with a low-stability layer

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Introduction

Night-side images of Venus taken by the IR2 camera on board the Venus Climate Orbiter/ Akatsuki has shown many features of the lower cloud layer. One prominent feature is a bright planetary-scale streak structure extending from high-latitudes to low latitudes on both hemispheres. Because the IR2 night-side images capture infrared radiated from the near-surface atmosphere, the bright regions indicate thin-cloud regions.

Numerical model and set up

We have performed high-resolution simulations of the Venus atmosphere by a simplified general circulation model, which is based on AFES: the Atmospheric general circulation model For the Earth Simulator. The horizontal resolution is T159 (i.e., about 0.75 deg x 0.75 deg grids) and the vertical resolution is about 1 km with the model top at 120 km. In the model, the atmosphere is dry and simply forced by the solar heating with the diurnal change and Newtonian cooling that relaxes the temperature to the horizontally uniform basic temperature which has a virtual static stability of the Venus atmosphere with a low-stability (0.1 K/km) layer from 55 km to 60 km.

Results

In our simulations, a planetary-scale streak structure similar to that observed by the IR2 night-side image is reproduced by strong downward flows in the vertical velocity field above the low-stability layer. Because downward flows can decrease cloud amounts and make a thin-cloud region, the reproduced streak structure is consistent with the observation. Seen from above the pole, the simulated streak structure shapes a huge spiral extending from the polar vortex to low latitudes. Such spiral may correspond to that observed by VIRTIS on board Venus Express. The streak structures on both hemispheres are synchronized, that is, the streak structures located in the same longitude. Our analyses show that the synchronization is due to equatorial Rossby-like and Kelvin-like waves with wavenumber 1, configuring vertical shear instability.

Further experiments and analyses suggest that the streaks of downward flow are caused by meridional tilting of the phase line of the equatorial Rossby-like waves. This tilting seems to be induced by high-latitudinal strong zonal winds that are reinforced by the baroclinic instability produced around the low-stability layer. The mechanism would be similar to that for the mid-latitude jets and baroclinic waves in the Earth atmosphere.

Acknowledgements

We thank all of the members and contributors of the Akatsuki project. This study was partly conducted under the Earth Simulator Proposed Research Project titled “Simulations of Atmospheric General Circulations of Earth-like Planets by AFES” and the simulations were performed on the Earth Simulator with the support of JAMSTEC. This study was also supported by MEXT as “Exploratory Challenge on Post-K computer” (Elucidation of the Birth of Exoplanets [Second Earth] and the Environmental Variations of Planets in the Solar System). This study was supported by JSPS KAKENHI 16H02225, 16K17809, and 17H02961.

The complex features and dynamics of the nightside clouds of Venus as revealed by Akatsuki and Venus Express

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The morphology of the Venus's dayside upper clouds and their motions have been extensively studied for about 90 years. Initial observations discovered an unknown absorber in ultraviolet images that allows to find contrasted features used to measure the superrotating winds at cloud level. The first space missions found more than 40 years ago a zoo of mesoscale cloudy features. Unfortunately, most of the observations have focused on these dayside upper clouds, and we are yet far away from a deep understanding on the role that the atmospheric dynamics play in the variety of shapes and contrasts observed on the clouds, the mechanisms behind the atmospheric superrotation or the importance of atmospheric waves and eddies. The exploration of the clouds and dynamics on the nightside of Venus delayed about half-a-century compared to the dayside, with the different Pioneer Venus and Venera probes and Vega balloons providing important data but at specific points and short instants, and not in a global hemispheric night vision of Venus clouds. The remote sensing of the night side presents the advantage of a wider multi-level sensing by combining observations at certain near-infrared windows (1.74, 2.32 and 3.20 μm) to observe the lower cloud's opacity and other infrared bands (3.8, 5.0, 10 μm) which permit to visualize the thermal emission of the upper clouds. The space missions Akatsuki (JAXA) and Venus Express (ESA) have revolutionized our knowledge of the nightside of Venus far beyond our expectations. The thermal emission from the night upper clouds shows features apparently unrelated to those observed on the dayside albedo, like fast bright filaments which seem to alter the vertical thermal structure, shear instabilities and abundant waves which seem stationary with respect to the surface and located above elevated terrains. At the lower clouds a remarkable periodical westward-propagating cloud discontinuity –that we have missed for decades– is present at low latitudes, non-stationary waves, frequent shear instabilities and mesoscale vortices. Besides, these morphologies, the superrotation at the nocturnal upper clouds is unexpectedly less homogeneous than on the dayside, while the lower clouds show a recurrent equatorial jet, and an apparent decadal variation when observations from ground-based, Pioneer Venus, Galileo, Venus Express and Akatsuki are combined.

Session 05

Session 05 Future Missions+A69s

Session Chair: Colin Wilson
Session Chair: Takehiko Satoh

Preparing for Venus Surface Exploration

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Exploration of the Venus surface and deep atmosphere to better understand terrestrial planets, including Earth, has been a long-standing objective of the Venus science community. However, the hostile environmental conditions at the surface coupled with thick acidic clouds and dense atmosphere have made achieving those objectives challenging. Previous landers survived only about 2 hours [1] limiting our knowledge of the constituents and processes near the surface. Remote sensing data in this region is generally limited to Magellan radar data, and coarse imaging at 1 micron windows [2-7]. NASA has begun to undertake steps to overcome the challenges and prepare to explore this complex and relevant region of Venus. For example, recent technology advances in sensors, electronics, power and other systems have been funded and this, combined with the new capabilities to replicate Venus conditions on Earth, are changing this paradigm.

One recent new capability is a facility that's capable of replicating Venus atmospheric conditions with high fidelity at essentially any altitude from the surface up to about 75 km. This facility, the Glenn Extreme Environment Rig (GEER), located at NASA's Glenn Research Center, is the largest volume and most comprehensive simulation capability known. GEER can replicate temperature and pressure conditions and, perhaps most uniquely, has the ability to create and indefinitely maintain relevant chemistry. This capability has been demonstrated in numerous tests, several of them lasting 60 days or longer. These successful tests have included Venus geological experiments [8], exposure tests for technology development efforts [9], material compatibility tests [10], and tests to support sensors and instrument developments. Given the new capability of GEER, the time is right to begin to experimentally explore the supercritical nature of this environment.

NASA has also begun development of a long lived Venus surface station. This project, called LLISSE (Long-Lived In-situ Solar System Explorer), is utilizing high temperature electronics and systems to develop a lander that can reliably operate on Venus for an extended period of time, in this case for at least 60 days! [11]. This long-lived lander will begin tackling temporal science of the deep Venus region, something never before attempted. If successful and flown, LLISSE will provide insight into the atmospheric dynamic processes and perhaps the super rotation phenomena. The current state of LLISSE will be discussed.

Further, NASA is investing in mission concept studies to help refine our plans and identify where critical investments are needed. One recent study is SAEVe (Seismic and Atmospheric Exploration of Venus) [12]. It explored what a mission designed around core LLISSE capabilities may be able to achieve if mass is not limited to 10 kg as originally scoped. The study showed that a pair of Venus landers designed to operate for a full Venus solar day could be implemented for an estimated cost of $100M US and stay within a "small sat"category. This mission concept will be presented.

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Solar Spectrum and Intensity Analysis Under Venus Atmosphere Conditions for Photovoltaics Operation

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Solar Spectrum and Intensity at Venus is significantly different from Earth. Due to its thick sulfuric acid clouds, solar illumination at Venus is very weak, altitude dependent and diffused. This analysis uses measured solar spectrum from Venera 11 [1] and Venera 13 [2] missions (Figure 1a). Venera 11 entered the Venus atmosphere at -14 degrees latitude at 11:10 AM local solar time (solar zenith angle 37°). Venera 13 entered the Venus atmosphere at -7.5 degrees latitude at 9:27 AM local solar time (solar zenith angle 38°). Both probes descended to the surface of Venus. Current solar cells do not function effectively in Venus aerial and surface environments, and are not suitable for long-duration Venus aerial or surface missions. This work is focused on the development of solar power system technologies required for mid/low altitude and surface Venus exploration mission concepts. Venus variable altitude or surface missions would require solar power systems that can operate at high temperature (200-465°C) for long duration, and generate power around 70-300 W/m^2 solar irradiance conditions. Based on Venera 11 descent probe measurements, we propose to develop solar cells as depicted in Figure 1b that can generate power for Venus aerial and surface missions [3]. Although current III-V multi-junction solar cells are typically designed to operate under AM1.5 or AM0 solar spectra, the objective here is to design a solar cell structure that is optimized for Venus red-shifted solar spectrum. High temperature Current-Voltage (IV) and spectral current density derived from external quantum efficiency (EQE) measurements under Venus conditions will be presented (Figure 1c).

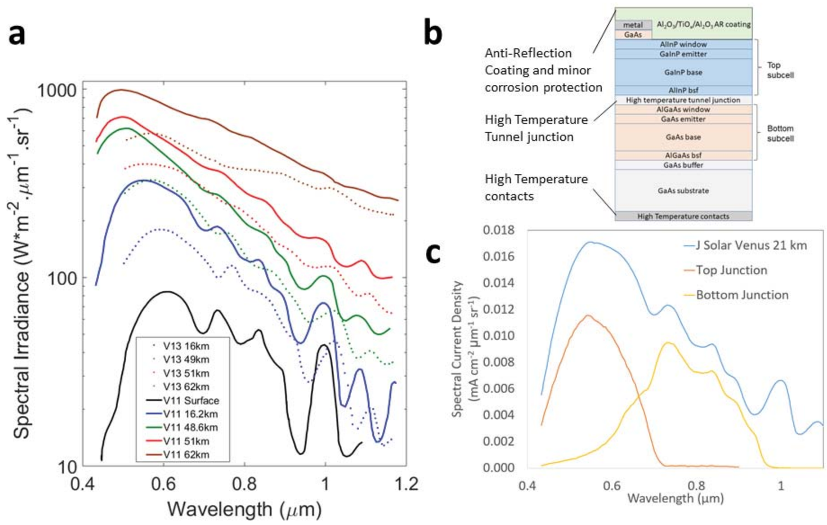

Fig. 1. (a) Solar spectra of the downward scattered solar radiation measured by the Venera 11 and Venera 13 descent probes. (b) Simplified cross-section schematic of a GaInP/GaAs 2J solar cell designed for Venus solar and high temperature operation. (c) Balanced spectral current density (~2.25 mA cm^2 sr^{-1} for both junctions) for a 21 km/300°C Venus optimized solar cell using the measured 300°C EQE weighted by the 21 km Venus solar spectrum.

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VENUS CLIMATE SOUNDER – A LIMB INFRARED RADIOMETER FOR THE MIDDLE ATMOSPHERE OF VENUS.

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Introduction: Despite remarkable progress in understanding the Venusian atmosphere, fundamental questions remain. The key drivers of the atmospheric superrotation are still not identified. The transport of angular momentum is at the core of this issue. Standing waves in the middle atmosphere, recently discovered in thermal imaging from the Akatsuki orbiter [1], offer a new window into likely mechanisms. Major questions include the torque exerted by the atmosphere on the surface due to mountain waves and the altitude at which these waves break. The Venus polar vortex is long-lived but continually evolving, and its development is unpredictable. Its dipole structure has only recently been modeled [2], showing that the thermal tide is a crucial driver of polar atmospheric structure, further complicated by wave interactions. The variability of SO_2 above the cloud layer is another long-standing mystery. UV nadir measurements at 70 km suggest SO_2 fluctuations from <100 to 400 ppb over decadal timescales [3]. Large volcanic eruptions or dynamical changes in the cloud layer may be responsible, but no convincing theory exists to date.

Fig. 1: The MRO/MCS flight instrument during thermal vacuum testing at JPL.

VCS Instrument: The Venus Climate Sounder (VCS) is a passive infrared, limb-sounding, filter radiometer ideally suited to address these questions from a future Venus orbiter. VCS builds on flight heritage from the Mars Climate Sounder (MCS, Fig. 1) [4], which has been operating for over 12 years on the Mars Reconnaissance Orbiter (MRO) [5].

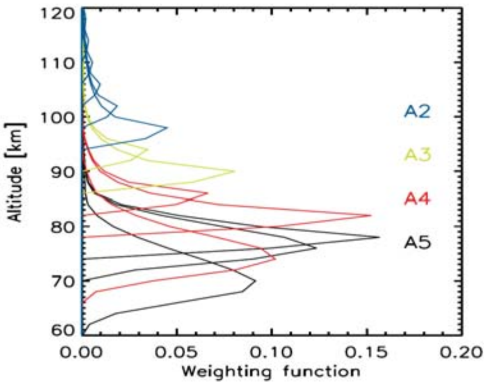

Fig. 2: Vertical response functions of a combined limb/nadir VCS temperature measurement from 500 km altitude. Colors indicate different channels covering the 15 µm CO_2 band.

VCS would use 9 IR spectral channels from 11-45 µm and one UV/vis./NIR channel. Azimuth and elevation actuators, each with a 270° range, would allow pointing anywhere in the downward hemisphere. Each channel would consist of a linear 42-pixel array of uncooled thermopile detectors that measures a radiance profile when aligned vertically on the limb, allowing profiling of temperature from near the cloud tops to ~120 km altitude (Fig. 2), cloud structure near the cloud tops, water vapor and SO_2. A low circular orbit would allow continuous limb profiling while an elliptical orbit would allow limb measurements near periapsis and pushbroom nadir measurements away from periapsis. Vertical resolution depends on orbit altitude, with scale height resolution obtained at ~500 km (Fig. 2) and half scale height resolution at 200-250 km. VCS has been proposed as an international contribution to the ISRO Venus Orbiter Mission to provide a 3D view of atmospheric mountain waves and study polar vortex and SO_2 variability through atmospheric profiling with scale height resolution.

Acknowledgments: Work at the Jet Propulsion Laboratory, California Institute of Technology, is performed under contract with the NASA.

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NASA Planetary Portfolio: Present and Future Plans

Lori S. Glaze
NASA, Planetary Science Division, Director

NASA's Planetary Science Division (PSD) and space agencies around the world are collaborating on an extensive array of missions exploring our solar system. NASA has always encouraged international participation on our missions both strategic (i.e., Mars 2020) and competitive (i.e., Discovery and New Frontiers) and other Space Agencies have reciprocated and invited NASA participation in their missions.

In the case of Venus, NASA has made many investments in future capabilities and potential mission concepts. In particular, NASA has supported US scientists as part of the Akatsuki Participating Scientist Program and has funded technology development activities needed for future Venus missions under the HOTTech, PICASSO, MATiSSE, GEER, PSDS3, and New Frontiers Programs.

In planning for possible future missions, NASA supported the 2017 Venus Aerial Platforms study, held at the Keck Institute for Space Studies (KISS), which explored technical capabilities of several modern approaches for conducting science from within the Venus atmosphere. In 2018, NASA supported the 2018 Venus Surface Platforms study to explore long-lived surface capabilities. NASA has also received multiple proposals for Venus Mission Concept Studies under a recent research solicitation in preparation for the next Planetary Decadal Survey. Selected studies will produce reports that will be provided to the Planetary Decadal Committee for consideration.

In collaboration, IKI/Roscosmos and NASA established a Venera-D Joint Science Definition Team (JSDT) in 2015. Over the last four years, the JSDT has refined the Venera-D mission science goals, priorities, and architecture, and studied possible NASA contributed elements to enhance and complement the mission. The JSDT Phase I report was completed on January 31, 2017 and the Phase II report, was completed on January 31, 2019.

NASA is also collaborating closely with ESA on the proposed EnVision M-5 mission concept. Over the last year, NASA has been engaged with the EnVision Science Study Team, identified potential NASA contributions, and participated in concept studies conducted at ESTEC.

Partnerships with other space agencies have the potential to significantly increase the science return while limiting the cost to each partner. International partnerships are an excellent, proven way of amplifying the scope and sharing the science results of missions. NASA has always encouraged international participation on our missions and other Space Agencies have reciprocated and invited NASA investigators to participate in theirs. As Director of Planetary Science at NASA, I will continue to seek cooperation with our strong international partners in support of planetary missions, including Venus missions.

Rotational motion of Venus and Envision determination

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The interior structure of Venus is still puzzling. The shape of this slow retrograde rotating planet is non-hydrostatic and the presence of a fluid core is still enigmatic. In order to assess information on its interior structure, it is crucial to determine geophysical parameters such as the k_2 Love number and its moment of inertia, on which we will focus here. The moment of inertia can be deduced from the measurement of the rotational motion of Venus and notably the length-of-day variations and precession-nutation. More precisely the rotational motion constrains the relative moment of inertia and then by using the gravity field coefficients it is possible to determine its mean moment of inertia.

The length-of-day of Venus seems to vary by 7 minutes according to the comparison of the observations taken at different epoch over 40 years. This study presents the different mechanisms, tidal torque from the Sun, atmospheric torques acting on the surface and fluid core-mantle coupling, that could play a role in this excitation. In addition, a precession-nutation model of Venus is built and their determination bears information on the relative moment of inertia. The interior parameters are estimated from recent viscoelastic models of Venus.

The rotational variations of Venus can be determined by the future Envision mission, that is presently pre-selected in Phase-A by ESA in the M5-program. Indeed, the radar instrument would observe some surface features several times during the mission. These control points will provide accurate measurements of Venus' rotation. The present work simulates the accuracy on the rotational parameters as a function of the characteristics of the control point network. It discusses the implications for the determination of Venus' interior structure.

ENVISION M5 VENUS ORBITER PROPOSAL: STATUS AND OPPORTUNITIES

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Introduction: EnVision [1] is a Venus orbiter mission that will determine the nature and current state of geological activity on Venus, and its relationship with the atmosphere, to understand how and why Venus and Earth evolved so differently. It is one of three finalists in ESA's M5 selection process and is entering phase A study; final mission selection is expected in June 2021. If selected, EnVision will launch by 2032 into a six month cruise to Venus, followed by aerobraking, to achieve a near-circular polar orbit for a 3-year nominal science phase.

Instruments and Science Operations: EnVision hosts three complementary instruments and a supporting investigation:

The Synthetic Aperture Radar, VenSAR, will:
- Obtain images at a range of spatial resolutions from 30 m regional coverage to 1 m images of selected areas; an improvement of two orders of magnitude on Magellan images;
- Measure topography at 15 m resolution vertically and 60 m spatially from stereo and InSAR data;
- Detect cm-scale change through differential InSAR, to characterize volcanic and tectonic activity, and estimate rates of weathering and surface alteration; and
- Characterize surface mechanical properties and weathering through multi-polar radar data.

The Subsurface Sounder, SRS, will:
- Characterize the vertical structure and stratigraphy of geological units including volcanic flows;
- Determine the depths of weathering and aeolian deposits; and
- Discover as yet unknown structures buried below the surface.

The Venus Spectrometer suite, VenSpec, will:
- Search for temporal variations in surface temperatures and tropospheric concentrations of volcanically emitted gases, indicative of volcanic eruptions; and
- Study surface-atmosphere interactions and weathering by mapping surface emissivity and gas abundances in the troposphere and mesosphere.

The Radio Science & Geodesy investigation will:
- Provide gravity and geoid data at a geologically-meaningful scale
- Measure spin rate and spin axis variations to constrain interior structure;
- Profile the atmosphere using radio occultation to understand volatile transport through the clouds.

Exhortation: EnVision will produce a huge dataset of geophysical data of a quality similar to that available for Earth and Mars, so will permit investigation across a large range of disciplines. Lab-based and modelling work will also be required to interpret results from the mission. We therefore invite scientists from across planetary, exoplanetary and earth science disciplines to participate in the analysis of the data.

The entire dataset obtained will be made publically available; much of the SAR dataset will be made available in near-real-time to facilitate wide use of the data. We reiterate the opportunity for science experiments and target selection, and encourage researchers to contact the EnVision team.

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Gravity and ephemeris experience with EnVision

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The EnVision mission is a candidate mission selected in the Phase A of the M5 call of the ESA's cosmic vision program. This mission aims to send an orbiter to Venus to detect any sign of geological activity. The radio-science experiment is one of the four experiments of the payload, and the gravity mapping of the planet is its main objective. The current solution derived from the tracking data of the Magellan spacecraft is indeed poorly resolved over large areas of the planet. In addition, the k2 Love number solution does not precisely constrain the fluid core size and the mantle viscosity which are key parameters driving the interior evolution of the planet, and so its geological history.
The gravity experiment will use the Doppler measurements of the carrier frequency of the radio-link that will be used for telemetry and for down-loading the data of the other instruments. A 2-way radio-link will be established between the spacecraft and ground-based tracking stations, with a X (possibly Ka) band uplink and a dual X/Ka band downlink. These measurements will be used to precisely reconstruct the orbital motion of the spacecraft from which the gravity field solution is retrieved.
In this study numerical simulations are performed to assess the improvement on the Venusian gravity field and k2 solution thanks to EnVision. The noise expected on the Doppler will be taken into account as well as the inaccuracy of the force model; the a priori gravity field, the atmospheric drag, the direct solar and albedo/Infra-red radiation pressure, and the residual accelerations generated by unbalanced wheel-off-loading attitude maneuvers.
The ranging measurements (round-trip light-time) will also be performed to improve the ephemeris of Venus. In this study we also assess the possibility to improve the measurements of the post-Newtonian parameters of the General Relativity, Solar mass and J2 gravity coefficient.

VENERA-D: Mission for long-term study of the atmosphere, surface, interior structure and solar wind interaction.

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Background: A joint NASA-IKI/Roscosmos Joint Science Definition Team (JSDT) was established in 2015. Within the overarching goal of understanding why Venus and Earth formed in the inner solar system from the same protoplanetary material took divergent evolutionary paths. The JSDT has the task of defining the science and architecture of a comprehensive Venera-D (Venera-Dolgozhivuschaya (long-lasting)) mission, aimed to study the atmosphere, surface, interior structure and solar wind interaction that would further our understanding of Venus as a system [1].

Venera-D science goals: Venera-D investigations would address the dynamics of the atmosphere with emphasis on atmospheric superrotation, the origin and evolution of the atmosphere, and the geological processes that have formed and modified the surface with emphasis on the mineralogical and elemental composition of surface materials, and the chemical processes related to the interaction of the surface and the atmosphere and the solar wind interaction.

Venera-D baseline and potential augmentation: The JSDT recommends, as a baseline mission, an orbiter and a VEGA-type lander with an attached long-lived small station (Long-Lived In-Situ Solar System Explorer, or LLISSE) [2]. While the lander will survive for 2-3 hours, LLISSE is predicted to survive 2-3 months on the Venus surface. Additional breakthrough science could be achieved by augmenting the baseline mission with additional potential contributed elements: two more complex long duration (>120 days on the surface) seismic stationsSAEVe (Venus Seismic and Atmospheric Exploration of Venus) [3]; a vertically maneuverable aerial platform/balloon (several weeks life time) and one or two sub-orbiters in the Lagrangian points L1 and L2 (from day side and night side respectively) or more LLISSEs.

Venera-D mission architecture: JSDT members from Lavochkin Association are leading the mission architecture development [4]. This assessment includes: (1) Development of the general configuration for both the orbiter and the lander; (2) Accommodation of systems and subsystems within the orbiter and lander; (3) Assessment of orbit options along with the strategy for descent and landing and long term observation of LLISSE; (4) Evaluation of telecommunication options from the spacecraft to Earth and from the lander and LLISSE to the orbiter; (5) Accommodation of the contributed elements in their own delivery system. Resourses for launch dates between 2026 and 2031 have been evaluated.

Ongoing activities of the Venera-D JSDT: The Phase II final report was published in January 2019 on sites NASA and IKI [5,6].The next phase (*Phase 3*) of development would focus on a deeper examination of the science and instruments of the baseline and augmented elements along with a more complete definition of the spacecraft requirements, assessment of data communications capability.The current JSDT extension to include pre-project engineers with expertise in telecom engineering, structural and thermal engineering, system engineering, and so on, is required.

Engagement of the broader science community is also required. Thus, Venera-D Joint Science Definition Team Workshop on potential landing sites and habitability in cloud layer is being planned for early October, 2019, in IKI, Moscow. Two workshops on Venus modeling were held in 2017: one at the NASA Glenn Research Center, and another at IKI in Moscow. Proceedings ("Venera-D Venus Modeling Workshop") are published in IKI (2018) and can be found online [7].

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CHEMIN-V: A DEFINITIVE MINERALOGY INSTRUMENT FOR THE VENERA-D MISSION

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X-ray diffraction (XRD) is the benchmark technique for definitive identification and quantification of minerals in rocks and soils. XRD can also determine the quantity of X-ray amorphous material present in sample, and when combined with X-ray fluorescence (XRF), the elemental composition of the non-crystalline component(s) can be determined. Taken together, these techniques provide a comprehensive *in-situ* analysis of planetary materials that can only be improved upon by sample return.

XRD was deployed in robotic planetary exploration for the first time on the Mars Science Laboratory (MSL) *Curiosity* rover. During its 6-year employment on Mars, CheMin established the quantitative mineralogy of martian soil [1], characterized the first habitable environment on another planet [2], and provided the first *in-situ* evidence of martian silicic volcanism [3]. CheMin is now employed in characterizing the depositional and diagenetic environments of basaltic lacustrine mudstones that comprise the lower strata of Mt. Sharp in Gale crater – elucidating for the first time, the early aqueous and oxidative history of Mars [4]. CheMin's mineralogical analyses on MSL are often completed over three Mars nights, totaling 20-30 hours. However, future landed missions to Venus, such as Venera-D, will only have ~2 hours in which to collect and analyze samples.

In the 15 years since the MSL CheMin instrument was designed, technological advances have been made that allow for reduced size and power, and more efficient data collection. This contribution discusses CheMin-V, an XRD/XRF instrument designed for the Venera-D lander. The geometry of the instrument permits simultaneous collection of XRD and XRF patterns of two samples using a single CoKα X-ray source. Based on tests performed on Venus regolith analogs using *Terra*, a fifth-generation CheMin spinoff XRD instrument, we are able to obtain a quantitative analysis of major mineral components (>5 wt.%) in as little as 15 minutes. *Terra* results substantially duplicate the refined mineral abundances obtained from 8 hour scans of the same materials using our commercial Rigaku diffractometer. The rapid analysis times of CheMin-V, expected based on the results from *Terra*, leave margin for sample delivery and data transmission. If desired, two additional samples can be analyzed with a second sample cell pair, rotated into position by a single actuator.

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Session 06

Posters (1)

Session Chair: Takeshi Horinouchi

Experimental investigation of wet atmosphere-surface interaction at the conditions of Venus surface: an example for early terrestrial planets.

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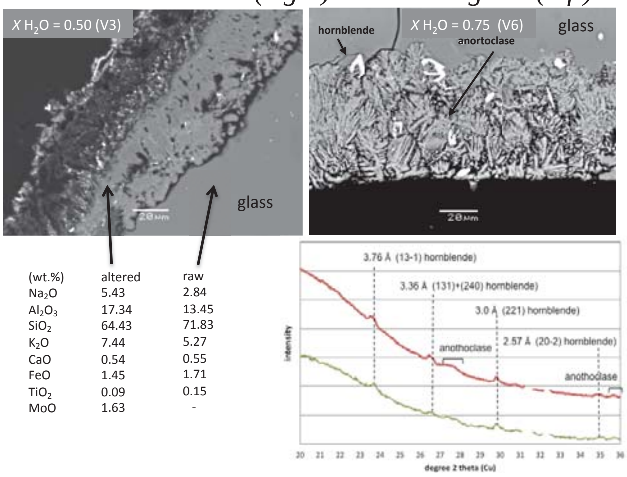
Introduction: Modern Venus is considered as a warm and dry planet. The low dielectric constant of the deep atmosphere precludes significant alteration today, except the formation of iron oxide on Fe-bearing minerals [1] and a global sulfurization of the surface [2,3]. Several hypotheses of atmospheric H_2O content variation with time ranged from a rapid early decline to a sporadic decline associated to sporadic influx from recent volcanism [4]. The aim of this study addresses the mineral transformation under a wet supercritical atmosphere in the CO_2-H_2O-S(trace) system, in continuation of [5]. We focused on the reaction rates monitored by the thickness of the alteration layer at the surface of tested materials exposed to the wet, low density, supercritical fluid at 470°C and 9 to 60 MPa.

Experimental Details: The experiments were conducted at 470°C in a 320 ml reactor made of a Ni-based alloy preventing corrosion and buffering the redox conditions closed to the present Venus deep atmosphere. The CO_2-based gas, initially at 9 MPa, contained 3.5% N_2, 130 ppm SO_2, 15 ppm CO and trace of H_2S. Various concentrations of H_2O were tested by injection of appropriate amounts of water, up to 60 MPa. Various silicate samples were exposed to alteration. The results focused on glassy materials, the alteration kinetics of which allowing accurate measurements in reasonable experimental time: a natural pumice, a synthetic basalt glass and a natural obsidian. The mineral transformations of the investigated samples were analyzed by scanning electron microscopy (SEM) and X-ray diffraction (XRD). The typical duration of the experiments was 1 week. Few runs were conducted for 1 day and 1 month to investigate the effect of time at constant water pressure.

Results: The alteration process differs from one glass to another. Obsidian recrystallized into an anorthoclase-hornblende assemblage. Basalt glass developed a chemically leached inner layer covered by a chlorite-sulfate enriched outer layer. Pumice, a porous material, fully recrystallized under the higher H_2O pressure. Examples are given in Fig.1.

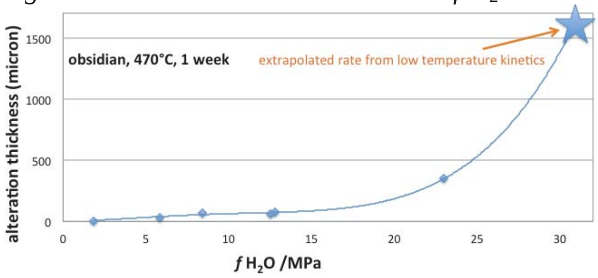
Discussion and concluding remarks: The fugacity of water in each run was calculated with available equations of state. Obsidian is used as a reference material here. The thickness of its alteration layer increased with fH_2O as showed in Fig.2. The data are processed through the Transition State Theory and a shrinking core model to take into account the surface reaction combined with diffusion processes. We proposed a method to extrapolate to supercritical conditions the kinetic laws established for minerals and glasses at lower temperature in condensed fluids. Although the short duration of the experiments makes speculative the extrapolation to the whole geologic history of Venus, we offer new insights to possible processes having affected the surface of this planet as well other terrestrial planets dominated by hot CO_2-H_2O atmosphere during their early history.

Fig.1: SEM observations and XRD pattern of altered obsidian (right) and basalt glass (left)



(wt.%)	altered	raw
Na_2O	5.43	2.84
Al_2O_3	17.34	13.45
SiO_2	64.43	71.83
K_2O	7.44	5.27
CaO	0.54	0.55
FeO	1.45	1.71
TiO_2	0.09	0.15
MoO	1.63	-

Fig.2: Obsidian alteration rate versus $f\,H_2O$



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LOW RADAR EMISSIVITY SIGNATURES ON CORONAE. J. F. Brossier and M. S. Gilmore, Wesleyan University, Planetary Sciences Group, Middletown CT, 06459 USA (jbrossier@wesleyan.edu)

Several studies [1,2] have recognized that many of the venusian highlands display anomalous decreases in radar emissivity. This phenomenon is thought to be the result of atmosphere-surface interactions in the highlands, and hence at lower temperatures [e.g., 3-5]. These reactions are a function of rock composition, atmospheric composition, and degree of weathering. The detailed variations in radar emissivity with elevation may yield insight into these characteristics. So far only the radiophysical behaviors of the tesserae, mountain belts and large volcanoes have been investigated [6-8]. Here we focus our study on a selection of coronae displaying reductions of radar emissivity with altitude. Coronae are irregular to circular structures characterized by a complex interior zone occupied by flows, domes and tectonic ridges, and like volcanic rises, they are suspected to be surface manifestations of mantle plumes [9,10].

The coronae are mapped by using Magellan Synthetic Aperture Radar (SAR) images at 75 m per pixel. Elevation and emissivity data are extracted to produce scatterplots of the variation of emissivity with altitude. The emissivity data are oversampled to 4.6 km per pixel. As found in previous works [1,5], the emissivity of several coronae declines with increasing elevation from a global mean value of around 0.8. We define the elevation at which an emissivity low occurs as an emissivity excursion. We found eight coronae with such excursions and they are located in three distinct regions: (1) Artemis, Ceres, Miralaidji and Atahensik in Aphrodite Terra, (2) Zisa and Maram in the Beta-Atla-Phoebe (BAT) region, and (3) Didilia and Pavlova in eastern Eistla Regio. The elevations and magnitudes of their excursions are variable from a region to another. We believe that other venusian coronae are not tall enough to display a clear change in radar emissivity with elevation, as they lie under 6054 km (or 2.2 km above a mean planetary radius taken as 6051.8 km [11]). Two coronae found in Aphrodite Terra, namely Ceres and Miralaidji have heights similar to Zisa and Maram in the BAT region, ranging from 6055.4 to 6056 km. For Ceres and Miralaidji, emissivity drops with elevation to values of 0.77-0.78, while emissivity reaches values as low as 0.50-0.51 in Zisa and Maram. In the two regions, emissivity remains constant with elevation until around 6055 km (Aphrodite) and 6053.5 km (BAT), and then smoothly declines to lower values on their highest ridges. Interestingly, two coronae found in eastern Eistla Regio, namely Didilia and Pavlova, exhibit a sharper emissivity excursion below 6054 km, unlike the gradual decline seen for the others, and reach values of 0.64 and 0.47, respectively. Excursions are mostly confined to the rims as they are the highest parts of the coronae in Aphrodite Terra and BAT region. The two exceptions are Didilia and Pavlova that have a central edifice (radial factures) taller than the highest rims. However, they only have subtle excursions of 0.75-0.78, unlike the rims.

These three clusters of coronae have low emissivity excursions and rates of decrease that indicate a different set of low-emissivity minerals are controlling these clusters relative to each other. The magnitude and elevation of these excursions may provide new clues about the composition and evolution of the magmas associated with the coronae at different corners of the planet.

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Cancelled

Crater Relaxation on Venus: Implications for Geologic and Thermal History.

Saman Karimi

Heavy ion flows in the upper ionosphere of the Venusian North Pole

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The solar EUV radiation creates the ionosphere on the Venusian dayside. Due to the slow rotation around its rotation axis, the solar EUV cannot maintain the nightside ionosphere. However, existing measurements have shown that there exist a substantial nightside; The Pioneer Venus Orbiter (PVO) mission showed that there is a large horizontal day-to-night flow of ions across the terminator in the equatorial region [Knudsen et al., 1979]. The trans-terminator flow is considered as the main maintenance mechanism of the nightside [Knudsen et al., 1980]. On the other hand, as the measurements were only conducted in the equatorial region, the global dynamics of the plasma flow pattern in the upper ionosphere, particularly in the polar regions are left as an open question.

The Venus Express (VEx) mission made measurements of the ionosphere near the North Pole of Venus. Specifically, during June-July 2014 the Venus Express (VEx) spacecraft entered an aerobraking mode, lowering its periapsis to 130 km [Svedhem et al., 2007]. This allowed for ionospheric ion measurements by the Ion Mass Analyser (IMA), part of the ASPERA-4 instrument package [Barabash et al., 2007], on board VEx.

In this study, we use the measurements of IMA during the aerobraking period to calculate the density and velocity of the heavy ions in the Venusian North Pole region. We find that the scale heights of the heavy ions are ~15 km below 150 km and ~200 km at 150-400 km altitude. This is consistent to what was observed near the equator by the Pioneer Venus mission [Taylor et al., 1980]. We also observe a clear trend of dusk-to-dawn flow along the terminator on the altitude range of 130-400 km. The average ion speeds were found at ~2-10 km/s. This is in contrast with the previous results in the equatorial terminator region from the PVO mission, where a day-to-night flow was dominant. The derived global flow patterns are interpreted by a thermal pressure gradient along the terminator, which forces the ionospheric ions across the polar region in the dusk-to-dawn direction.

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Eight years of VEX-VeRa radio sounding of the Venus ionosphere

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The Venus Express Radio Science Experiment VeRa sounded the Venus ionosphere from 2006 to 2013 at two coherent downlink frequencies driven by an Ultrastable Oscillator (USO). The use of the dual-frequency one-way radio link at X-band and S-band allows the derivation of the true ionospheric electron density profile without contributions or perturbations by the spacecraft´s residual or periodic vibrational motion. More than 900 electron density profiles from 15 occultation seasons in eight years of operation from solar minimum 2007 to solar maximum 2014 were recorded. The observations cover almost all solar zenith angles, local times and planetary latitudes. On average, the Venus ionosphere shows a large-scale two-layer structure with a well defined base at 110 km altitude, a lower layer V1 formed by photo-ionisation of solar X-ray and secondary ionisation and a main layer V2 formed by solar EUV. Peak densities and altitudes of both layers depend on the influx of solar radiation and the solar zenith angle. The transport region between the topside and the ionopause shows a variety of plasma scale heights. The ionopause is identified in most cases and their varying altitude depends on the pressure balance between the solar wind and the ionospheric plasma. The V2 peak density as a function of solar zenith angle follows the well known Chapman relation but the V2 peak altitude is constant at 140.7 km for solar zenith angles <65° but shows an increasing scatter for larger solar zenith angles but does not drop to lower altitudes in contrast to PVO observations (Cravens et al., 1981). A sporadic layer of extra ionisation below V1 is still under investigation and may be caused by enhanced ionisation of NO2 as Peter (2018) has concluded from Mars Express radio sounding of the Mars ionosphere.

Simulations of Ion Flow and Energy Transfer in the Venus Environment

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Introduction

This project is driven by the question, "What drives the retrograde super rotating zonal flow (RSZ) of the Venusian upper atmosphere?" The primary goal of this research is to test the hypothesis by Lundin et al., (2011), [1] that the orbital motion of Venus combined with its' interaction with the solar wind drives asymmetric plasma winds that in turn drive atmospheric neutral winds via ion-neutral collisions leading to the observed RSZ flow. To accomplish the objective, two sophisticated and well established three-dimensional simulations codes are combined. The neutral atmosphere is modeled using the Venus Thermospheric General Circulation Model (VTGCM) [2,3,4]. The solar wind interaction is simulated using the HALFSHEL hybrid particle code (cf. 5, 6 and references therein). Both codes have all the necessary physical and chemical processes need to successfully achieve this objective. Along the way to reaching the research objective we have learned a great deal about the Venus solar wind interaction, specifically about the observed night side ionospheric structures and solar wind ion deposition. This talk will review what we have learned and the implications for the RSZ being driven by the combination of orbital motion of Venus and its' interaction with the solar wind.

Observations

The solar wind interaction with the atmosphere/ionosphere of Venus was the focus of both the Pioneer Venus Orbiter (PVO) and the Venus Express (VEX) missions. PVO reported finding finger like structures on the night side of the planet. Within the structures density drop out (< 10 cm^{-3}) would occur. Additionally the night side structures were predominately found toward the dawn side of the planet. VEX found that the flow of solar wind H^+ and ionospheric O^+ ions near Venus are characterized by a marked asymmetry in the direction of the RSZ neutral flow.

Results

The results from the simulations show excellent agreement with the PVO observations. Tests reveal that the ambipolar electric field, produced by gradients in the electron pressure is the cause of these structures. Furthermore it is found that the atmospheric dynamics affect the plasma interaction. The energy and momentum deposited into the Venus atmosphere by both the solar wind and the ionospheric ions is mapped to the atmosphere. The results show that the atmosphere and ionosphere are coupled in a variety of ways such as photo-chemistry, ion transport, ion-neutral collisions electro-magnetic fields and particle deposition.

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Toward Development of Coupled Kinetic-Fluid Model of Venus Thermosphere-Exosphere System Interacting with the Ambient Solar Wind

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Because Venus has no substantial planetary magnetic field the fast-flowing solar wind plasma can propagate to regions close to the planet. Therefore, the distribution of thermal atomic oxygen in the thermosphere, hot oxygen in the corona, and the resulting pickup oxygen ions are essential for determining the overall interaction of the planet with plasma of the ambient solar wind. To investigate the effect that this interaction has on the plasma-exosphere-thermosphere system we have initiated a project where this coupled system will be examined using a combination of Venus Thermosphere General Circulation model (VTGCM), Adaptive Mesh Particle Simulator (AMPS) and Block Adaptive Tree Solar-wind Roe Upwind Scheme (BATSRUS) codes.

Each of the employed codes will cover a physical sub-domain such that the coupled combination of the codes self-consistently describe the studied environment. The physical sub-domains are organized such that (1) VTGCM produces a self-consistent calculation of the thermosphere/ionosphere providing a spatial distribution of the thermal oxygen as well as all the dominant species, (2) the calculated distribution of the major species is used to derive the three-dimensional hot oxygen corona distribution using AMPS modeling of Venus' exosphere and corona. In turn, that provides the spatial distribution of pickup ion sources for (3) a three-dimensional magnetohydrodynamic calculation of the planet's interaction with the ambient solar wind using BATSRUS.

Here, we present recent results of applying this approach to investigating interaction of Venus with the plasma of the ambient solar wind where we focus on modeling the extended oxygen corona coupled with that of the background thermosphere. Support for this work is provided by NASA grant 80NSSC17K0728 from the Solar System Workings Program.

The Impact of Venus Middle Atmosphere Aerosol Heating upon SO_2 and CO Density Distributions through GCM Model Simulations

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Introduction and Motivation. One of the major goals of the Venus Express (VEx) mission has focused upon increasing our understanding of the highly variable global circulation and wave processes impacting the Venus mesosphere-thermosphere (~80 – 200 km). Several VEx instruments (e.g. SOIR, SPICAV and VIRTIS) and ground based observations have provided measurements that characterize the upper atmosphere structure and underlying variable dynamics during the solar minimum-to-moderate period of the solar cycle when VEx measurements were obtained (2006-2014). For example, SOIR and VIRTIS-H profiles of dayside temperatures, and SO_2 and CO densities as have been obtained and analyzed [1, 2]. These datasets were used to establish a statistically averaged mean state (versus latitude) and characterize the variability of the upper mesosphere and lower thermosphere structure. Our overall goal is to examine this spatial and temporal variability about the mean, thereby providing constraints for the VTGCM SO_2 and CO distributions (plus variable planetary and tidal wave driven features) [3, 4], and further understanding the nature of the unknown UV absorber.

Venus Express Measurements and Usage. A detailed study of the VEx/VIRTIS-H measurements of the limb emission of CO in the 4.7-micron spectral region has been carried out [2] as well as a comprehensive study of various observations of SO_2 in the Venus middle atmosphere [5, 6]. We review these existing measurements that provide constraints on SO_2 and CO densities, as well as the changing global circulation patterns and wave processes. We also provide a re-analysis of data-VTGCM comparisons of dayside SO_2 and CO density profiles as a function of latitude and altitude (~100-150 km). The underlying VTGCM processes are quantified and discussed.

VTGCM Modeling. The Venus Thermospheric General Circulation Model (VTGCM) has been recently improved [3, 4] by including new chemistry (OH nightglow, SO_x, $[SO]_2$), modern heating and cooling formulations (e.g. aerosol heating). For this study, the heat balance upgrades below ~100 km are shown to be important, owing to their impact upon lower thermosphere SO_x and CO densities for comparison to SOIR and VIRTIS-H datasets. Also, implications and insights to the nature of processes that could contribute to the absorption of the UV in the enigmatic 320-400 nm range are also examined. Other conference presentations will focus upon VTGCM studies that address: (a) OH nightglow as a tracer of the upper atmosphere global circulation [7], (b) gravity wave and planetary wave impacts on the Venus thermosphere [4], and H_2O, SO_x photochemistry [7, 8, 9] and $(SO)_2$ photochemistry [7, 8].

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The global variation of Venus cloud investigated from IR1 onboard AKATSUKI

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Venus is our nearest neighbor, and has a size very similar to the Earth's. However, previous observations discovered an extremely dense (92 bar at the surface) and CO_2-rich atmosphere, with H_2SO_4 thick clouds. The Venus cloud consists of H_2SO_4 main cloud deck at 47 – 70 km, with thinner hazes above and below. The upper haze on Venus lies above the main cloud surrounding the planet, ranging from the top of the cloud (70 km) up to as high as 90 km.

Near infrared (0.986 μm) dayside image of Venus has taken by solid state imaging (SSI) of the Galileo spacecraft (NASA). It appears almost flat, there are some small scale features with a contrast of 3 % [Belton et al., 1991]. In Takagi and Iwagami. (2011), it may be calculated that the source of the contrast of the order of 3 % in near infrared Venus dayside image is due to variation in the cloud optical thickness.

On December 7, 2015, AKATSUKI (JAXA) approached Venus and the Venus orbit insertion was successful. After the Venus orbit insertion, many 0.90 μm Venus dayside images were taken by the 1 μm near infrared camera (IR1) onboard AKATSUKI.

In this study, Venus cloud variations are investigated from 0.90 μm Venus dayside images taken by IR1 camera globally. Further, some meteorological changes that contribute to cloud variation are investigated with radiative transfer calculation included high-altitude cloud model obtained from Venus Express/SOIR observation. Furthermore, I will introduce observation plan with PIRKA telescope of Hokkaido University.

Development of a Venus' cloud formation scheme for a convection resolving model

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Although convection has been suggested to occur in the lower part of Venus' cloud layer by some observational evidences, its structure remains to be clarified. In the previous studies, Baker et al. (1998, 2000), Imamura et al. (2014), and Lefevre et al. (2017) try to simulate Venus' cloud-level convection, but their models they utilized do not consider cloud formation process. Our purpose is to develop new cloud formation scheme and to perform numerical simulation using the scheme in order to investigate a possible structure of Venus' cloud-level convection and clouds distribution.

Our cloud formation scheme is based on Imamura and Hashimoto (1998). The number densities of sulfuric acid (H2SO4) and water (H2O) in the gas and liquid phases are calculated. Sedimentation of H2SO4-H2O solution droplets and chemical reactions of sulfuric acid are also considered. The scheme is implemented into our convection resolving model developed by Sugiyama et al. (2009). The model is based on the quasi-compressible system (Klemp and Wilhelmson, 1978), and is used in the simulations of the atmospheric convections of Jupiter (Sugiyama et al., 2011, 2014) and Mars (Yamashita et al. 2017).

In our poster, we will show the details of our cloud formation scheme and demonstrate some results of our calculation using similar settings of Imamura et al. (2014).

Venusian cloud physics investigated by a general circulation model

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Abstract

We developed a simplified cloud physics model for Venus and implemented it into a Venus general circulation model (AFES-Venus) [1,2]. Our cloud model includes condensation, evaporation and sedimentation of cloud droplets. In the present model, the distributions of the cloud and condensable gases (H_2O and H_2SO_4 vapors) are calculated. Cloud is highly and moderately thick in the high and low latitudes, and it is thinnest in the middle latitude region. Temporal variation of the cloud thickness is outstanding in low-latitude and zonal wavenumber-1 and -2 structures can be seen there. These structures are qualitatively consistent with the previous infrared measurements [3,4]. might be associated with the atmospheric waves in the cloud such as Kelvin wave and thermal tides. H_2O and H_2SO_4 vapor mixing ratios increase with latitude in the cloud layer and sub-cloud region, respectively. The former is attributed to the vertical atmospheric motion enhanced in the low stability layer in the high latitude region. The latter is associated with the large mass loading located in the polar lower cloud, which induces the large amount of the cloud sedimentation and evaporation.

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Composition and clouds, some insights and questions from the coupled IPSL Venus GCM.

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We have coupled new codes of photochemistry and microphysics to the LMD general circulation model of Venus (Lebonnois et al., 2016). The photochemical package is based on our photochemical model already in use for Mars (e.g., Lefèvre et al., 2008). The model provides a comprehensive description of the CO_2, sulfur, chlorine, oxygen, and hydrogen chemistries with state-of-the-art kinetics data. It also includes a simplified treatment of cloud microphysics that computes the composition, number density, and sedimentation rates of sulfuric acid aerosols based on observed altitude-dependent size distributions. We will describe the results obtained with this first three-dimensional model of the Venus photochemistry. The space and time distribution of key chemical species will be discussed and compared to observations performed from Venus Express and from the Earth. We will place particular emphasis on SO_2, which is subject in the GCM to three-dimensional transport, convective mixing, condensation-evaporation-sedimentation via H_2SO_4 in the cloud layer, and photochemistry above the clouds.

In addition to the photochemical code, which only contains a simplified microphysics, we have developed a comprehensive microphysical scheme: The Modal Aerosol Dynamics of Venusian Liquid Aerosol cloud model (MAD-VenLA) uses an implicit moment scheme to describe the particle size distribution and the microphysical processes in 0D. The particle size distribution is assumed to be log-normal and is described by two moments: total particle number (zeroth moment) and total particle volume (third moment) of the size distribution (Seigneur et al. 1986, Burgalat et al. 2014). This 0D model has been tested against a reference model (SALSA, Kokkola et al. 2008). We have developed a 1D extension to our model to be able to represent a source of aerosol particles that can act as condensation nuclei and to be able to calculate the sedimentation of our cloud droplets. We are currently coupling MAD-VenLA with the 1D version of the IPSL Venus GCM and will be able to do 3D simulations in the future. This will enable detailed investigations on the coupling of cloud microphysics with atmospheric chemistry, and later on also with radiative transfer and dynamics.

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Interactions between the topography and the atmosphere on Venus

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A major discovery of the Akatsuki spacecraft is the presence of a massive 10,000 km long bow-shaped wave at the cloud top, stationary with the surface [1]. This wave is a mountain wave, occurring at multiple locations over equatorial highlands in the afternoon [2]. This is indicative of a direct influence of the surface on the atmosphere at altitudes as high as the cloud top (70 km).

In order to investigate this wave, a Global Circulation Model (GCM) is a tool of choice, especially since measurements of the deep atmosphere of Venus are very limited. In this study, we used the Institut Pierre-Simon Laplace (IPSL) Venus GCM. It includes a realistic topography from the Magellan mission and its effects well below the horizontal resolution (typically 300 km at equator) via a gravity wave drag parameterization [3,4]. This capability allows us to explore the conditions for the creation of the bow-shaped wave, and its dependence on local times. A very good match between the model and the observations from 4 solar days of observations by Akatsuki [2] is obtained, both temporally and spatially.

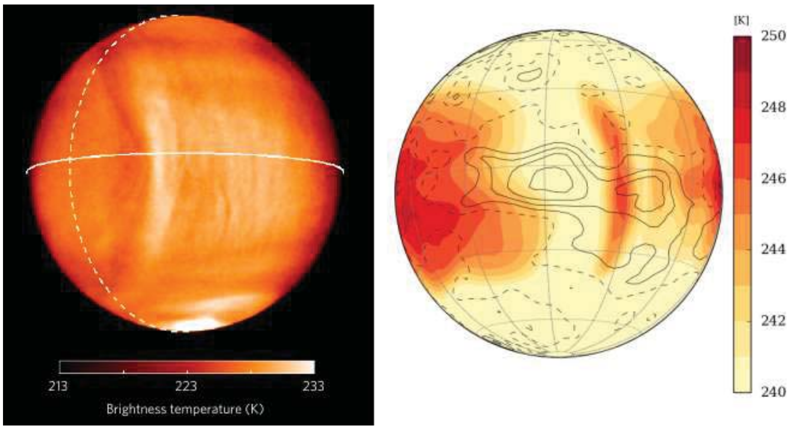

Figure : Mountain wave at the cloud top seen as a disturbance in the brightness of the cloud top [1] (left), and in the simulated temperature field of the IPSL VGCM [2] (right).

These mountain waves contribute to a substantial part of the exchange of angular momentum between the surface and the atmosphere. The other contributions come from the diurnal thermal tide and surface baroclinic waves with the same period as the super-rotation. The angular momentum and its exchange between different physical systems (atmosphere, solid body, Sun) is crucial to understand Venus and some of its unique features, such as the super-rotation of the atmosphere and the retrograde spin of the solid body.

In the light of this recent discovery and modeling of Venusian mountain waves, it appears that atmospheric measurements within and above the cloud deck can now directly inform us on the circulation at the surface. Moreover, the instantaneous rotation of the solid body and its fluctuations are also very desirable measurements that could inform us on the rate of momentum exchange with the atmosphere.

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Acknowledgments

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Cancelled

Cloud tracking on Venus using Rotation Invariant Phase Only Correlation

Keishiro Muto

The study on the reproducibility of cold collar assuming radio occultation measurement by small satellites

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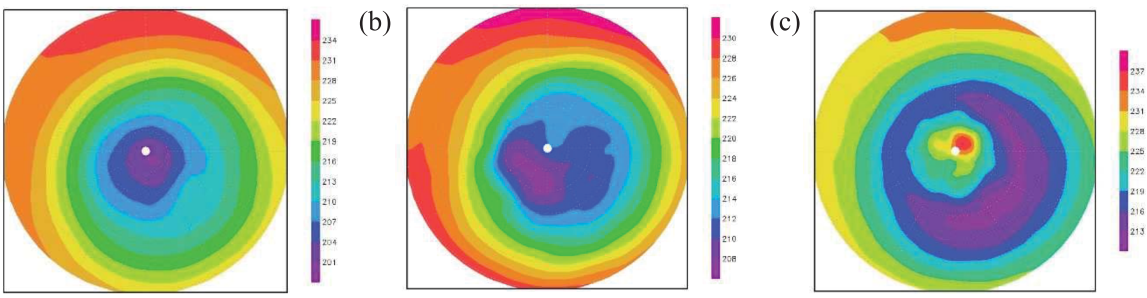
In the Venus atmosphere, there is a unique phenomenon called "cold collar". Cold collar is a structure where the temperature at 60-80° hatitude is lower than that of polar region at the altitude of about 65 km. So far, we developed Venusian atmospheric GCM (AFES-Venus)[1] based on the atmospheric GCM for the earth simulator (AFES). Recently, we have further developed Venus AFES local ensemble transform Kalman filter (LETKF) data assimilation system (VALEDAS)[2].

In this study, we prepare idealized observations assuming radio occultation measurement by small satellites and assimilate them to AFES-Venus by VALEDAS. Idealized observations are provided from French Venus atmospheric GCM (LMD/VGCM), in which cold collar is realistically reproduced[3]. We study the reproducibility of cold collar by changing the condition of idealized observations such as time interval, places and numbers. Below figures show temperature distributions at 30-90°N at the altitude of about 66 km; (a) One vertical profile of temperature observation at (85°N, 180°E) with every 2 Earth hour, (b) two ones at (85°N, 90°E) and (85°N, 90°W) with every 4 Earth hour, and (c) three ones at (85°N, 60°E), (85°N, 180°E), and (85°N, 60°W) with every 6 Earth hour. In the poster, we will show the effectiveness of radio occultation measurement by small satellites.

(a)



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Temperature and wind variations in Venusian mesosphere and lower thermosphere by mid-infrared heterodyne spectrometer in 2018

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The temperature discrepancies between observations by VEX/SOIR and general circulation models in the altitude of 80 - 100 km have not been properly interpreted (Bougher et al., 2015; Gilli et al., 2017). In addition, the mesospheric dynamics located between retrograde superrotational zonal wind (cloud deck) and subsolar-to-antisolar flow (above 120 km altitude) have not been well understood due to lack of observations. On the other hand, the lower thermosphere has been observed by mid-infrared heterodyne spectrometer (MIR-HS). Temperature in this region varied extensively between 140 K and 240 K, and wind velocity changed intensely from 130 m/s to 190 m/s for a terrestrial day (Sornig et al., 2013; Krause et al., 2018). The purpose of our observations is to solve temperature and wind variations in Venusian mesosphere and lower thermosphere with continuous observations by mid-infrared heterodyne spectrometer.

Our Mid-Infrared Laser Heterodyne Instrument (MILAHI) have been inserted to Tohoku 60 cm telescope located the summit of Mt. Haleakala in Maui, Hawaii (Nakagawa et al., 2016). MILAHI has 10 μm CO_2 laser as local oscillator. The field of view is 4 arcsec with 60 cm telescope and in the wavelength of 10 μm. MIR-HS can retrieve temperature and wind in different altitude between dayside observations of 100 – 120 km and nightside observations of 70 – 100 km with these spectra.

Dayside observations were conducted between 24th and 27th in June, 2018. Observed points were North, South, disk center, and equator. Temperature distribution showed both latitudinal dependence in 25th and convergence at 200 K in 26th.

Nightside observations were conducted from 11th to 13th, 19th, and 20th in November, 2018. Apparent diameter of Venus changed between 55.4 and 49.4 arcsec after inferior conjunction. We observed equator with three days, north 33° and south 33° for diurnal and latitudinal variations with integration times of 80 - 130 minutes. The observed spectra in the unit of relative intensity are under conversion because the retrieval with AMATERASU is necessary to use absolute radiation. We will show retrieved temperature profile and wind velocity at this presentation.

Doppler-wind observations of Venus mesosphere: Comparison with new GCM experiments

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Abstract:

Atmospheric dynamics of Venus' mesosphere (~70–120 km in altitude) still remains as a puzzle. There are several observations of mesospheric wind (more precisely, wind velocity projected along the line-of-sight of observation) at ~95–110 km, derived from Doppler-shift measurements of CO spectra at millimeter and submillimeter wavelengths. They show the presence of strong temporal variation [e.g., Lellouch et al., 1997, 2008; Clancy et al. 2012]. The earlier attempt to interpret those observations was to consider the mesospheric global circulation as *a linear combination* of two wind regimes: a super-rotating retrograde zonal flow (hereafter, RZ) and a subsolar-to-antisolar flow (SSAS). The former wind regime is well known as the global circulation of the Venus troposphere, and the latter is often referred to a circulation in the upper thermosphere where large thermal gradient between the day and night hemispheres exists. The mesosphere, which lays between the troposphere and thermosphere, has been considered as a dynamically transient region from RZ to SSAS. However, not a few results of the observed Doppler-wind, particularly those of spatially-resolved maps from interferometer observations, cannot be satisfactory explained by such a simple combination of RZ and SSAS [e.g., Moullet et al., 2012].

A new interpretation was proposed by Hoshino et al. (2012, 2013) after the development of a new Venus upper atmospheric general circulation model (GCM). One of the key achievements of their GCM is the inclusion of vertical propagation of gravity waves, and the wind data obtained by their GCM showed a qualitative representation of one of previously observed Doppler-wind maps which has been unexplainable by the simple combination of RZ and SSAS. Recently, Gilli et al. (2017) developed another GCM which uniquely covers from the ground to thermosphere, and succeeded in obtaining an overall agreement with the thermospheric temperature profiles measured by Venus Express and some ground-based instruments.

This presentation revisits past observational dataset of Doppler-wind taken at several local times of Venus, and compares them with numerical experiments from recently developed GCMs.

What controls the strength of super-rotation in terrestrial atmospheres?

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The atmospheric dynamics of Venus and Titan are characterised by fully-developed super-rotation. An atmosphere can be expected to super-rotate when its thermal Rossby number is large (Mitchell and Vallis, 2010), and when acceleration of zonal flow at the equator, associated with the presence of equatorial waves, overwhelms deceleration due to the dissipation of waves propagating out of the mid-latitudes (Laraia and Schneider, 2015). At present, however, there exists no predictive theory for super-rotation, or scaling that describes how the strength of super-rotation varies with planetary parameters. This motivates the question that forms the title of our research: *What controls the strength of super-rotation in terrestrial atmospheres?*

GCM simulations of the Venusian atmosphere have demonstrated the strength of super-rotation to be sensitive to specific aspects of model configuration, such as the inclusion of a diurnal cycle, and the static stability of the atmosphere (Lebonnois et al., 2010; Sugimoto et al., 2019), and to input parameters, such as the planetary rotation rate, and the magnitude of cloud level heating (Yamamoto and Takahashi, 2009, 2016). Given the sensitivity of Venus GCM results to their specific configuration, the following additional question must be raised: *Are Venus' atmospheric dynamics typical of a Venus-like planet?*

In this work, we present results from a series of idealised GCM experiments where the planetary rotation rate is varied between $\Omega = \Omega_E$ and $\Omega = \Omega_E/2048$, where Ω_E is the Earth's rotation rate. To do this we use `Isca`; a framework for building three-dimensional models of planetary atmospheres (Vallis et al., 2018). The model configuration used here is based on the Held–Suarez benchmark for an Earth-like atmosphere.

In these experiments the strength of super-rotation is found to increase proportionally with $1/\Omega^2$ until a critical rotation rate is reached ($\sim \Omega_E/16$), below which it remains constant as Ω is further reduced. To understand this behaviour, we investigate the zonally-averaged zonal momentum budget in each of our experiments. Early analysis suggests that the critical rotation rate is reached when the horizontal eddy scale, which is found to scale with the equatorial deformation radius, reaches the planetary scale.

The strength of super-rotation on Venus exceeds the limiting value found in our idealised experiments by a significant factor (~7 times greater). This is not surprising, given the differences between our model atmosphere and Venus' atmosphere. However, we hypothesise that an upper limit on super-rotation strength, of the type found in our experiments, is ubiquitous across terrestrial atmospheres with the exact value set by atmospheric composition and structure. For the case of Venus, we suggest that properties of the atmosphere's vertical structure, particularly the existence of regions of low static stability, are crucial to the maintenance of strong super-rotation in line with previous work (e.g. Sugimoto et al., 2019).

To continue our investigation, we are developing a grey-radiation GCM that will allow us to investigate how specific properties of an atmosphere can influence the strength of super-rotation. This will be done using `Isca`, which can be configured to use a wide range of physics packages, and orbital and planetary parameters can be easily varied. Our aim is to bridge the gap between idealised studies that make use of the Held-Suarez framework, and Venus and Titan 'specific' studies where sophisticated models are used to produce a realistic atmospheric circulation.

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The relationship between wind shear and eddy momentum forcing in the Venusian atmospheric super-rotation

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Abstract

I present an analysis of eddy momentum forcing on the Venusian atmospheric super-rotation and the associated meridional circulation using a simple Transformed Eulerian Mean (TEM) Equation framework. The TEM framework commonly treated in textbooks such as Holton (2004) employs a quasi-geostrophic approximation that ignores the cyclostrophic terms. The inclusion of the cyclostrophic terms allows examination of the relationship between the background zonal wind's vertical and horizontal wind shear and the eddy momentum forcing. In my presentation, I first show the derivation of TEM equations assuming gradient wind balance and beta-plane approximation. Using the framework, assuming that a prescribed background wind (i.e., atmospheric super-rotation) remains constant in time, the balance between eddy momentum flux and eddy thermal flux can be analytically calculated for various assumed background zonal wind structures.

Two scenarios have been hypothesized for the direction of eddy momentum flux as reviewed by Sanchez-Lavega et al. (2017). In one scenario, referred to as the Gierasch-Rossow-Williams (GRW) mechanism after Gierasch (1975) and Rossow and Williams (1979), the Hadley circulation first accelerates the prograde mid-latitude jets, which subsequently become barotropically (or baroclinically) unstable and excites waves, which in turn cause equatorward momentum flux and accelerate the equatorial atmosphere, resulting in super-rotation. In an alternate scenario, referred to as the Non-classical GRW Mechanism, the Hadley circulation first accelerates the retrograde surface wind, which interaction with the surface induces the transfer of prograde momentum from the solid planet to the atmosphere, and excites vertically propagating waves, which cause vertical momentum flux and accelerates the equatorial super-rotation at the cloud-top.

Using the gradient wind TEM framework, I examine the direction of angular momentum transport in the equatorial region of Venus to delineate implications of classical vs. non-classical GRW mechanisms. In my study, I explore various cases of equatorial winds with different vertical and horizontal wind shear scenarios to examine the momentum balance as well as their effects on the meridional circulation. I envision that this approach will help improve our understanding of the eddy momentum forcing necessary to maintain the Venusian atmospheric super-rotation.

A novel cloud tracking method and results from Akatsuki

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*: presenting, 1: Hokkaido Univ., 2: JAXA/ISAS, 3: AIST, 4: Univ. Shiga Prefecture, 5: Chiba Inst. Tech., 6: Hokkaido Information Univ.

We present a novel automated cloud-tracking method and its error evaluation used to process data from Akatsuki. Also, we present rich examples of cloud tracking and the subtlety.

Our method is based on the traditional template match, but we use multiple images harmoniously to derive consolidated cloud motion vectors. This method improves the precision and decreases the erroneous template match. The resultant first guess is improved by a relaxation-labelling approach. For this purpose, we have developed an evaluation based on the principle that we termed as “deformation consistency.” Accuracy evaluation is particularly important for quality control. We have devised the precision measurement based on the sharpness of cross-correlation surface peaks. We further conduct screening based on deformation consistency.

We will also provide examples of cloud tracking results and how they are compared with radiance images. We will also present topics of interest from the cloud tracking using images from the UVI and IR2 instruments, supplementing the invited talk by Horinouchi et al.

Part of the topics of this presentation has been published in the following papers:

Ikegawa and Horinouchi (2016) *Icarus,* 271, 98-119, doi:10.1016/j.icarus.2016.01.018.

Horinouchi et al. (2017) *Measurement Science and Technology,* 28(8), 085301, doi: 10.1088/1361-6501/aa695c.

Horinouchi et al. (2018) *Earth, Planets, Space*, 70:10, doi:10.1186/s40623-017-0775-3.

Local-time variation of the zonal wave number spectra derived from the Venus cloud-top Temperature observed by Akatsuki LIR

Tetsuya Fukuhara, Aya Nagata, Takeshi Imamura, Makoto Taguchi

The Long-wave infrared camera (LIR) on board Akatsuki detects thermal infrared radiation at wavelengths of 8–12 µm from cloud-top level (65 km) of Venus to provide brightness temperature map. LIR mainly has obtained Venus disk images with more than 50,000 km distance along Akatsuki's elliptical orbit. Meanwhile, LIR obtained more than 500 of close-up images at equatorial region with fine spatial resolution. In this study, temperature deviations were derived from the close-up images in latitude from 30 to -30 degree. After that, zonal wave-number spectra of the temperature deviation at mesoscales (wavelengths of 20–1000 km) were obtained in 5 degrees step of latitude as a function of local time (LT). The result shows that the temperature deviation is obviously high in LT 14:00–18:00, and the spectral peak corresponds to the wavelengths of 500 km. The temperature deviation would be caused by the stationary gravity wave discovered by LIR initial observation (Fukuhara et al., 2014, Nature Geo). We could detect the stationary gravity wave in the LIR image not only in the Venus disk image but also in the close-up image. Another high temperature deviation is seen in LT ~23:00, and the spectral peak corresponds to the wavelengths of ~150 km. A previous numerical simulation (Imamura et al., 2014, Icarus) has predicted that temperature deviation at the cloud-top level can be caused by upward propagation of the gravity wave, which is generated by the convection in the cloud layer of the night-side of the equatorial region. Our result can support existence of such upward propagation of the gravity wave in the cloud level of Venus.

TRACKING VENUS'S Y-FEATURE DURING VENUS EXPRESS AND GROUND-BASED OBSERVING

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We are investigating the dynamics of Venus's atmosphere in an attempt to link variability of atmospheric superrotation to the existence and occurrences of the Y-feature. The atmospheric superrotation, in which the equatorial atmosphere rotates with a period of approximately 4-5 days (~60 times faster than the solid planet), has forcing and maintenance mechanisms that remain to be explained. Temporal evolution of the zonal wind could reveal the transport of energy and momentum in or out of the equatorial region, and eventually shed light on mechanisms that maintain the Venusian superrotation. We postulate that the Y-feature is a manifestation of equatorial waves (either Kelvin, Rossby, or a combination of the two in nature) that may play a role in such energy transport that could affect Venus's superrotation. To understand the connection between the Y-feature and the superrotation, we must determine the frequency of the Y-feature's existence, the variability of the atmospheric wind field, and analyze the connection between the two to determine to what extent the Y-feature plays a role in Venus's superrotation.

We characterize the existence of the Y-feature's occurrence and phase speed between 2006 and 2017. It is observed in ultraviolet images captured by the Venus Monitoring Camera on board the ESA Venus Express (VEX) spacecraft which observed Venus's southern hemisphere as well as the Ultraviolet Imager on the Akatsuki spacecraft. We also extend our analysis to ground-based observations between 2016 and 2019. This includes data captured with the 3.5 m Astrophysical Research Consortium telescope at the Apache Point Observatory (APO) in Sunspot, NM and small 10-inch scale telescopes at Hampton University in Hampton, VA. Images we have captured demonstrate that, even under unfavorable illumination, it is possible to see large features that could be used to confirm the Y-feature existence to later be compared to future wind analyses of Akatsuki images. The tracking of the Y-feature during VEX and Akatsuki is discussed and the analysis of such occurrences and wind field variability is ongoing.

Radio-holographic methods for inversion of radio occultation experiments of past Venus' spacecraft

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We present a plan to reprocess complex radio occultation signals of past Venus' missions with novel methods that have been tested on the Earth's atmosphere, and the results obtained so far. We are compiling raw datasets of multiple radio occultation sessions on Venus with different spacecraft covering four decades of observations, with the following three objectives: 1) to produce atmospheric profiles of Venus' atmosphere with sub-Fresnel vertical resolution, 2) to allow the correct processing of radio occultation data in the presence of multi-path phenomena, and the use of new models and composition assumptions of the atmosphere, and 3) to enable the analysis of the temporal variation of temperature profiles with an extended coverage of spatial and solar illumination conditions.

By using novel radio-holographic techniques (e.g., Jensen *et al*. 2003, Jensen *et al*. 2004, Gorbunov 2002, Imamura *et al*.), we intend to provide temperature profiles with very high (sub-Fresnel) vertical resolution, essential to investigate the unstable regions of the atmosphere. Additionally, radio-holographic techniques have been largely used to address multi-path phenomena in radio occultation experiments of the Earth's atmosphere (e.g., Gorbunov 2002). In Venus, multi-path interference have been detected in radio occultation observations in latitudes above 75° at the altitude where the tropopause is located (Pätzold et al. 2007). When this phenomenon is ignored or undetected in the data reduction, the temperature values for the tropopause region can be in the order of ~15 K off. Imamura *et al.* (2018) showed that the holographic technique can resolve features as small as 150 m in height.

Past and current models employed to process Venus radio occultation experiments make use of the hydrostatic balance assumption, where the atmosphere is assumed to be well-mixed with a constant molecular composition (Limaye *et al.* 2018). Limaye *et al.* (2018) pointed out that in view of the measured vertical gradient in the abundance of Nitrogen below 64 km, the mean molecular weight will not be constant over the altitude range of the occultation profiles. Peplowski & Lawrence (2016) extended the altitude to 64 km over which the Nitrogen abundance has been measured with high accuracy, thereby confirming the gradient in the nitrogen mixing ratio based on MESSENGER neutron spectrometer observations, which was initially detected by Oyama et al. (1980). Lebonnois & Schubert (2017) suggested that it is possible that the absence of Nitrogen near the surface can render the lower atmosphere of Venus to be adiabatic rather than superadiabatic based on the VeGa 2 lander temperature profile. This condition has never been considered in the derivation of neutral atmospheric profiles from Venus radio occultation experiments, and would affect all calculations of altitude that involve the hydrostatic balance assumption and the adiabatic lapse rate (Lebonnois & Schubert, 2017).

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Measuring the properties of acidophilic bacteria under Venus cloud conditions

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Many of the fundamental questions concerning Venus have not yet been answered [1]. One of them concerns the possible existence of any life forms (i.e. single-cell organisms) [2]. In the past, Venus likely had an ocean on its surface and a habitable climate [3,4]. In the present Venusian lower clouds layer (47.5-50.5 km above surface), the pressure is close to 1 atm and temperature – about 60°C [5]. Such atmospheric conditions are suitable for some strains of earth bacteria, including termophilic acidophiles, and question is whether similar species exist on Venus.

Acidophilic bacteria are microorganisms adapted to life in acidic environment. Acidophiles can be classified according to the preferred pH (where those living in pH 3-5 are called "moderate" and those in pH below 3 – "extreme acidophiles") or preferred temperature (where "moderate thermacidophiles" live at a temperature of 40-60°C).

Metabolism of some acidophiles can be described as chemoautotrophism. It is based on the redox transformations of iron and sulfur compounds, which can be found in the Venus atmosphere. They assimilate carbon from inorganic sources, such as carbon dioxide (CO_2), using four possible metabolic pathways: The Calvin-Benson-Bassham cycle, reductive tricarboxylic acid cycle, the acetyl-CoA pathway and the 3-hydroxypropionic cycle [6]. Among acidophilic bacteria, *Acidithiobacillus ferrooxidans* could theoretically exist in atmospheric conditions of the lower layer of Venus clouds – average temperature, pH, available sources of energy and coal are suitable for this strain [5].

The basic difficulty in life detection lies in lack of universal or unequivocal marker of life, detectable by spectral analyses. In case of Earth, oxygen and methane could be considered such markers. In case of Venus, sulfuric acid could be such a marker, as it may be product of acidophilic chemoautotrophs. On Venus, the COS discovered in the atmosphere could have biogenic origins, not considering possible detection of methane [7].

Ultraviolet radiation, electrical activity [8] and cosmic rays [9] are known to have damaging effects on terrestrial bacteria, and may also be a factor on Venus [10]. The question is: whether there is life on Venus – can some microorganisms survive in the cloud layer conditions? The hypothesis regarding the existence of an ecological niche for terrestrial bacteria can be tested in isolated laboratory conditions.

Laboratory experiments can provide some guidance by examining the survival and reproducibility of some candidate species under the Venus cloud conditions. The key issue is

accurate reconstruction of the chemical and physical structure of the Venusian atmosphere in the laboratory and culturing of *Acidithiobacillus ferrooxidans* (or similar thermacidophilic strain) under such conditions.
We are embarking on carrying out research on the *Acidithiobacillus ferrooxidans* strains whose UV spectra correspond with the electromagnetic spectra recorded on Venus.

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Ka Band Opacity of Sulfuric Acid Vapor at Venus: Initial Results

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Prior and ongoing spacecraft missions, specifically *Pioneer Venus*, *Magellan*, *Venus Express*, and *Akatsuki*, have performed radio occultation measurements to measure the atmospheric structure of Venus down to the refraction limit of 33 kilometers. The difference between the measured signal attenuation and the attenuation expected for a CO_2/N_2-only atmosphere can be used to retrieve the abundance of H_2SO_4 vapor, due to its significant opacity at microwave frequencies [1-4]. While radio occultation experiments at Venus have previously used S Band and X Band frequencies, potential future missions to Venus, such as the ESA's *EnVision* and the Roscosmos *Venera D*, will likely fly with Ka Band occultation capabilities. As with prior radio occultation studies, laboratory measurements of the absorption of the atmospheric constituents of Venus at Ka Band are necessary for retrievals of their abundance.

In addition to the bulk CO_2/N_2 atmosphere, the trace microwave absorbers at Venus are H_2SO_4 cloud aerosols, SO_2, and, H_2SO_4 vapor. While Fahd and Steffes made measurements of the dielectric properties of liquid H_2SO_4 solutions at Ka Band frequencies, no measurements of SO_2 or H_2SO_4 gas phase absorption have been made under relevant conditions [5]. For SO_2, however, a common lineshape model fits both lower and higher frequency measurements, suggesting that this model is valid at Ka Band. This is not the case for laboratory measurements of H_2SO_4 vapor. Models derived from laboratory measurements of H_2SO_4 vapor opacity from 2-22 GHz and 75-140 GHz are not consistent, and extrapolation of either model to Ka Band frequencies for radio occultation could lead to inaccurate abundance retrievals [2,8].

To resolve this discrepancy, laboratory measurements of the Ka Band (24-40 GHz) opacity of H_2SO_4 vapor under Venus conditions have been undertaken. A semiconfocal microwave open resonator has been designed to perform differential measurements of the absorption of H_2SO_4 vapor mixed with up to 3 bars of CO_2 from 530-550 K. Initial results of these measurements will be presented and discussed in the context of prior measurements.

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Cancelled

LEAVES - A SWARM PROBE MISSION CONCEPT TO VENUS' CLOUDS.

J. A. Balcerski

Radio Sounding of the Venusian Atmosphere and Ionosphere with EnVision

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EnVision is a one of the final candidates for the M5 call of the Cosmic Vision program from ESA. It is dedicated to unravel some of the numerous open questions about Venus' past, current state and future.
The Radio Science Experiment on EnVision will perform extensive studies of the gravitational field but also Radio Occultations to sense the Venus atmosphere and ionosphere at a high vertical resolution of only a few hundred metres.
These radio occultations provide electron density profiles in the ionosphere and atmospheric density, temperature and pressure profiles in the upper troposphere and mesosphere (~40 - 90 km). Two coherent frequencies (X- and Ka-band) will be used to separate dispersive and nondispersive effects. This allows to distinguish between ionospheric wave structures and other noise induced effects in the ionosphere.
The use of Ka-band, which has never been used to sense the Venus atmosphere before, and allows to study the H2SO4 absorption in the Venus cloud layer due to its high sensitivity to sulfuric acid absorption. Ka-band is also sensitive to liquid H2SO4 which allows (in combination with X-band) to distinguish between gaseous and liquid H2SO4 absorption features on Venus for the very first time.
The short orbital period of EnVision in combination with its very small orbital inclination allows to cover all latitudes, longitudes, local times and solar zenith angles on Venus. Especially short-term variations caused by atmospheric waves can be identified to study traveling or stationary small-scale atmospheric structures.

DEVELOPMENT OF THE VENERA-D SPACECRAFT DESIGN.* A. Kosenkova[1], I. Lomakin[1], A. Martynov[1], P. Pisarenko[1]. [1]*Lavochkin Assoc., Russia.*

Background: Building on the results of the highly successful Soviet Venera and VEGA missions [1], along with the Pioneer, Magellan [2,3], and more recent Venus Express and Akatsuki missions [4,5], a Joint NASA-IKI/Roscosmos Science Definition Team (JSDT) was established in 2015. Within the overarching goal of understanding why Venus and Earth took divergent evolutionary paths, the JSDT has the task of defining the science and architecture of a comprehensive Venera-D (Venera-Dolgozhivuschaya (long-lasting)) mission. The baseline Venera-D concept includes two elements, an orbiter and a lander, with the payload for distance and contact analysis, including detachable elements such as aerial platforms that can flow in the atmosphere, small long-lived surface stations, small satellite. In January, 2017 the JSDT completed the first phase and generated a report to NASA - IKI/Roscosmos of its findings [6]. The second phase of the JSDT activities is currently underway with a focus on refining the science investigations, undertaking a compressive development of the core orbiter and lander mission architecture, a detailed examination of contributed elements and aerial platforms that could address key Venus science [7, 8].

Venera-D spacecraft design: Lavochkin Association creating the spacecraft design. This work includes: (1) Development of the general design and configuration for the spacecraft; (2) Accommodation of systems and standalone devices within the spacecraft; (3) Assessment of orbit options along with the strategy for descent and landing and long term observation for long-lived stations; (4) Forming the radio communications between Earth, spacecraft, surface stations, satellites. Launch dates between 2026 and 2031 have been evaluated.

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Spectroscopic observation of the Venus atmosphere by a circumpolar stratospheric telescope FUJIN

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Dynamics of the Venusian atmosphere is characterized by a westward fast flow called by super rotation, of which the maximum speed reaches 100 m/s at an altitude of 70 km above the equator, 60 times faster than the rotation speed of the solid body. Attempts to reproduce the high-speed wind by numerical models have been partially successful, however, ambiguity that the models assume distributions of solar heating and chemical species in the cloud deck remains. The main reason for this ambiguity is that an absorber with a wide absorption band in the wavelength range of 320 to 500 nm has been still unidentified. The ultraviolet absorption band in the wavelength region shorter than 320 nm is well explained by absorption by SO_2, but the absorption in the wavelength region longer than 320 nm cannot be explained by it. It has recently been shown by a spectroscopic observation during Venus fly-by of Messenger that S_2O or OSSO is the most promising candidate for regenerating the edge of the absorption band between 320 and 500 nm. Since the wavelength resolution of the past spectroscopic observations was not higher than 4 nm, the characteristic fine absorption structure of S_2O and OSSO could not be resolved. In order to identify the absorbing species, we propose an observation with a spectrometer exceeding the spectral resolution of 0.4 nm by a balloon-borne telescope FUJIN-2, which will be lifted up to the polar stratosphere where ultraviolet radiation from Venus can reach. A ground-based spectroscopic observation of Venus was conducted by the Pirka telescope in Hokkaido, Japan to demonstrate performance of a spectrometer for a future observation by FUJIN-2. A result of the test observation and the details of FUJIN-2 project will be presented.

VERITAS (VENUS EMISSIVITY, RADIO SCIENCE, INSAR, TOPOGRAPHY AND SPECTROSCOPY): A PROPOSED DISCOVERY MISSION.

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Introduction: VERITAS addresses one of the most fundamental questions in rocky planetary evolution: why did these twin planets diverged down different evolutionary paths? Venus may hold lessons for past and future Earth. Venus' hot lithosphere may be a good analog for early Earth, which may limit the development of plate tectonic [1]. Determining the factors that lead to the initiation of plate tectonics would inform our predictions for rocky Earth-sized exoplanets. The conditions leading to Venus' greenhouse atmosphere may also inform our understanding of Earth's future. VERITAS would answer key questions about Venus' geologic evolution, determine what processes are currently active, and search for evidence for past or present water.

Payload: The VISAR X-band [2] measurements include: 1) a global digital elevation model (DEM) with 250 m postings, 5 m height accuracy, 2) Synthetic aperture radar (SAR) imaging at 30 m horizontal resolution globally, 3) SAR imaging at 15 m resolution for targeted areas, and 4) surface deformation from RPI at 2 mm precision for targeted, potentially active areas.

VEM [3] will produce surface coverage of most of the surface in 6 NIR bands located within 5 atmospheric windows and of 8 atmospheric bands for calibration and water vapor measurements.

VERITAS will use Ka-band uplink and downlink to create a global gravity field with 3 mgal accuracy / 145 km resolution (130 spherical harmonic degree and order or d&o) and providing a significantly higher resolution field with much more uniform resolution than that available from Magellan.

Geologic Evolution: VERITAS answers key science questions via: 1) examining the origin of tesserae plateaus -possible continent-like features, 2) assessing the history of volcanism and how it has shaped Venus' young surface, 3) looking for evidence of prior features buried by volcanism, and 4) determining the links between interior convection and surface geology. In particular, VERITAS will examine the stratigraphy and nature of tesserae deformation features, determine the processes modifying impact craters, search for evidence of pre-existing features such as buried impact basins, and determine the origin of tectonic features such as huge arcuate troughs that have been compared to Earth's subduction zones.

Water and Surface Composition: VERITAS looks for the chemical fingerprint of past water in the form of low Fe, high Si rock in the tessera plateaus and larger tesserae inliers, and for present day volcanic outgassing of volatiles in the form of near surface water variability associated with recent or active volcanism.

Current Activity: Several studies have found evidence of current or recent volcanism on Venus. [e.g. 10]. VERITAS uses a variety of approaches to search for present day activity, including 1) tectonic and cm-scale volcanic surface deformation, 2) chemical weathering, 3) thermal emission from recent or active volcanism, 4) topographic or surface roughness changes, and 5) comparisons to past mission data sets.

Gravity: The Magellan spherical harmonic gravity field has an average resolution of only 550 km, which is too low to determine elastic thickness [12]. VERITAS data, with an average resolution of 145 km, will enable estimation of elastic thickness (a proxy for thermal gradient) and resolution of specific geologic processes [13].

Conclusions: VERITAS will create a rich data set of high resolution topography, imaging, spectroscopy, and gravity. These co-registered data will be on par with those acquired for Mercury, Mars and the Moon that have revolutionized our understanding of these bodies. VERITAS would be an extremely value asset for future Venus missions, providing a very accurate topography plus surface composition map to optimize targeting of probe or lander missions as well as for later investigations of surface change.

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Exploration of Venus with Aerial Platforms : J. A. Cutts* , J. L. Hall, L. H. Matthies and T. W. Thompson, [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive Pasadena, CA 91109, James.A.Cutts@jpl.nasa.gov.

The Venus Aerial Platform Study, sponsored by NASA's Planetary Science Division, examined alternative approaches for exploring Venus with aerial vehicles in order to develop a Venus Aerial Platform Roadmap for the future exploration of the planet. Two Study Team meetings were conducted in May and December of 2017: the first focused on the scientific opportunities offered by aerial platforms at Venus, while the second meeting examined the technologies needed for operating in the severe Venus environment. More than 60 scientists and engineers have been involved in the study. The final report was completed in October 2018 (Ref1). This abstract describes the key findings of the study.

Aerial Platform concepts examined include vehicles which operate at a single fixed altitude, have the ability to change altitude, and have full three dimensional mobility. In general, enhanced mobility requires additional mass for the power and propulsion systems which has the inevitable consequence of lower payload mass fraction given the same instrumentation suite. For all concepts, payload fractional percentiles as a function of launch mass are in the single digits. The study found that variable altitude concepts represented a sweet spot offering much more science than a fixed altitude platform yet avoiding the high complexity and low payload fractions of platforms with full three dimensional mobility. While developing these key mobility technologies is paramount, the study also found that there are other capabilities vital to the scientific productivity of an aerial platform mission are including navigation and localization, relay telecommunications of data, and miniature scientific instruments. .

The Venus Exploration Analysis Group (VEXAG) is now updating a set of strategic documents covering future exploration of Venus by NASA. The findings of the aerial platform study and a parallel study on Venus Surface Platforms are being incorporated into the planning. Potential mission scenarios involving aerial platforms will be discussed.

Ref 1: Aerial Platforms for the Scientific Investigation of Venus: Summary Report by the Venus Aerial Platforms Study Team https://www.lpi.usra.edu/vexag/reports/Venus_Aerial_Platforms_Final_Report_Summary_Report_10_25_2018.pdf

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Session 07

Clouds and Chemistry (2)

Session Chair: Emmanuel Marcq
Session Chair: Takao Sato

Cytherometeorology

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In the interest of continuity, I'll present some of my intended work from IVC2018 (updated where progress has been made), and add some related work that has proceeded from that work in a slightly different direction. Hence, the following abstract begins identically to out IVC2018 abstract, but with an addtional paragraph describing the newest work.

Variations in the condensational clouds of Venus at altitudes between roughly 45 km and 60 km altitude were first revealed by Allen & Crawford (1984). Understanding these variations was a primary goal of the VIRTIS instrument on Venus Express (Drossart et al., 2007). And these variations are also being leveraged by Akatsuki in a continuing effort to understand the super-rotation of the Venus atmosphere (Nakamura et al., 2016).

We previously characterized the evolution of individual features by using data from VIRTIS-M-IR on Venus Express to quantify the variability of those features (McGouldrick et al., 2012). That work found that individual features evolved on time scales typically of about one day (24 hours), though smaller features were seen to form and/or dissipate on much shorter time scales (as short as the 30 minute cadence of the analyzed data). That work also found that the mesoscale dynamics in the vicinity of the features was consistent with the circulation that would develop in response to convergence and divergence on an Earth-sized planet having a seven-Earth-day rotation period. More recent work found a roughly 150-Earth-day periodicity in the 1.74μm radiance, indicating long-term, periodic, variations in the cloud cover are also present (McGouldrick & Tsang, 2017). These long-term variations were most pronounced at mid-latitudes ($30° - 60°$), but could not be ruled out at equatorial latitudes ($0° - 30°$), due to the observation geometry of VIRTIS. No long-term polar ($60° - 90°$) trends were noted.

In the present work, we build on those previous efforts in two ways. First, we demonstrate a baseline whereby results from VIRTIS (a medium-resolution imaging spectrometer) can be quantifiably compared with images through the several filters of the IR2 camera on Akatsuki. Next, we quantify the physical changes in the clouds that are observed at different times of high or low overall cloud opacity, and attempt to leverage this information to produce a reasonable picture of both long- and short-term cloud evolution in the constantly changing, capricious, clouds of Venus.

The Akatsuki Spacecraft is capable of elucidation of both global atmospheric dynamics (i.e., the super-rotation) and mesoscale atmospheric dynamics, due to its particualr orbit that allows observing the full disk of Venus at a number of filter-specified wavelengths, with time cadence on the order of an hour, and for up to nine days at a time (until the orbit brings the spacecraft so close that Venus exceeds the instrumental fields of view). Here, we describe the analysis of the driving dynamics associated with certain mesoscale features observed in the Akatsuki IR2 camera data. This work focuses on just a single orbit of Akatsuki, but the features and behaviors we describe appear to be common in the Venus atmosphere; future work will extend to the full available dataset. We make comparisons with similar terrestrial phenomena; and assess the implications for energy and momentum transport that may affect the overall global atmospheric dynamics.

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Climate control on Venus: Connections among clouds, UV absorber, surface chemical reaction, and atmospheric circulation

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George L. Hashimoto (Department of Earth Sciences, Okayama University)

It has been suggested that the climate of Venus is controlled by atmospheric SO_2 concentration (e.g., Hashimoto and Abe, 2005). Although SO_2 is a minor constituent of Venus' atmosphere, there are several ways to affect the energy balance of Venus. The atmospheric SO_2 concentration is likely related to the planetary albedo, since SO_2 is a precursor material of Venus' sulfuric acid clouds which cover the entire planet. Also the absorption of solar radiation is controlled by the distribution of unknown UV absorber, and some of sulfur bearing species have been suggested as candidates for the unknown UV absorber.

On the other hand, it has been argued that the abundance of atmospheric SO_2 concentration is controlled by chemical reactions between the atmosphere and planetary surface. Since chemical reaction depends on the temperature, surface chemical reactions would create climate feedback loops. It has been discussed that types of feedback loops depend on the assumption of materials on the Venus' surface (e.g., Hashimoto and Abe, 2005). To understand the stability of Venus' climate, it is necessary to elucidate the materials on the surface of Venus.

I suggest that the meridional circulation is also connected to climate feedback loops. Some of the surface chemical reactions are controlled by the oxygen fugacity at the surface of Venus which is likely affected by transport of CO produced by photochemical reactions in the upper atmosphere. Since the strength of the meridional circulation is influenced by the distribution of the absorption of solar radiation, it is reasonable to suppose that it creates climate feedback loops. It would be worth to examine the role of atmospheric circulation on the CO transport and the climate feedback loops.

Maintenances of Venusian Sulfuric Acid Clouds due to Chemistry and Dynamics Simulated by a General Circulation Model

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Abstract

Sulfuric acid clouds are important in the determination of Venusian climate through their radiative processes, and the main observational object of the Japanese Venus Climate Orbiter "Akatsuki" for the investigations of atmospheric dynamics. We have implemented the sulfuric acid cloud formations and related chemical processes into a Venusian General Circulation Model (VGCM) developed by Ikeda (2011), and investigated their distribution and the formation systems. The implemented chemical processes include the reactions to determine the abundances of H_2SO_4 vapor, SO_3, SO_2 and H_2O, and are critical in the reproduction of the realistic cloud maintenance processes. With the chemical processes, the simulated latitudinal distributions of the optical thickness of clouds qualitatively agree with the observational results by the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) onboard Venus Express (VEX), and also the simulated vertical profiles of H_2SO_4 vapor agree with the Magellan radio occultation data, in low- and mid- latitudes (0-60 degrees). With this model, we investigated the maintenance and circulation processes of the sulfuric acid clouds and vapor in the latitude regions. Our model indicated that, in the upper cloud region (60-80km), the production of clouds by the condensation of H_2SO_4 resulting from chemical processes is the largest at ~65 km altitude, and flows upward and poleward by the meridional circulation and vertical diffusion. Meanwhile, in the lower cloud region (50-60km), H_2SO_4 vapor transported by the advection and vertical diffusion condenses into the cloud in the equatorial region of 50-54 km altitude, and the formed clouds are transported poleward along the meridional circulation. These cycles are consistent with those simulated in a 2-D latitude-altitude model by Imamura and Hashimoto (1998), and we first reproduced the cycle with a 3-D model.

Modeling the Distribution of Sulfur Species in the Atmosphere of Venus

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The photochemistry of sulfur species in the upper atmosphere of Venus is not well understood. The parent molecules originating in the deep atmosphere are most likely SO_2 and OCS. At and above the cloud tops, these molecules are photolyzed, leading to the production of S, SO, SO_3 and H_2SO_4 (Mills et al. 2007). Recent work (Frandsen et al. 2016) suggests that the SO dimer (OSSO) could be as abundant as SO between 50 and 70 km.

We explore the effects of new reactions involving OSSO and S_2O, which could provide important new sources of S_2 in the upper atmosphere of Venus. With these new sources of S_2, production of S_2 and hence polysulfur (S_x) could be much larger than in the earlier model of sulfur chemistry (Yung et al. 2009), where S_2 is mainly derived from OCS + hν $\rightarrow$ CO + S, followed by OCS + S $\rightarrow$ CO + S_2. In the current model, which includes these new reactions, production of S_2 does not directly involve S atoms, as it did in the previous model. In that model, the path for producing S_2 via S competes with the fast reaction S + O_2 $\rightarrow$ SO + O, thereby greatly reducing the yield for S_2 production.

The implications of our new model are that more complex sulfur compounds, beyond OCS, SO, SO_2, SO_3 and H_2SO_4, could contribute to the absorption of UV in the enigmatic 320-400 nm range. These results may be useful for interpreting new observations obtained from Japan's Venus Climate Orbiter, Akatsuki.

Puzzling Cloud Cover of Venus

Sanjay S. Limaye

The global images returned by the four imaging cameras on Akatsuki orbiter of the day and night side of Venus reveal a very dynamic cloud cover with contrast patterns across wavelengths (Limaye *et al.* 2018b; Peralta *et al.* 2019). Vortices, large and small scale waves, sharp boundaries can be seen in the multispectral images suggesting a more complex dynamics interaction between meso-scale and large scale circulations and with surface topography. Analysis of the day side limb in the images yields information about the haze layer above the nominal cloud tops from the day side images, while the LIR camera images at 8-12 µm yield information about the temperatures at the slant unit optical depth level globally.

On the night side cloud features seen in the Akatsuki images at 1.74, 2.26 and 2.32 µm are visible due to the spatially variable transmission of the radiation emitted from below the clouds as it escapes to space. What causes these opacity differences is not clear. The morphology of the night side features suggests some influence of local circulation. Given the ubiquitousness of the primary cloud particles (~ 1 µm radius) it is not easy to understand why contrasts exist at all on the day and night sides without considering the altitude dependent local circulations about which we know very little.

It has been known for some time that in reflected light images of Venus, the contrasts peak at about 370 nm and decrease to barely discernible at shorter and longer wavelengths. Sulfur dioxide has been identified as one of the species that is likely responsible for contrasts observed in the 283 nm images but observed contrasts at longer wavelength images indicate that other species are required to produce them. More than a dozen species have been proposed for explaining the absorption of sunlight, but the identity of the absorber(s) and their nature are still a mystery.

There is a growing evidence that more than two absorbers may be required to understand the contrasts on Venus(Jessup *et al.* 2018). The available data are not adequate to confirm whether the other absorbers are gaseous, particulate or even organic. (Limaye *et al.* 2018a) have revisited the possibility of life in the clouds of Venus explored whether microorganisms may contribute to the contrasts seen on both day and night side of Venus.

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Spectral Properties of Unusual Nightside Cloud Features on Venus

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Venus' middle and lower cloud decks are backlit by thermal photons emitted from Venus' surface and lower two scale heights. Within CO_2 windows at 1.74 and 2.3 μm, the clouds show up as silhouettes on Venus' night hemisphere. The Akatsuki mission's IR2 camera has imaged some distinctive cloud features in these wavelength bands, such as paired vortices and sharp discontinuities, thousands of km long in the N/S direction (Peralta et al. 2019). Following the lead of the IR2 camera, we obtained image sequences and spectral image cubes of Venus' nightside from the IRTF using the SPEX spectrograph for periods of ~3 weeks during each of the last two inferior conjunctions (April-May 2017 and Nov-Dec 2018). SPEX observations were generally taken from 6 to 10 AM local time (HST). Each 4h observing window consisted of thousands of 0.5s exposures in selected filters (1.74 or 2.26 μm) and simultaneous image cubes, which were produced by obtaining spectra while driving the spectral slit across Venus' disk slowly, over a 15- or 30-min period.

We have some indication that sharp discontinuities are different from most of the other cloud features seen on the night side: they maintain a recognizable pattern for weeks, and they circumnavigate the planet in 4-5 days, much faster than the usual 7-8 period for nightside cloud features. The spectra taken across the discontinuities lets us, in theory, investigate cloud properties such as particle sizes and H_2SO_4 concentrations (Barstow et al. 2012), as well as map concentrations of trace gases CO, OCS and H_2O. We report on the spectral information for clouds on the night side and compare spectral results for cloud features with particular morphologies.

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Session 08

Posters (2)

Session Chair: Makoto Taguchi

THIRTY DAYS ON VENUS: CHEMICAL AND ELECTRICAL CHANGES MINERALS EXPOSED TO THE GLENN EXTREME ENVIRONMENT RIG (GEER). M. S. Gilmore[1], A. R. Santos[2], J. P. Greenwood[1], N. Izenberg[3], G. Hunter[2], A. Treiman[4], and D. Makel[5], [1]Wesleyan University, 265 Church St., Middletown CT, 06459 USA mgilmore@wesleyan.edu, [2]NASA Glenn Research Center, Cleveland OH, [3]Applied Physics Lab, Laurel, MD, [4]Lunar and Planetary Institute, Houston TX. [5]Makel Engineering, Chico, CA.

The NASA Glenn Extreme Environment Rig (GEER) is a pressure vessel that can simulate Venus conditions of pressure, temperature and atmospheric composition. We placed a number of natural mineral samples in GEER at an approximation to Venus conditions: T = 733 K, P = 93 bars, 96.5% CO_2, 3.5% N_2, 180 ppm SO_2, 51 ppm OCS, 30 ppm H_2O, 12 ppm CO, 2 ppm H_2S, 0.5 ppm HCl and 2.5 ppb HF. The run lasted 30 days at Venus conditions. Minerals were selected to address two sets of questions:

Venus Apatites. Several of the mountaintops of Venus display anomalous radar emissivity and backscatter that has been explained as a consequence of the presence of ferroelectric minerals at high elevations, where ferroelectric minerals are created or precipitated in rocks over time by chemical reaction(s) with the ambient atmosphere [1,2]. That basaltic rocks and tessera materials both show this change in radar emissivity and backscatter suggests a ferroelectric mineral that is ubiquitous in igneous rocks [3]. We seek to test the hypothesis of [2] that exposed grains of fluorapatite ($Ca_5(PO_4)_3F$), the more common apatite mineral in igneous rocks on Earth [2-4], will convert to chlorapatite ($Ca_5(PO_4)_3Cl$), which is ferroelectric, under Venus surface conditions. To test this idea, in this experiment we reacted two fluorapatites and one chlorapatite.

Venus Surface Mineralogy In-Situ Instrument System (V-Lab). V-Lab is a proposed *in situ* reaction chemistry experiment where geological materials whose core properties may change over time upon exposure to the Venus atmosphere will be placed on a microsensor platform. Changes in this geological material as monitored through electrical measurements will give an indication redox solid-gas reaction(s) in the Venus environment. Comparison of the reaction chemistry between different material types will provide an improved understanding of the effect of the Venus surface atmosphere on known geological materials. In our experiment, we sought to determine if any compositional and/or electrical properties changed in samples upon exposure to simulated Venus atmosphere in GEER over a 30-day run. The results will help us to focus on minerals that are good candidates for a platform like V-Lab. The reactants include: hematite (α-Fe_2O_3), magnetite (Fe_3O_4), anhydrite ($CaSO_4$), pyrite (FeS_2), a mid-ocean ridge tholeiitic basalt (Juan de Fuca) and calcite ($CaCO_3$).

Analyses. Color changes are observed in some apatite samples after the GEER run. The minerals will be analyzed by with a Hitachi Field Emission Gun Scanning Electron Microscope SU 5000 (FE-SEM). Elemental maps with sub-micron scale resolution will be produced and examined to document the alteration products of the minerals. For the apatites, we will look to see whether ferroelectric phases such as chlorapatite are formed due to reaction in a Venus-like atmosphere over the time frame of the experiment. For all solid samples, we will look for compositional changes due to solid-gas reactions.

We will also test if the reactions in the Venus chamber produce changes in electric properties of tested solids. The electrical impedance and capacitance of several samples (two of the apatites, hematite and magnetite), measured both before and after the GEER run, will be analyzed and compared. Such changes may be relevant to the anomalous radar behavior at high altitudes on Venus.

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Cancelled

Self-Consistent Reference Seismological Models for Determining Venus's Interior Composition

C. T. Unterborn

The Emissivity of Pyrrhotite/Basalt Mixtures at Venusian Temperatures

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Introduction: An abrupt decrease in emissivity has been observed on several highland regions on Venus [1-3]. Researchers have suggested that perhaps a loaded dielectric can cause the low emissivity signal [1-3]. Pyrrhotite (Fe_7S_8), a common mineral in basalt, has been discussed as a possible source [3], and could be the dielectric mineral. However, the emissivity of a loaded dielectric has never been obtained at Venusian temperatures. Using the spectrometer at the DLR we studied the emissivity of varying concentrations of pyrrhotite in basalt at the NIR atmospheric windows on Venus.

Methods: Experiments were completed in the Planetary Emissivity Lab at the DLR. The tested samples were basalt, 98 vol% basalt – 2 vol% pyrrhotite, 80 vol% basalt – 20 vol% of pyrrhotite, and pyrrhotite. All samples were ground and sieved to 212-280 µm. We used a Bruker Vertex 80V spectrometer to obtain the emissivity of various mineral mixtures at three different temperatures representative of Venus: lowlands (460°C), mid-elevation (420°C), and highlands (380°C). The observed wavelengths were between 0.85-1.2 µm. After the completion of the experiments all samples were analyzed with an XRD to observe any changes to their composition.

Results: The emissivity of basalt decreases from 380°C to 420°C, but increases to a greater emissivity than the spectra obtained at 380°C when heated to 460°C. In the 98 vol% basalt – 2 vol% pyrrhotite mixture the emissivity taken at 380°C and 460°C are the same, but the emissivity is lower at 420°C. The emissivity obtained at 420°C and 460°C have lower emissivity than the basalt spectra taken at the same temperatures. The spectra obtained at 380°C is the only one that has a higher emissivity than its corresponding basalt spectra. Overall the emissivity of the 80 vol% basalt – 20 vol% pyrrhotite was higher than the corresponding basalt spectra. Further analysis needs to be completed on the pyrrhotite spectra, but preliminary results show a horizontal and vertical shift with temperature.

XRD analysis revealed the formation of pyrite, magnetite, and hematite in the pyrrhotite sample after heating. Pyrrhotite, as well as the previously mentioned minerals, could not be detected in the basalt/pyrrhotite mixtures.

Discussion: The loaded dielectric theory does not hold for pyrrhotite mixtures with 20 vol%. The only two instances where the emissivity decreased was in the 98/2 mixtures heated to 420°C and 460°C. The lack of pyrrhotite and the increase in emissivity in the 80/20 mixtures points to the formation of some mineral with a lower dielectric constant than pyrrhotite. The drop in emissivity at 420°C in the basalt and basalt/pyrrhotite mixtures is due to a mineral that is present in the basalt and is not related to pyrrhotite.

Conclusion: Our results demonstrate that temperature plays an important role in emissivity and can cause noticeable shifts in the spectra. We found that 20 vol% of pyrrhotite caused an increase, and not a decrease in emissivity as originally proposed. The emissivity of the 20 vol% pyrrhotite at all temperatures is very distinct and can be distinguished from our basalt. Once the emissivity of pure pyrrhotite has been analyzed, and the composition of the 80/20 basalt/pyrrhotite mixture has been determined, we can better understand the reason behind the increase in emissivity. The data obtained here can be used to better understand data collected from future orbiters sent to Venus.

Acknowledgements: Europlanet 2020 RI has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654208.

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Cosmic rays detected by LAC on board Akatsuki

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Cosmic rays, high energetic particles from astrophysical sources outside the solar system, are an important contributor to planetary radiation environments. On Venus, cosmic ray cause ionization in the atmosphere, and this effect is considered as a dominant ionization source. Meanwhile, we have known that some bodies within the solar system shine to X-rays, and in the case of Venus, charge exchange interactions between highly charged ions in the solar wind and the Venusian atmosphere would be one of the X-ray sources.

Our understanding of the environment of the high energetic particles around the Venus orbit is limited. Therefore, the detection of cosmic rays by the instrument onboard Venus orbiter provides us precious information. Lightning and Airglow Camera (LAC), which is one of the onboard instruments of Akatsuki, is a new type of lightning detector equipping 8×8 pixels (16×16 mm) APD (avalanche photodiode) detector and enables detecting optical lightning flash with 30 kHz sampling rate. LAC adopt the pre-trigger sampling method to record pulsed signal by using half of 64 pixels. Despite no detection of flashes attributable to lightning, LAC recorded over 400 cosmic ray events during the 40 observation session of LAC from August 2016 to December 2018.

The estimated average event rate of LAC was 0.0033 events/min/mm^2. Since, the previous detection by Pioneer Venus star sensor [Burucki et al., 1981; 1991] was 0.28 (or 0.12 during quiet sun) events/min/mm^2, this low event rate might be caused by the LAC shielding is much less susceptible to cosmic ray triggers than PVO. The output peak values of the pulsed signals have covered almost from 6 digits to 80 digits, and intense events having large peak value (>80 digits) seem to be randomly recorded. Since the energy of cosmic ray is high enough to excite photo-electron inside the detector, this wide range of the peak values can be caused by the incidence angle of cosmic rays to the face of APD detector. Under this assumption, the possibility of the incidence angle (θ_i) is proportional to $\sin 2\theta_i$ when we expect the isotropic cosmic ray incidence. We conducted statistical analysis with 431 recorded cosmic-ray events and found that detected events roughly follow the assumed isotropic incidence relation (Fig. 1). Additionally, the event rate dependence on Venus–Spacecraft distance was investigated (Fig. 2), and the data appear to indicated a slightly low event rate around 1.0×10^4 and 1.5×10^4 km. Since Venus lacks a magnetic field, there is no plausible explanation for this dependence on the observation distance so far if the "dip" rates is real.

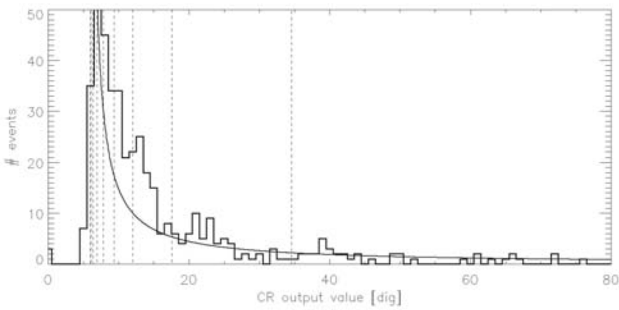

Fig. 1: Cosmic-ray event distribution in the maximum recorded signal levels. The solid line shows the expected event number assuming the particle isotropic incidence, and the vertical dashed lines show the representative incidence angle with 10 degree intervals.

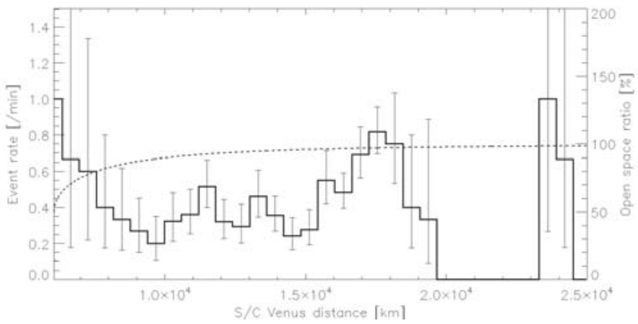

Fig. 2: Event rate distribution in a distance from the center of Venus and spacecraft. The dashed line shows the percentage of the solid angle occupied by Venus disk at each distance.

A review of photochemical reactions and electrical discharge in the atmosphere of Venus with special focus on lightning in the cloud region

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Investigations are carried out on the lightning regions in Venus based on previous works with the help of photochemical model published by Krasnopolsky 2011[1]. Venus can be considered to be an optically active planet with phenomenon like reflection and refraction ruling to some extent which possibly imposes a difficulty in studying the phenomenon of lighting, sprites and sferics. It is also found that optical and radio refractivity increases at low altitudes[2]. Optical phenomenon should also be taken into account while studying the dense planet. Several evidences of electromagnetic bursts were measured by various landers and orbiters studying Venus atmosphere (Venera landers, Venus Express and the Pioneer Venus Orbiter). The electromagnetic bursts that are taking place in the cloud region in the form of lightning or fluorescence might be a result of momentum transfer, solar convection and charge dispersion in the clouds of Venus. Polydisperse and monodisperse charging of ions will help understand the possibility of photochemical reactions taking place in the clouds regions. This research is oriented to demonstrate that lightning is a cumulative effect of factors such as planet's rotation, super-rotation of the clouds, Galactic cosmic rays which ionize the particles below the upper cloud layers etc. A novel study on the feasibility of the photochemical reactions is carried out so as to check the possibility of lightning and or fluorescence in the cloud cover.

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Role of a Weak Planetary Dipole Moment on Venusian Upper Atmosphere and Near Space Environment

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Venus, the twin planet of Earth, still has a number of unsolved mysteries in its near space environment and upper atmosphere, including occasional large polar magnetic field structures observed by Pioneer Venus Orbiter (PVO) and Venus Express (VEX). Here we explore the consequences of a weak planetary dipole magnetic field of Venus using the BATS-R-US multi-species magnetohydrodynamic (MS-MHD) model. In this study, we extend the model lower boundary into the planetary interior by including an electrically conductive core and a resistive mantle. The newly developed Conducting-Core-Surface-to-Interplanetary-Space MS-MHD (CCSIS-MS-MHD) model solves the planetary interior, planetary ionosphere, and solar wind-Venus interaction in a self-consistent way. We run several different cases based on different solar cycles with different dipole moment strength and polarity (the equatorial surface magnetic field strength, B0, is 0nT, 1nT, 3nT, 10nT, respectively). We plan to investigate the consequences of a weak planetary magnetic field on the Venusian ionosphere and magnetic topologies. We aim to explain the longtime mysteries observed by VEX and PVO.

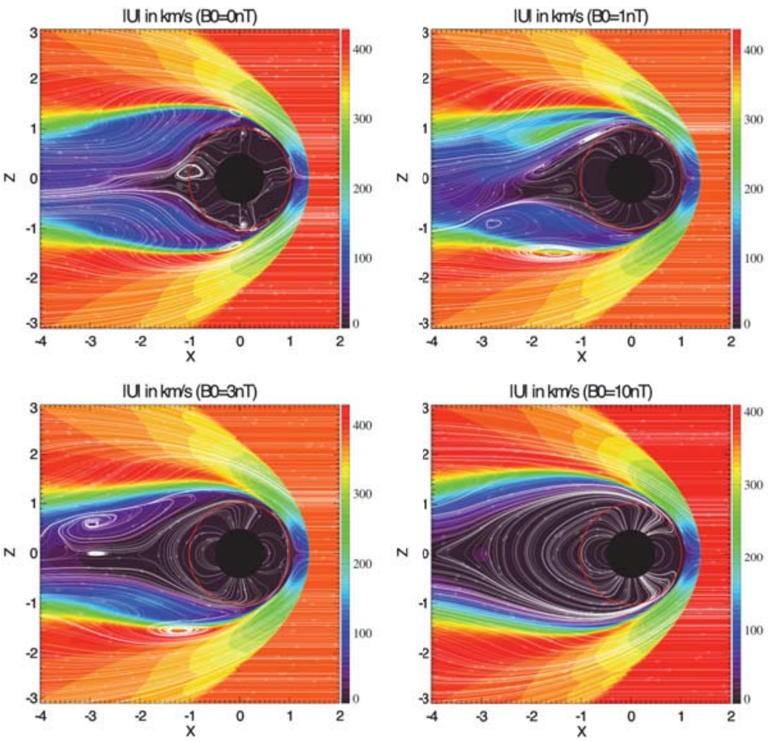

Figure 1 The calculated magnetic field and velocity in the meridian (x-z) plane with different dipole moment strength (the equatorial surface magnetic field strength, B0, is 0nT, 1nT, 3nT, 10nT, respectively). Interplanetary magnetic field (IMF) is assumed to be a Parker spiral. The four cases shown in the plot are based on solar cycle maximum conditions. The color depicts the magnitude of speed, |U|, in km/s and the white streamlines are the magnetic field lines. The red circle shows the surface of Venus and the black sphere (0.5 R_V) is the conducting core. The region between the core and the surface is the resistive mantle.

Search for lightning discharge in Venus with Akatsuki/LAC and Pirka telescope

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The existence of lightning discharge in Venus has been controversial for three decades, which might be attributed to the luck of conclusive observational evidence. There had been no satellite payload intentionally designed for the detection of lightning phenomena using radio wave or optical sensor. LAC, lightning and airglow camera, on board Akatsuki spacecraft, is the first sensor optimized for the lightning optical flash measurement in planets other than the Earth. It is expected that LAC could conclude this 30-year discussion on the existence of lightning in Venus. Unique performance of LAC compared to other equipment used in the previous exploration of Venus is the high-speed sampling rate at 20 kHz with 32 pixels of Avalanche Photo Diode (APD) matrix, enabling us to distinguish the natural optical lightning flash from other pulsing noises, including artificial electrical noise and cosmic rays. We selected OI 777 nm line for lightning detection, which is expected to be the most prominent emission in CO2-dominant atmosphere based on the laboratory experiments.

The regular operation of LAC for lightning hunt was started on December 1, 2016. Due to the elongated orbit than that planned originally, we have an umbra for approximately 30 min to observe the lightning flash in the night side of Venus every 10 days, which is almost 1/20 rate of the original plan. The triggering parameter was set so as to optimize for the light curve similar to the normal lightning in the Earth and data obtained totally for about 4 hours were examined. However, we couldn't find any lightning signals. Adding to this triggering parameter set, we added one more parameter set, optimized for sprite type emission with duration of up to 10s of ms. These two sets are in rotation at every 60 sec. Furthermore, in order to investigate fainter emissions, we are now conducting successive force triggering recordings without any threshold, achieving 5 times better sensitivity than the intensity of 1 digital unit at best. Here we report the detailed strategy and the latest status of the LAC observation and discuss the possible explanation for the occurrence rate estimated by all LAC observations.

Also we will make ground observation with a high-speed photometer installed at Pirka telescope, a 1.6-m reflector deployed by Hokkaido University. Here we report the outline of the instrumentation and strategy of the observation.

Simulations of Vertical Profiles of Sulfur Oxides in Venus' Mesosphere

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The primary sulfur species in Venus' atmosphere, sulfur dioxide (SO_2), is a precursor for the sulfuric acid that condenses to form Venus' global cloud layers and may be a precursor for the unidentified UV absorber(s), which, along with CO_2 near the tops of the clouds, appears to be responsible for absorbing about half of the solar energy deposited in Venus' atmosphere [1]. Published simulations using standard photochemistry [2,3] indicate the mixing ratio of SO_2 should decrease roughly monotonically with increasing altitude as the source for SO_2 is the troposphere, although a small inversion is evident in one set of simulations [3]. Observations, however, despite disagreeing on the magnitude of the phenomenon, have consistently found an inversion layer in the upper mesosphere (above about 85 km altitude) where the mixing ratio of SO_2 increases with increasing altitude [4,5,6]. Simulations using H_2SO_4 as the medium for transporting sulfur from the lower mesosphere to the upper mesosphere that replicated the upper mesosphere SO_2 inversion layer [2,7] either required assumptions that stretch the boundaries of known laboratory data or had a calculated H_2SO_4 abundance that exceeds the observational upper limit on upper mesospheric gaseous H_2SO_4 [8]. S_8 remains as a viable alternative medium by which sulfur can be transported from the lower mesosphere to the upper mesosphere but there are significant uncertainties due to lack of laboratory data [7]. Another possible alternative is transport via a combination of sulfur-chlorine-oxides [9].

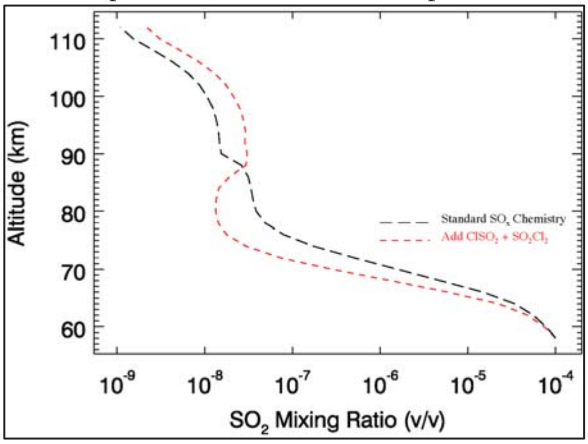

Figure 1. Simulated SO_2 mixing ratio using a modified version of the Zhang et al [2] model with SO_2Cl_2 and $ClSO_2$ (red short-dashed) and without (black long-dashed) [after 9].

The Caltech/JPL photochemical model [10] was used for the numerical simulations. It applies a common core of atmospheric physics to all planets, drawing planet-specific information from custom databases, and converges to a steady-state solution via a finite-difference iterative algorithm. For these simulations, the 1-d continuity equation is solved simultaneously for all species over 58–110 km altitude. Vertical transport via eddy diffusion is set based on observations, as are the lower boundary conditions for HCl, CO, and OCS.

Preliminary results using a modified version of the Zhang et al [2] model suggest the inclusion of both $ClSO_2$ and SO_2Cl_2 in the model and adjustment of selected reaction rate coefficients within their standard uncertainties can produce at least a factor of two upper mesosphere inversion for SO_2, Figure 1. The results from simulations using a more comprehensive photochemical model will be presented.

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Photochemical Control of the Distribution of Venusian Water and Sulphuric Acid Aerosols in the Clouds and Upper Haze of Venus

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Introduction and Motivation. The large variability of H_2O and SO_2 in the atmosphere of Venus above the cloud tops is puzzling, especially since there is little evidence for their variability in the lower atmosphere. We note three important related facts: (1) The abundances of H_2O and SO_2 in the middle atmosphere are of the same order of magnitude ~10-40 ppm, (2) there is a rapid decrease in H_2O and SO_2 just above the cloud tops, resulting in sharp vertical gradients in their vertical profiles, and (3) the primary removal mechanism for H_2O and SO_2 above the cloud tops is formation of H_2SO_4 aerosols. In this talk we examine the possibilities that H_2O and SO_2 could be regulated in a chemistry-transport model and related consequences for microphysical cloud modeling. Above the cloud tops, SO_2 exchanges rapidly with SO and SO_3. However, formation of H_2SO_4 followed by condensation sequesters SO_2 in aerosol particles and remove it from active chemistry. The reaction that forms H_2SO_4 appears to involve a complex with H2O:

$$SO_3 + H_2O = SO_3{\cdot}H_2O \qquad SO_3{\cdot}H_2O + H_2O = H_2SO_4 + H_2O$$

Modeling Conclusions. Using the CARMA 3.0 microphysical cloud model with model atmospheres from the Caltech/JPL KINETICS photochemical model we can describe changes in the Venus atmosphere due to variations aerosol distribution from the equator to the poles, effects due to changing lower boundary conditions, and effects due to changes in chemistry due to water nominal, water rich, and water poor conditions, specifically:

A. Photochemical Modeling [1, 2]:

1. SO_2 and H_2O can regulate each other via formation of H_2SO_4
2. Small changes in the transport rates for SO_2 may result in large changes in SO_2 above cloud tops.
3. Below a critical value, H_2O could be completely sequestered by H_2SO_4 aerosols (chemical bifurcation).
4. Combination of the above could explain some of the observed variabilities in SO_2 and H_2O in Venus' middle atmosphere.

B. Microphysical Cloud Modeling using photochemical model atmospheres [2, 3, 4]:

1. Using model atmospheres with different lower boundary water mixing ratio values for water definitely affects the microphysics equatorial latitudes and exhibits particularly extreme behaviour different for chemical bifurcation cases corresponding to a collapsed water condition in the atmosphere.
2. This difference is more than PVO vs. VEx epoch differences.
3. Large differences occur in the precipitation cycle at the equator (a factor of ~3 decrease in timescale from 15 ppm to 35 ppm lower boundary water mixing ratio values (i.e. ~2 years vs ~8 months).
4. Upper haze layer (84 km) at all latitudes shows a large increase in 0.3-0.6 micron sized particle when comparing a 15 ppm lower boundary water mixing ratio to 35 ppm, particularly at the poles.
5. This makes sense, since with a chemical bifurcation there is much more SO2 present under collapsed water conditions.

References: [1] Zhang et al. (2012); [2] Parkinson et al. (a), PSS Venus Special Issue, 2015; [3] Parkinson et al. (b), PSS Special Issue, 2015; [4] Gao et al. (2014)

Title: Venus Cloud Top Chemistry, Convective Activity and Topography: A Perspective from HST
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Affiliations: (1) Southwest Research Institute, Boulder, USA; (2) LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France; (3) Space Science Institute, Boulder, USA; (4) Australian National University, Canberra, Australia; (5) University of Wisconsin, Madison, USA; (6) Space Telescope Science Institute

In 2010/2011 we used Hubble Space Telescope (HST) to obtain spectra Venus' cloud top properties over Aphrodite Terra (at 200-600 nm) and plains region located downwind of Aphrodite (at 200-300 nm) [1-2]. For each observation two 0.1" wide maps of the cloud top radiance were obtained as function of latitude over local solar times extending from 7 to 11 hr. (Fig. 1a). Our analysis of these data [1-3] revealed the following key trends:

- The cloud top albedo at 245 nm varied in the same manner as the 365 nm albedo (Fig 1b); this suggests that the same material and/or mechanism controls the distribution of the species controlling the 245 nm and 365 nm cloud top albedo. RT modeling indicates that multiple scattering through the cloud top SO_2 gas was not the primary source controlling the 245 nm albedo. As the source of the 365 nm absorption remains unidentified, these results support that the unknown absorber either has more than one source [e.g., 4-6] and/or it has a continuum extending shortward of 300 nm [7-8]
- On each date the minimum albedo (at 245 or 365 nm) was observed at the equator, and increased in brightness with increasing latitude; as expected if the species controlling the albedo at these wavelengths is dominantly controlled by Hadley cell circulation [9]. This was true independent of the observed SO_2 gas latitude distribution gradient.
- At local solar times (LSTs) between 10 and 11 hr, the 245 nm albedo above the plains darkened rapidly with increasing LST; however, over Aphrodite only limited (~0-10%) albedo darkening was observed between 10 and 11 hr (Fig1c). The time at which these darkening manifest correlates directly with the previously observed and well documented manifestation of subsolar convective activity at Venus' cloud tops.[10-12]
- The equatorial SO_2 gas abundance decreased by a factor of 3 directly over Aphrodite within a 5-day period (Fig1d); additionally, the latitude distribution of the SO_2 reversed from decreasing with increasing latitude, to increasing with increasing latitude. These behaviors suggest a decline in the large-scale mixing via the Hadley cell circulation sufficient enough to allow photochemical depletion of the low-latitude SO_2 gas abundance within a 5 day period. [1,9]

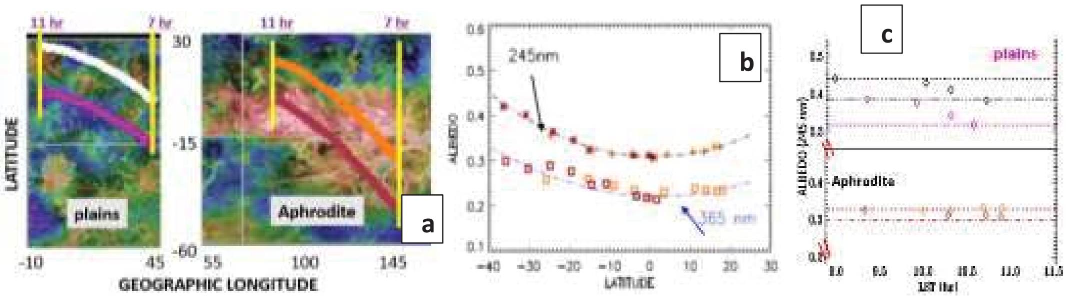
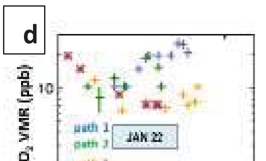


Figure 1 (a) HST slit paths shown in white & pink and orange and red; (b) 245 nm and 365 nm albedo latitude variations; (c) albedo vs. LST for slit paths shown in (a); (d) observed SO_2 latitude variation over Aphrodite



Models of the subsolar convective mixing mechanism (e.g., [13]) show that excitation of convective activity may expand from the boundary between the middle and upper clouds to the cloud tops, directly impacting the transport of materials between the cloud layers. These models show that the vigor (vortex velocity and eddy mixing rate, κ_m) of the convective activity and the atmospheric stability gradient between the stability layer (in the middle cloud) and the upper cloud determines the altitude range over which gases and trace species such as the unknown absorber(s) may be mobilized. In those cases where the temperature differential between the stability layer and upper cloud is limited, the convective mixing will not expand beyond the original length of stability layer, preventing the manifestation of the cell features at the cloud top. Thus, we infer that the required temperature differential is not achieved above Aphrodite pre-noon. However, we presume that the mountain only delays the timing at which the convective cells manifest at the cloud tops due to an expanded convective mixing layer, as these cells have been observed at Aphrodite longitudes near 1:16 hr [12].

Based on the HST observed LST and latitude albedo variations we conclude that topography impacts the vertical distribution of Venus' unidentified absorber(s) through both large and small-scale mixing processes. As this (these) species have a direct impact on Venus' radiative balance, climate and cloud super-rotation, we strongly advocate for future observations that can uniquely and contemporaneously characterize Venus' cloud top albedo and chemistry relative to Venus' underlying surface topography and zonal cloud motions.

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Cloud morphology and wind measurements by the Akatsuki 1-μm camera

Iwagami N (none) and J. Peralta (Japan Astronautical Exploration Agency)

Venus is often called as a sister of the Earth because of its similar size and distance from the Sun. However, their resemblances end here, since the Venus atmosphere is mostly composed of CO2 and surface pressure and temperature as high as 90 atm and 740 K, respectively. Its atmosphere is dominated by a phenomenon called “super rotation”, which has been investigated by meteorologists for more than half a century, manifesting as fast wind speeds that at the cloud top achieve velocities of ~100 m/s, 60 times faster than that of the solid globe. However, the accelerating mechanism of the super rotationn is yet unknown. Remote wind measurements on Venus have been conducted mainly in the UV region, where the presence of an unknown absorber allows the tracking of clouds. On the contrary, cloud tracking with images in near-infrared (NIR) wavelengths (which allow to sense a deeper level than UV images) is difficult due to the faint contrast of just a few percent. Here we present the analysis of 900-nm images of Venus’s dayside clouds, taken by the IR1 camera onboard JAXA’s Akatsuki mission. We have inspected 984 images covering from 07 December 2015 to 09 December 2016, attending to suitable values of spatial resolution and phase angles. We investigate both global and local properties of the clouds to see their temporal and spatial variations in 900-nm images. A comparison with UV images is also undertaken to gather information about acceleration processes and different contrast-forming heights. Considerable hemispherical asymmetries and sharp changes are sometimes observed Venus's albedo at this infrared wavelength. This may indicate that 900-nm contrasts nm might be at least partly formed by an unexpected unknown absorber. The zonal and meridional wind profiles found are similar to those of previous NIR measurements but displaying faster zonal winds at the equator, suggesting that equatorial jets are also apparent on the middle clouds of the dayside. The winds during the Akatsuki missions were also combined with measurements from amateur observations and during the Venus Express mission, revealing that the zonal winds seem to steadily increase along 10 years.

Enormous cloud cover as seen by Akatsuki/IR2 on the night-side disk of Venus

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Night-side observations in transparency windows of Venus' CO_2 atmosphere allow visualizing inhomogeneous clouds in ~50 to ~60 km altitudes (the lower part of ~20-km thick cloud layer). The IR2 camera on board Akatsuki captured such images at 1.735, 2.26, and 2.32 μm wavelengths. In the IR2 night-side data, an enormous cloud of greater opacity and very sharp edge in the front (western end) is seen repeatedly. This feature seems to encircle the planet with a period of ~4.5 days (Peralta, in preparation).
Although interesting, property of particles in this feature was not studied before due to difficulty of photometric measurements in IR2 night-side data. This difficulty comes from a combination of the intense day crescent of Venus and an extended tail of IR2 point-spread function (multiple reflection in the detector is believed to be the cause). We have developed a technique to restore the contrast of the night-side data to a reasonable level by deconvolution so that the photometric studies can be done with IR2 night-side data.
The data acquired on 18th and 27th August 2016 are analyzed. We have performed a series of radiative transfer computations to reproduce both 1.735- and 2.26-μm opacities in this enormous cloud. Properties of the cloud particles will be presented and possible mechanism of this remarkable phenomenon will be discussed.

Understanding the formation of super-rotation under zonally symmetric thermal forcing

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Due to the latitudinal dependence of solar heating, the radiative equilibrium temperature of the Venus atmosphere has a large equator-to-pole difference. The corresponding gradient wind has a rotation speed much faster than that of the planetary rotation. As well known, however, this state is not possible if the flow is purely axi-symmetric (Hide's theorem), but studies since Gierasch's (1975) have demonstrated that eddy angular momentum transport can facilitate it. Consequently, to question how the angular momentum is transported has been at the center of the studies of super-rotation with three-dimensional numerical models.

One can, however, regard that *the super-rotation is naturally driven thermally*, if eddies can *passively* adjust angular momentum to re-establish thermal wind balance in response to thermal forcing. This study is conducted to investigate whether this view is justified.

A two-dimensional hemispheric model assuming the meridional symmetry was developed for this study based on the transformed Eulerian mean (TEM) equations. The gradient wind balance is supposed, so temperature is tied to the angular momentum. The diabatic forcing affects the time evolution through the meridional residual circulation obtained by a kind of the Sawyer-Eliassen equation. The eddy momentum transport is expressed as the divergence of the EP flux. Three eddy effects are parameterized: convective, symmetric, and barotropic-baroclinic instabilities. No explicit eddy diffusion/viscosity is included. The model is driven by thermal forcing expressed as Newtonian cooling with a realistic vertical distribution of the relaxation coefficient. Surface friction is introduced as the Rayleigh friction at the lowest level. When it is tuned off, the total momentum is conserved nearly perfectly.

In the control run in which the initial state is at rest (relative to the planetary rotation) and meridional thermal forcing is weak (in terms of the pole-to-equator basic temperature contrast), super-rotation developed in the cloud-layer and descended to extend eventually over the full depth with a realistic strength. Eddy forcing associated with the symmetric instability is the main driver, but the barotropic-baroclinic instability also plays a significant role. The result suggests that these instabilities can act like the horizontal eddy viscosity in Gierasch's study and, with meridional circulation, draw angular momentum from below. A substantial super-rotation develops down to some level even when the surface friction is turned off by making the lower atmospheric flow slightly reversed; the surface friction is important to realize realistic total angular momentum. Overall, the view can be justified.

The Venus AFES LETKF Data Assimilation System (VALEDAS)

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The Venus AFES (Atmospheric GCM for the Earth Simulator) LETKF (local ensemble transform Kalman filter) Data Assimilation System (VALEDAS) has been developed to make full use of the observational data and tested for Venus AFES simulations excluding the thermal tides [1]. The result shows that the system works well with observation with periods less than 12 hours, but its impact is quite limited in the case of daily observation. Here, we further proceed to the data assimilation with horizontal winds derived from Venus ultraviolet (UV) images taken by the Venus Monitoring Camera (VMC) onboard the Venus Express (VEX) orbiter using Venus AFES simulations *including* the thermal tides in order to investigate the impact of the data assimilation on the thermal tides and the general circulation [2]. The results show that three-dimensional structures of the thermal tides are significantly improved not only in horizontal winds but also in temperature field. The zonal mean fields of the zonal wind and temperature are also improved globally (Figure). Currently, Ensemble Forecast Sensitivity to Observations (EFSO) technique is implemented to quantify how much each observation improves the Venus AFES forecasts. The system would be useful to produce reanalysis from the Venus Climate Orbiter 'Akatsuki'.

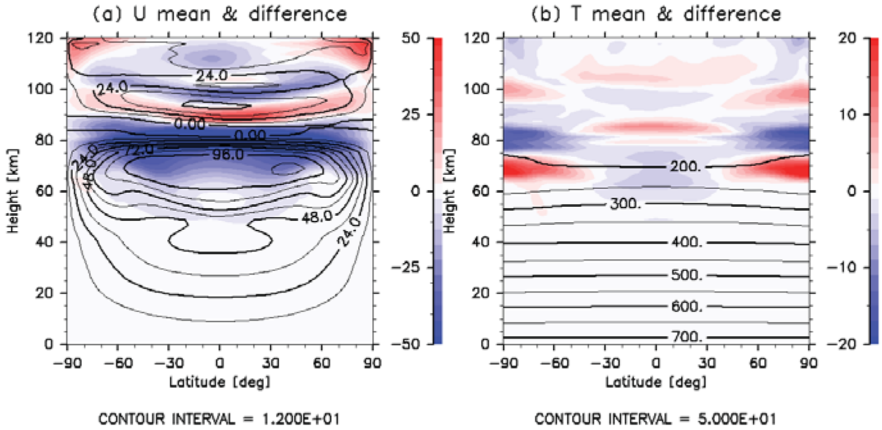

Figure: Zonal mean zonal wind (a; contours, m s^{-1}) and temperature (b; contours, K) in a latitude–height cross section averaged over the last 30 Earth days in Epoch 4. Color tones show deviations from those obtained by Venus AFES without data assimilation.

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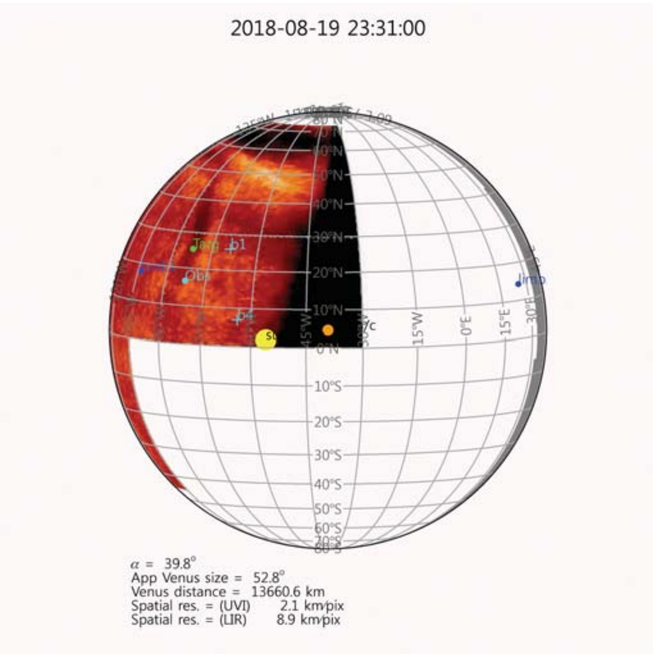
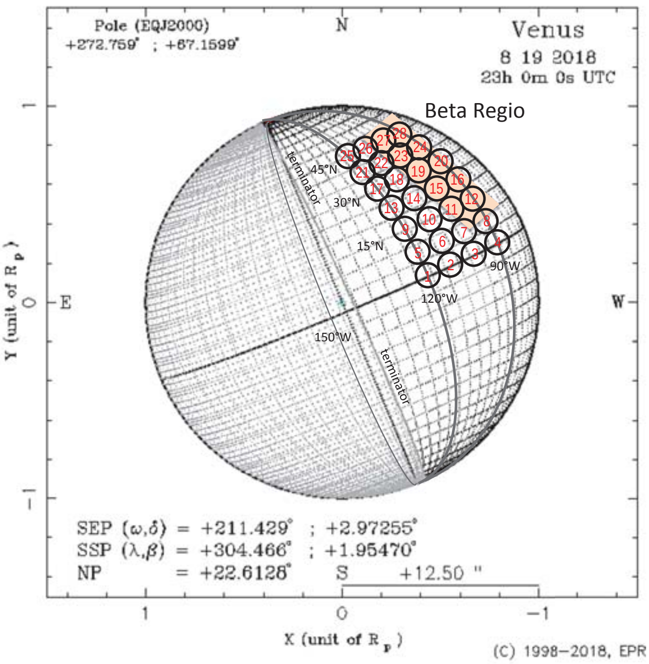
Clouds Top Wind Measurements and Thermal Properties near Beta Regio (25N, 283E)

Thomas Widemann, Pedro Machado, Yeon Joo Lee, Ruben Gonçalves, Daniela Espadinha, Francisco Brasil, Claire Moutou, Takeshi Imamura, Kandis Lee Jessup, Candace Gray, Makoto Taguchi, Shigeto Watanabe, Takehiko Satoh

A joint CFHT/ESPaDOnS – VLT/UVES – Akatsuki/UVI-LIR Campaign took place during Akatsuki's Aug. 19-29 2018 Pericenter Passages targeting Beta Regio (25°N 283°E) on Aug 19 (#18-005) and Aug 29. The 3.60-meter Canada-France-Hawaii telescope (CFHT) with ESPaDOnS visible spectrograph provides high-resolution spectra (R~80000) from 0.37 to 1.05 μm to map cloud top winds at the same time and with the same geometry as UVI and LIR observations. VLT/UVES provides high spectral resolution long slit data of R~40,000 in the 0.3-1.10 μm range and in addition to Doppler winds, provides constraints on the spatial distribution of the unknown UV absorber and sulfur-bearing trace gases abundances.

Both ESPaDOnS and VLT/UVES observational technique of Doppler velocimetry in visible solar lines have proven a reference technique to measure instantaneous wind circulation at Venus. Perihelion observing from Akatsuki allows for UVI cloud morphology and UV reflectivity at cloud top level. This will also be compared to Akatsuki LIR imaging near 10 μm that have monitored cloud-top temperature in the same region. Preliminary results will be presented at the meeting.





Structures of planetary-scale waves at Venusian cloud top revealed by an improved cloud-tracking method tolerant to streaky features

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Ultraviolet (UV) images of Venus show various features of clouds due to inhomogeneously distributed UV absorbers in the cloud layer. Cloud tracking has been widely used to derive atmospheric motion. As for Venus atmosphere, long term variations of super-rotation (Kouyama et al., 2013), properties of atmospheric waves (e.g. Kouyama et al., 2015; Limaye, 1988), and a relationship between the cloud morphology and wind velocities (Del genio & Rossow, 1990) have been studied.

The atmosphere in the high latitudes of Venus are considered to be unstable due to the strong latitudinal shear of the mean zonal wind associated with mid-latitude jets. A momentum transport caused by such regions is essential to understand the mechanism of super-rotation. However, the discussions of these studies are limited to low latitudes due to the difficulty in cloud tracking in high latitudes, where streak features are predominant. Because the displacement of such streaks along the streak direction cannot be identified, uncertainties in estimated cloud motion vectors become large (Ikegawa & Horinouchi, 2016).

To solve this problem, we developed a method to increase the accuracy of cloud tracking by eliminating streaks from the images. The algorithm finds the orientation of streaks in an image making use of the nature that the brightness gradient takes a minimum along streaks, and then remove the streaks by differentiating the image along the estimated orientation.

Using UV (365 nm) images obtained by UVI on Akatsuki, we deduced velocity fields with cloud tracking proposed in this study. Spectral analysis of the time series detected significant periodicity associated with planetary-scale waves even in high latitudes. We present horizontal structures of the planetary-scale waves and associated momentum transports.

Venus conference

Title

Gravity wave packets detected in radio occultation temperature profiles of the Venus atmosphere

Abstract

Temperature profiles has been obtained from 2016 by the radio occultation experiment in the Venus orbiter mission Akatsuki. The radio occultation experiment is a method that measures the change of the atmospheric refractive index as a change of the frequency of the signal received on the ground. At the opportunity when the radio wave transmitted from Akatsuki toward the Earth pass through the planetary atmosphere, the wave is refracted and then reaches the receiving station. We can retrieve the vertical profiles of the pressure and the temperature from each refractive index profiles. In the temperature profile obtained in this way, variations due to various atmospheric disturbances are observed. We focus on gravity waves which are thought to play an import role in driving the general atmosphere circulation.

Gravity waves are small-scale waves with the restoring force being the buoyancy in the atmosphere. Gravity waves play a role in carrying the momentum in the vertical direction. So, it results in acceleration or deceleration of the mean wind by passing momentum on the background atmosphere while dissipating. This process should affect the global structure of the high-speed zonal wind. However, since gravity waves have properties that the spatial scale is small and the wave period is relatively short, it is difficult to capture the spatial structure by observation. The latitudinal profile of the amplitude of short vertical-scale temperature disturbances, which are thought to be associated with gravity waves, has been investigated; however, the dominant wavelength and the typical vertical extent have not been studied.

In this study, we applied wavelet analysis to the temperature profiles and extracted spatially localized temperature disturbances. Though there have been studies that apply Fourier transform to the temperature data, Fourier transform assumes infinitely lasting waves and it is not suitable for extracting spatially localized wave packets. Wavelet analysis is an effective way of obtaining the periods and the amplitudes of waves in such finite intervals. In this presentation, we report the result of wavelet analysis applied to the temperature data obtained with high vertical resolution by radio holographic method. From the obtained results, we also report the relationship between the length and the packet length of gravity wave in the atmosphere.

Solar related variations of the cloud top circulation above Aphrodite Terra from VMC/Venus Express wind fields. Comparison with Akatsuki (first results from IKI).

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In this work we continued and detailed analysis of the cloud top zonal wind deceleration [1]. From tracking of the cloud features in the VMC/Venus Express UV images [2,3] we found that the zonal wind at the cloud top is decelerated by 13.4±4.4 m/s above Aphrodite Terra, a vast highland in the equatorial region. This value is statistically significant since typical SEM (standard error of the mean) is 1-2 m/s. The meridional wind component is also affected by the surface topography. We also found that the influence of topography on the cloud top winds depends on local solar time. The most pronounced deceleration of the zonal wind is observed at noon above Ovda Regio, the highest province of Aphrodite Terra. Later in the afternoon the area of slow wind moves downstream and fades out by the evening. The amplitude of the wind deceleration decreases and shifts downstream as we move south from Aphrodite Terra. We tentatively attributed the observed wind deceleration to interaction of the gravity (mountain) waves generated by Aphrodite Terra with the atmospheric circulation. The perturbation of both zonal and meridional wind components was observed in the equatorial region around 13-14 h and may be explained by a solar tide.

Our first results obtained from Akatsuki images by using algorithms for VMC/Venus Express, as well as conclusions presented in [4], confirm the deceleration of the zonal wind connected with the solar tide. To research the influence of topography on the atmosphere circulation, a longer observation series is necessary.

Acknowledgements

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Venusian yearly-scale variation of super rotation seen in Akatsuki observations

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Abstract:

Based on Venus Monitoring Camera (VMC) observations onboard Venus Express, it has been reported that the super-rotation of Venus atmosphere at the cloud top level showed temporal variations with a time scale of Venusian year (224 Earth days), whose peak-to-peak amplitude was 20 m s^{-1} (Kouyama et al., 2013) in low latitudes, and a decadal scale in which the super rotation increased 30 m s^{-1} over 6 years (Khatunsev et al., 2013). Since the amplitude of the variations reached 30% of the typical zonal wind speed of the super-rotation (100 m s^{-1}), there should be active momentum transportation mechanism in Venusian atmosphere.

To continue monitoring the variation, we have measured wind speed at the cloud top level based on Akatsuki UVI observations with a newly developed cloud tracking technique (Ikegawa & Horinouchi, 2016; Horinouchi et al., 2017) since Akatsuki's Venus orbiter insertion (VOI-R). To extract the temporal variation more clearly, we reduced local time dependence in zonal winds by measuring deviation of zonal wind speed from zonal wind speed at a reference day (= 400th day after VOI-R) with respect to each local time. The zonal wind speed repeated 10 m s^{-1} increasing and decreasing within just 100 Earth days (Figure 1), and a Venusian year scale variation seemed significant (Figure 2). Since a Venusian year scale variation was also seen in VMC observations, the Venusian year may be a typical time scale of the super-rotation at the cloud top. Unlike Venus Express observation period, the zonal wind showed a long-term decreasing trend. Since momentum transportation by planetary scale waves or variation of thermal condition may affect the variation of zonal wind speed, we will also show the temporal variation of planetary scale wave signatures seen in wind speeds and thermal tide components.

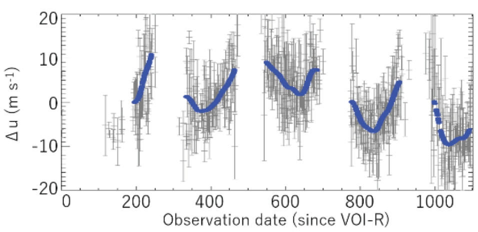

Figure 1. Temporal variation of zonal wind speed (relative to day 400) at the equator in Akatsuki observation. Smoothed profiles are shown with blue lines.

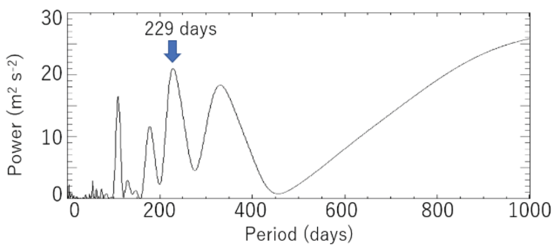

Figure 2. Periodogram of zonal wind speed variation.

Investigating the Influence of Wave Variations on Venus' Cloud-level Atmosphere using a Middle Atmosphere Model

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We make use of a Venus middle atmosphere general circulation model to determine how propagating waves influence the winds and temperature structure at cloud altitudes. Observations at Venus' cloud levels show the presence of waves with many different periods and wavelengths, and include gravity waves, thermal tides, Rossby waves, and Kelvin waves. The sources and importance of different waves, their interactions, and their changes over time are not well understood. We have developed a model of Venus' middle atmosphere, based on the Geophysical Fluid Dynamics Laboratory Flexible Modeling System spectral dynamical core. The lower boundary is raised in altitude relative to the surface to just below the cloud deck (i.e. to ~40 km altitude or ~4 x 10^5 Pa), to focus on the dynamics of the cloud-level atmosphere. The upper boundary height is around 95 km (~3 Pa). We use a Newtonian cooling radiation formulation in these simulations, based on the Held-Suarez scheme for the relaxation of temperature to a specified radiative equilibrium. We have introduced a simple linear friction within the first ~2 km from the lower boundary to maintain zonal and meridional winds within observed values, since the lower atmosphere is not simulated directly in this model. We introduce wave forcing near the lower boundary of the model to simulate waves which are assumed to be propagate upwards from the lower atmosphere. In this investigation, we study the influence of propagating Kelvin and Rossby waves. We modify wave forcing parameters and perform sensitivity tests to determine the effects of the different waves on the atmosphere at cloud altitudes. The results of simulations are validated in comparison with observations, including measurements from probes and observations from the Akatsuki and Venus Express missions.

Eight years of VEX-VeRa radio sounding of the Venus atmosphere

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The Venus Express Radio Science Experiment VeRa performed regular radio-sounding experiments of the Venus neutral atmosphere using the spacecraft radio subsystem in the one-way radio mode at X-band (8.4 GHz) and S-band (2.3 GHz). The radio links were stabilised by a dedicated onboard ultrastable oscillator. More than 800 atmospheric profiles could be retrieved between July 2006 and January 2014. Radial profiles of neutral number density from the atmospheric-induced Doppler shift during the occultations cover the altitude range from the upper troposphere (~40km) to the upper mesosphere (~90 km). These are then used to derive vertical profiles of temperature and pressure. The spatial coverage of previous radio occultation measurements is generally quite limited, but the extensive VeRa data set covers almost all latitudes, longitudes, and local times, thus providing the unique opportunity to study the global atmospheric structure and dynamics at high vertical resolution. Static stability profiles retrieved from the data provide valuable information about atmospheric instabilities in the region of the middle cloud layer. Small-scale fluctuations in the thermal profiles reveal significantly enhanced gravity wave activity in the adjacent lower mesosphere with a strong latitudinal gradient. Global-scale wave phenomena can also be retrieved from the data set. Thermal tides are especially pronounced at low latitudes with a dominating semidiurnal wave structure in the upper mesosphere. The tides are generated in the cloud layer and propagate upwards and downwards from this region, leading to a redistribution of momentum and energy in the Venus atmosphere. The thermal profiles can also be used to retrieve zonal winds if the assumption of cyclostrophic balance is applied. The presentation will give a comprehensive overview of the atmospheric scientific results that could be achieved with VeRa so far.

SULFURIC ACID VAPOR IN THE ATMOSPHERE OF VENUS AS OBSERVED BY THE VENUS EXPRESS RADIO SCIENCE EXPERIMENT VERA.

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The main cloud deck within Venus' atmosphere, which covers the entire planet between approx. 50 and 70 km altitude, is believed to consist mostly of liquid sulfuric acid. The temperature below the main clouds is high enough to evaporate the H2SO4 droplets into gaseous sulfuric acid forming a haze layer which extends to altitudes as deep as 35 km. Gaseous sulfuric acid in Venus' lower atmosphere is responsible for a strong absorption of radio waves as seen in Mariner, Pioneer Venus, Magellan and Venera radio science observations. Radio wave absorption measurements can be used to derive the amount of H2SO4 in Venus' atmosphere. The radio science experiment VeRa onboard Venus Express probed the atmosphere of Venus between 2006 and 2014 with radio signals at 13 cm (S-band) and 3.6 cm (X-band) wavelengths. The orbit of the Venus Express spacecraft allowed to sound the atmosphere over a wide range of latitudes and local times providing a global picture of the sulfuric acid vapor distribution. We present absorptivity and H2SO4 profiles derived from X- and S-band signal attenuation for the time of the entire Venus Express mission. More than 600 H2SO4 profiles show the global sulfuric acid vapor distribution covering the northern and southern hemisphere on the day- and night side of the planet. A distinct latitudinal H2SO4 gradient and a southern northern symmetry are clearly resolved. Observations over 8 years allow the study of long-term variations. Indications for temporal H2SO4 variations are found, at least at northern polar latitudes. The results shall be compared with observations retrieved by other experiments (VIRTIS, SPICAV) onboard Venus Express as well as with previous observations like Mariner, Pioneer Venus and the Magellan spacecraft.

Akatsuki's IR2 Nightside Photometry Restoration by Deconvolution in 2.26um and 1.735um filters

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Akatsuki's IR2 camera captures images of Venus at different filters: 1.735um, 2.26um, and 2.32um. At near-dawn/dusk views (~90 to 115-degree phase angles) of these infrared images, the nightside photometry is contaminated by the intense dayside reflectance. As the potential well of a pixel is overfilled with incoming generated photoelectrons, the pixel is saturated and hence no longer contain information. This saturation can occur both in the dayside and nightside near the terminator.

Owing to the saturation problem, main task of the restoration process is thus to simulate both day and night sides to replace the information loss in saturation. The IR2 camera's point spread function (PSF) was modelled using Moffat's function. Then, deconvolution by the model-PSF can restore the nightside photometry of unsaturated pixels. This presentation will show how the dayside is being modelled by Radiative Transfer (RT) calculation using the latest cloud model parameters determined from Akatsuki data. Furthermore, we will show detailed procedure in simulating the nightside radiances of both 2.26um and 1.735um. In brief, the nightside simulation uses nightside photometry of two filters. Then, it converts the dayside-free nightside photometry from one filter into another using RT-calculated 'conversion coefficients'. We present our Restoration by Deconvolution (RD) results of the selected dates. The restored images were limb darkening corrected. Effectiveness of the RD-restored images will be evaluated by comparing sharpness of individual pixels and radiances transiting from day to night.

Evaluating the synthetic model with known answer image, the accuracy of RD was determined to be about ~99.4%. Correlation plot of the unsaturated nightside radiances between two filters (2.26mm and 1.735mm) were produced to extract possible 'branch' phenomena. The branching in the correlation plot indicates the differences in the optical depths of different particle size modes (Carlson et al. 1993). There were some hints of 'branch' in the latest correlation plot using restored data.

Restoration of the nightside photometry will provide many research opportunities such as the cloud dynamics transiting from the dayside into the nightside. Moreover, interesting cloud features such as vortices, instabilities, and streaks are more distinct in recovered images. This in overall opens up new possibilities to understanding the evolution of cloud motion in the middle cloud layer.

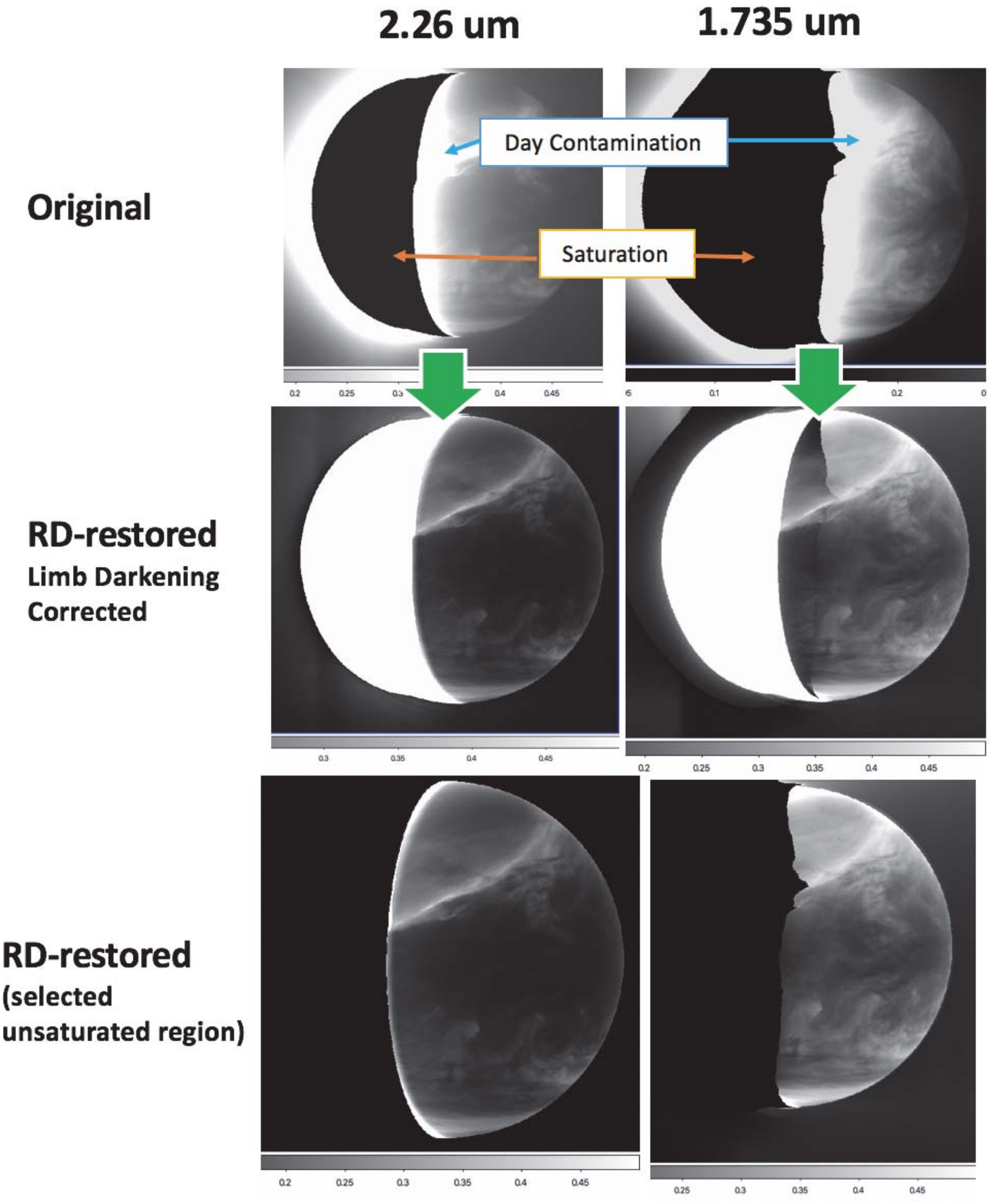

Figure 1 – Example of IR2 image at 2.26um and 1.735um before and after RD restoration. 2016/08/25, 06h data.

An experiment to investigate Venus's deep atmosphere.

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The characteristics of the Venus atmosphere closest to the ground are still unknown to a large degree. The only reliable temperature profile measured below 12 km altitude was obtained in 1985 by the VeGa-2 lander (Linkin et al., 1986). This profile, obtained during the ~1h descent, is highly unstable in the lowest 7 km, meaning that the near-constant vertical gradient is steeper than the adiabat, a characteristic that may be explained by a variation of the abundance of nitrogen from 3.5% at 7 km altitude to 0 at the surface, as proposed by Lebonnois & Schubert (2017). The physics of the composition gradient is difficult to understand in the absence of more information, however, considering the observations in a recent experiment (Hendry et al., 2013) it is here conjectured that this gradient could result from gravity effects inducing a density-driven separation of nitrogen and carbon dioxide.

To investigate the behavior of the CO_2-N_2 mixture under conditions ranging from the Hendry et al. (2013) experiment to the near-surface atmosphere of Venus, we have designed an experiment that was conducted at the Glenn Extreme Environment Rig (GEER) (Kremic et al., 2014), at NASA Glenn Research Center in Cleveland in August 2018. The CO_2-N_2 gas mixture went through experimental conditions of 100 bar at various temperatures in a 60 cm vertical steel cylinder with an internal diameter of 8.7 cm. The composition of the gas mixture was measured by gas chromatography at the top, middle and bottom of the vessel, to investigate the vertical composition gradient. The first step in our experiment is to use the Hendry et al. (2013) experimental conditions, with a mixture of 50% CO_2 / 50% N_2 at 296K and 100 bar, and inquire whether the strong vertical gradient observed in the 18-cm tall Hendry et al. (2013) experimental vessel is reproducible: 70% nitrogen at the top, 10% only at the bottom. Then, fixing the temperature at 310K and the pressure at 100 bar, we varied the abundance of nitrogen from 50% to 3%, to reach a proportion resembling the Venus atmosphere. In a second phase, maintaining the pressure at 100 bar and the nitrogen abundance at 3%, the temperature was increased step-wise up to 735K, so as to reach Venus's near-surface conditions. At every step, the vertical gradient of nitrogen in the 60-cm high vessel was measured.

Results of the experiment will be shown, and their consequences for the lower Venus atmosphere will be discussed.

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Stationary wavy features and Banded structures at Venusian cloud top extracted by averaging multiple LIR images

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Venus' cloud-top temperature distribution is now continuously mapped by LIR (Long-wave Infrared camera) mounted on the Venus orbiter Akatsuki. Fukuhara et al. (2017) analyzed LIR data and reported the existence of bow-shaped structures extending over 10,000 km in the north-south direction. The features are fixed in position without flowing with the super-rotation and appear above highlands with altitudes higher than 3 km. It was suggested based on a comparison with numerical simulations that the features are gravity waves generated by near-surface flows impinging on mountains. Kouyama et al. (2017) observed stationary features over 4 Venus days and revealed that the features tend to occur in the local afternoon. Gravity waves, whose restoring force is buoyancy, transport horizontal momentum in the vertical direction and accelerate or decelerate the background wind when they dissipate. Therefore, stationary gravity waves influence the general circulation of the atmosphere. In order to estimate the influence, it is essential to reveal the spatial and temporal distributions of gravity waves.

In the previous studies using LIR data, only planetary-scale stationary features have been investigated. On the other hand, Peralta et al. (2017) analyzed the data taken by VIRTIS onboard Venus Express, and reported the existence of many small-scale stationary features; however, VIRTIS can observe the night side only, and the observations were confined to the high latitude of the southern hemisphere because of the geometry of the orbit. Therefore, we intend to investigate with a new analysis method the topographical and local time dependency of small-scale, weak stationary features by using LIR data, which can observe all latitude regions at any local time. Though the S/N ratio of LIR is lower than VIRTIS, averaging of multiple images can suppress noises and at the same time emphasize stationary patterns. By using this method, small-scale, stationary wave trains were newly found above relatively-low topographic rises with altitudes of 1-3 km. In addition to stationary features, zonally-elongated banded structures were also found in averaged LIR images. Such structures have once been detected in LIR images taken during Akatsuki's Venus flyby in 2010 (Taguchi et al., 2012); the new analysis confirmed that banded structures are ubiquitous at the cloud top. The orientations of the banded structures are different from those of dark streaks found in ultraviolet images.

Remote sensing studies of our sister planet: Exploring Venus using planetary glider and CubeSat constellation

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The technical paper proposes optimal interplanetary trajectory from Earth to Venus following the deployment of an unmanned robotic glider for exploring the atmosphere of Venus and a constellation of CubeSats deployed in different orbits of Venus to ensure global coverage for remote sensing application. Primary payload will be a glider that will study the atmospheric behavior of the Venus below the clouds of Venus at an altitude of ~40-50 Km. The glider provide a unique opportunity for high resolution surface observations and detection of gases in minor traces while it is airborne thereby providing more valuable data by transmitting it to the CubeSats orbiting the planet than a single lander or an orbiter mission. Trade studies regarding the scientific payload onboard the glider will be included. As Venus has a super-rotating atmosphere, where the clouds travel 60 times faster than the rotation of the planet, the stability of the glider is important. Investigations are conducted for atmospheric flight in the flight altitude below the cloud layers, some standard airfoils are modelled and Computational Fluid Dynamics analysis is done in COMSOL Multiphysics for Venusian atmospheric conditions. From the set of observations, the airfoil having high lift coefficient can be used for the design of the glider's wings thereby producing maximum lift force during the time of flight which is crucial for such exploratory missions. For the CubeSats constellation, they will be remotely tracking the clouds and can be used to study the plasma interactions. At the end of mission life of these CubeSats, it is proposed to deorbit all at once at different locations so as to gather global framework of the cloud movements across the planet. As these CubeSats enters the atmosphere, it will burn up during its Entry-Descant phase before which they'll transmit all the atmospheric entry data. This data can be accumulated and analyzed for the pattern in the cloud motions and other phenomenon taking place in the upper atmosphere. If this mission concept is implemented in future, it is expected to yield great results to study and model the atmosphere of our sister planet.

Zonal mean structure of Venus atmosphere observed in a Venus general circulation model, DCPAM, with explicit radiative transfer calculation

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Introduction

A unique zonal wind in Venus atmosphere, super-rotation, has been investigated by a lot of previous researchers with numerical simulations as well as ground-based and spacecraft observations. Among the studies with numerical simulations, Lebonnois et al. (2010) and Ikeda (2010) performed general circulation model simulations with an explicit radiative transfer model. On the other hand, we have been developing a general circulation model for planetary atmospheres. In addition, we have just developed a Venus radiation model, which can be used in a general circulation model. In this study, we try to perform general circulation model simulations of Venus atmosphere by the use of our Venus radiation model.

Model

The general circulation model used in this study is DCPAM (http://www.gfd-dennou.org/library/dcpam/). The model is based on primitive equation system and the equation system is solved by a spectral transform method. The DCPAM includes physical processes of radiation and turbulent mixing processes. In addition, heat diffusion in soil is considered to evaluate surface temperature. The radiation model implemented into the DCPAM has also been developed in our group, and is based on a correlated k-distribution method. Radiative fluxes calculated by this radiation model are compared well with observed ones.

Results

We performed two experiments with and without surface orographic variation. Resolution of experiments is T15L52, in which the model has 48 (longitude) times 24 (latitude) grids in horizontal direction and 52 layers in vertical direction. Initial conditions for those experiments are the same, and are motionless atmospheres with horizontally uniform temperature distribution based on VIRA.

Statistically steady states are achieved after about 100000 Earth days from the start of integrations. In steady state, prograde zonal winds with velocity of about 50 m/s in low and middle latitude are maintained at cloud layer in the two experiments.

Meridional circulation observed in the model has large direct cells in both hemispheres. But, the structure of meridional circulation is different between those with and without surface orography. The direct cells in the experiment without surface orography have vertical extent from the ground up to top of the model, except for low latitude region just above the ground where indirect cells form. However, in the experiment with surface orography, the cells are split in the vertical direction at bottom of cloud layer. In the presentation, several other differences in meridional circulations observed in the model will also be described.

Observing Venus with NASA's Terrestrial Balloon Program

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For ground-based observers, Venus' makes a compelling target during inferior conjunctions (Venus passing between the Sun and Earth). These opportunities occur every 19 months. During inferior conjunctions, Venus presents its night hemisphere (useful for mapping surface emissivities, trace gases below the cloud tops and cloud tracking in the middle and lower cloud decks) and its angular size exceeds 35 arcsec over a 3-month period, getting as large as 60 arcsec. Venus is well-suited as a target for NASA's new breed of super-pressure balloons, which are expected to carry 2-ton science payloads to altitudes of 110,000 ft (33.6 km) for flights lasting as long as 100 days.

A balloon-borne telescope has several advantages over a ground-based campaign to observe Venus:

- Continuous viewing of Venus, potentially 24/7 over the entire 100-day flight, regardless of Sun elevation and terrestrial cloud cover.
- Access to the entire spectrum from 0.2 to 2.55 µm except for 240 - 290 nm. The 2.55 µm region is blocked from ground-based telescopes but is diagnostic of the height of the cloud base (Barstow et al. 2012).
- Extremely high image quality, with no degradation due to atmospheric seeing.

Consider a nominal reference mission with the following attributes: a 2m aperture telescope, CMOS detectors for UV wavelength bands 200-240 nm and 290-600 nm and HgCdTe detectors for the 0.8 - 2.55 µm range. At the 1.735 µm window, where the middle and lower cloud decks appear with the most contrast, the diffraction limit of a 2m aperture is 0.22 arcsec, equivalent to 53 km on Venus when Venus' disk subtends 50 arcsec. At that resolution, cloud tracking over 4h intervals will determine velocities with RMS errors of less than 1 m s^{-1}. An infrared spectrograph with a spectral resolutions of R = 3500 will map trace gases CO, OCS, H_2O, SO_2, HCl and HF. A UV spectrograph with a resolution of R = 2000 will be sensitive to OSSO, a recently proposed candidate for the unknown UV absorber (Frandsen et al. 2016).

In summary, a balloon mission centered around an inferior conjunction could provide a data set for tracking cloud motions with errors under 1 m s^{-1} from the lower cloud deck to the cloud tops. A 2m aperture telescope could resolve 50 - 70 km features on the night side (clouds at 45 - 57 km at 1.74 µm) and 15 km features on the dayside (e.g., cloud tops at 0.365 µm). Unlike ground-based observations, a super-pressure balloon would provide a continuous, pole-to-pole record of Venus for a 100-day period, sufficient to address outstanding questions about energy deposition, circulation, thermal structure and atmospheric chemistry. Unlike space-based missions, a balloon mission would cost a few tens of $M, as opposed to several hundred $M. Furthermore, balloon payloads are often recovered and reflown, which would allow a payload to observe Venus during successive inferior conjunctions.

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A Lightweight Imaging/Altimeter Radar for Venus Exploration

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The Applied Physics Lab (APL) has a long history of involvement in the design, development, and testing of space-borne radars including GEOSAT and TOPEX and the airborne altimeter that was the model for the delay-Doppler processing on the ESA CRYOSAT altimeter, as well as the Synthetic Aperture Radar (SAR) imaging experiment Mini-RF on Lunar Reconnaissance Orbiter.

APL has designed a multimode radar instrument for Venus exploration, compatible with NASA Discovery-class or ESA Medium-class mission budgets. The lightweight S-band instrument exploits the flight-proven APL Frontier radio with commercial Solid State Power Amplifiers and a deployable 4.6m mesh antenna. The electronics and antenna have masses of 42 and 44kg respectively, and a DC average power of 175 W (survey mode, 36m SAR resolution).

From a 300-400km orbit at Venus, the instrument can perform global SAR mapping as above, and spotlight high-resolution (6m) imaging using higher power. In altimeter mode, the 3.5km footprint is sharpened along-track to 200m. The instrument architecture permits polarimetric, interferometric and passive radiometry observations.

3-D structure of a thermal tide in the Venus atmosphere

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Brightness temperature of the Venus disk obtained by Longwave Infrared Camera (LIR) onboard Akatsuki shows clear limb darkening in the low and middle latitudes. Limb darkening is an apparent temperature decrease from the center to the limb of the Venus disk. It is caused by thermal and radiative characteristics that the sensing altitude of LIR increases as an emission angle, which is a zenith angle of direction of emission from the Venus atmosphere to the sensor, increases and that the atmospheric temperature monotonically decreases with altitude. In higher latitudes limb brightening is observed, because an inversion layer exists at the cloud-top altitudes in higher latitudes. In other word a profile of the limb darkening reflects vertical distributions of atmospheric temperature and optical thickness of cloud particles. Taylor et al. [1980] presented local time dependence of limb darkening using brightness temperature data obtained by the Pioneer Venus orbiter, but did not mention its physical mechanism. In this study horizontal distributions of brightness temperature obtained by LIR when Akatsuki was in the altitude range from 60,000 to 100,000 km during the period from October 19, 2016 to July 17, 2018 were analyzed to investigate the vertical structure of temperature distribution above the cloud-tops based on the emission angle dependence of the sensing altitude. Each brightness temperature image with 328 x 248 pixels was divided into 3280 x 2480 sub-pixels, and 32 successive images were accumulated after precise adjustment of the Venus disk position to improve S/N. Then average brightness temperatures were derived as a function of the emission angle for 24 local time zones and 9 zonal belts with a latitudinal width of 10° within ±45°. A local time-latitude map of averaged brightness temperature for each emission angle shows a clear semi-diurnal tide component. The amplitude of the semi-diurnal tide peaks at the equator and gradually decreases as latitudes, whereas its phase seems constant in all latitudes. A vertical cross section of the brightness temperature deviations above the cloud-tops in the equator region shows that the phase of the semi-diurnal tide shifts upstream as the altitude increases. It is suggested that the thermal tide is generated in the cloud deck by solar heating and propagates upward.

PROSPECTS FOR THE INVESTIGATION OF VENUS' INTERIOR USING INFRASOUND

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With surface temperature and pressure as high as 450 C and 90 atmospheres respectively, Venus presents a formidable challenge to any missions that aim to perform conventional seismology. However, Venus' dense atmosphere offers unique opportunities for performing remote seismology using sensors deployed on a balloon platform in the mid-atmosphere. Earth-like temperature and pressure at 50-60 km altitude allow for mission lifetimes to be much longer than those of surface landers.

In this presentation, we will explore the possibility of mapping seismic activity on Venus, including quakes and volcanic eruptions using infrasound (pressure waves with frequencies less than 20 Hz) as a remote sensing tool and discuss the progress our group has made in the last year towards this goal.

The efficiency of infrasound generation from seismic activity relies heavily on the coupling between the solid planet and the atmosphere. The dense atmosphere on Venus couples ground motion signals up to 60 times more efficiently into the atmosphere, generating infrasound signals that may be detected by pressure sensors floating on balloons in the mid atmosphere. Further, acoustic sensors used to capture infrasound may also be used to investigate low-frequency, large-scale planetary atmospheric features such as planetary-scale gravity waves, which have recently been observed by JAXA's Akatsuki mission.

Our team has been involved in a campaign to use the Earth's atmosphere as an analog testbed for Venus to demonstrate the feasibility of balloon-based infrasound science on Venus and address the challenges associated with it. While infrasound has been recorded from seismic events such as quakes and volcanic eruptions on Earth by terrestrial stations, its detection from balloon platforms is a relatively new area of research. In recent experiments, we demonstrated that infrasound signals from weak artificially created earthquakes could be detected by barometers suspended from balloons. Further, we have also shown the detection of infrasound from rocket launches over 200 km away. These experiments are helping us address strategic knowledge gaps, which would allow for the detection and characterization of seismic infrasound on Venus. Results from the above campaign activities will be summarized in our presentation.

In the future, we look forward to conducting campaigns to detect and characterize infrasonic signals in the Earth's stratosphere – the closest analog to what we would expect in Venus' atmosphere at 55-60 km altitude. Proving the feasibility of this technology in the Earth's stratosphere would make a strong case for the detection of similar signals on Venus, which would pave the way for the study of its interior, a long-cherished goal of the Venus community.

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Session 09

Atmospheric Structure

Session Chair: Takeshi Imamura
Session Chair: Yeon Joo Lee

A fully coupled photochemical-condensation model of the Venus atmosphere from the ground to 110 km

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Ground based, Venus Express, and Akatsuki observations have provided a wealth of information on the vertical and temporal distribution of clouds and many chemical species in the Venusian atmosphere [1, 2,3]. Previous modeling efforts have focused on either the gas chemistry [4-6] or the sulfuric acid aerosols [7,8], and also typically modeled the lower (0-50 km) and middle (40-100 km) atmospheres separately. In the middle atmosphere of Venus, the chemical reaction $H_2O + SO_3 \rightarrow H_2SO_4$ is highly energetically favored. As such, chemical models generally struggle to self-consistently calculate SO_X and H_2O abundances. To avoid this, many models hold the concentrations of the condensible species, H_2O and H_2SO_4, fixed [4,5]. In models where these species are calculated self-consistently the model results are highly sensitive to the boundary conditions in the cloud level [8].

In this work we introduce a new photochemical-condensation framework to understand the interaction among gas, haze, and cloud in Venus' atmosphere. First, we extend the domain of the 1D photochemistry model of Zhang et al. (2012) [5] to encompass the region between the ground and 110 km and implement a simple condensation scheme of sulfuric acid clouds with gravitational settling. We simultaneously solve for the chemistry and condensation allowing for self-consistent cloud formation. With this model we aim to reproduce the following observations to which a satisfactory explanation has is lacking:

- Near constant water vapor mixing ratio in the middle atmosphere [10]
- SO_2 vertical profile including an inversion at high altitudes (>70 km) [2]
- H_2SO_4 gas mixing ratio and cloud acidity measurements [1,11,12]

In coupling the lower and middle atmosphere we find that could level boundary conditions of previous models had a strong control on their results. In addition we find that the vertical abundance of water vapor can be explained by assuming its abundance is buffered by condensation and evaporation. The main free parameter in this modeling is the cloud acidity. Using a single cloud acidity profile we can also match observations for the H_2SO_4 vapor. We find that condensation-chemistry interactions could stabilize the H_2O-H_2SO_4 system. We will also discuss the implications this has for the sulfur mass budget and dynamics of the middle atmosphere.

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The Dust Cycle on Venus

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Before the greenhouse effect due to carbon dioxide on Venus was fully recognized, the idea that wind friction and dust in the lower atmosphere (the 'aeolosphere') might warm the surface was advance by Öpik (1861), and a dust insulation model was explored by Hansen and Matsushima (1967). Like many "wrong" ideas in science, these hypotheses may yet contain an element of truth.

Measurements by the Venera and Pioneer Venus descent probes show that the Venus atmosphere below the main cloud deck is 'clear'. However, it should be recognized that this may be a somewhat relative term – the dynamic range of the instrumentation used is modest, and the fact that there is already so much opacity above 40km makes radiative-convective models somewhat insensitive to the introduction of dust in the lower atmosphere. Both Pioneer Venus and Venera measurements show variations in opacity in the lowest few kilometers – implying, perhaps, sources and sinks. Recently, Venera -13 and -14 electrical data have been suggested to be consistent with the presence of charged aerosols in the lowest 40km of the atmosphere (Lorenz, 2018).

It is striking that out of only two occasions (Venera 13 and 14) when multiple panoramas were taken at a landing site in the space of about an hour, sand and dust were observed to move. Such an event might typically take months or years to observe on Earth, Mars or Titan! It can therefore be argued (Lorenz, 2015) that surface windspeeds on Venus not infrequently exceed the transport (saltation) threshold and the possibility exists that surface dust-lifting may be common. Additionally, there is the prospect of injection of volcanic ash into the atmosphere. Some of these processes may also be associated with electrical activity. Compared to Earth and Mars, the effectiveness of snow-out or rain-out processes on Venus will be poor.

The possible dust generation, injection and removal processes on Venus will be reviewed and the extent and character of lower atmospheric dust considered. In-situ measurements (optical and/or electrical) on future missions will be needed to resolve the question.

Modeling of Observations of the OH Nightglow in the Venusian Mesosphere

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Introduction and Motivation. Airglow emissions, such as NO and O_2, have been observed previously on Venus and provide insight into chemical and dynamical processes that control the composition and energy balance in the upper atmosphere. The OH airglow emission had been observed previously only in the Earth's atmosphere which was discovered in high-resolution spectra of the Earth's atmosphere [1] and were successfully modeled [2]. More recently, OH airglow emissions have been detected on Venus by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) onboard Venus Express (VEx) [2, 3] and Mars by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter (MRO) [5].

Venus Express Measurements and Usage. Venus airglow emissions have been unambiguously detected in the wavelength ranges of 1.40−1.49 and 2.6−3.14 µm in limb observations by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on the Venus Express (VEX) spacecraft. These emissions are attributed to the OH (2−0) and (1−0) Meinel band transitions as well [3]. The integrated (slant path) emission rates for the OH (2−0) and (1−0) bands were measured to be 100±40 and 880±90 kR respectively, both peaking at an altitude of 96±2 km near midnight local time for the considered orbit.

KINETICS/VTGCM Modeling. Photochemical (Caltech/JPL KINETICS) and GCM (VTGCM) model calculations suggest the observed OH emission is produced primarily via the Bates-Nicolet mechanism, as on the Earth, although the Venus' background atmosphere is different than that of the Earth. The models are able to distinguish relative contributions due to different key photochemical reactions that contribute to observed features from the VEx VIRTIS data.

Volume emission rates (VERs) are calculated first within the KINETICS and VTGCM codes (photons/cm3/sec) as a summation of the contributions from each OH vibrational level, following a single quantum cascading scheme. We are then able to obtain slant emission rates (MR) which are calculated by multiplying the VER by the local scale height at a given tangent path level along the line of sight in the atmosphere. We compare the results of these calculations with various analyses of the VEx observations [3, 5] and discuss implications of interesting aspects of the data modeling effort.

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Studying the polarization in CO_2 absorption bands of Venus atmosphere

Abstract

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The strong CO_2 absorption bands of Venus have been used in the past to constrain the cloud top altitude and to determine the water content close to Venus' clouds and hazes. Such retrievals (Ignatiev et al., 2009; Fedorova et al., 2016) have primarily been performed using total flux data in these absorption bands obtained from previous Venus missions. It is known that polarized fluxes are more sensitive to the presence of various cloud particle modes, but this sensitivity is not fully understood yet in the absorption bands. Here, we use a highly accurate radiative transfer code which includes polarization to model the polarized fluxes of light emerging from the top of the atmosphere in the wavelength region between 1.4 and 1.5 microns. We perform a sensitivity analysis of the behavior of absorption band depth to various types of model atmosphere scenarios (e.g. cloud and haze top altitude, cloud and haze opacity, scale height) with varying cloud and haze particle properties (e.g. particle effective radius, refractive index). We also perform a comparison between the total reflected flux and degree of polarization with different atmosphere types at varying observational geometries. We show that the signal inside the absorption band at different band depths presents unique polarization signatures that can help identify the particle properties and cloud top variability. We note that the degree of polarization of light is highly sensitive to particle properties and should add invaluable independent information to the study of Venus clouds and hazes.

Variations of lower clouds and water vapor amount in deep Venus atmosphere based on night windows observations by the SPICAV-IR/Venus-Express.

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An optically thick cloud layer is one of the reasons of the greenhouse effect forming the current Venus climate. It obstructs remote observations of the lower and middle atmosphere. Thermal IR emission formed below clouds escapes to space only at wavelengths of several narrow transparency windows between strong CO_2 absorption bands. Their intensity is modulated by scattering within the clouds and absorption by lower atmosphere minor gases. The main component of cloud aerosols is the H_2SO_4 solution. Four modes of prevailed particles were identified which are forming three cloud layers. The biggest particles of mode 2' (r ~ 1.2 μm) and mode 3 (radius of 3-4 μm) are concentrated in the middle and lower cloud layers (46-50 km). The latter ones are the most massive and determine the opacity and bulk of the Venus clouds [1].
The SPICAV IR dataset obtained in 2006-2014 with had a good spatial coverage of almost the whole globe. The instrument covered 5 night windows at 1, 1.1, 1.18, 1.28 and 1.31 μm. The emission originates from the surface and the first scale height (0-15 km) of the atmosphere are observed in the 1.1- and 1.18-μm windows covering the H_2O absorption band. According to the recent ground-based observations and data obtained by SPICAV-IR and VIRTIS of the Venus Express a water volume mixing ratio varies about 30-35 ppm below clouds [3-5]. The 1.1- and 1.18-μm windows are also sensible to surface emissivity changes and clouds parameters. The 1.28-μm intensity is modulated only by variations of clouds. However its considering spectral range is limited by the oxygen emission at 1.27 μm forming at 95 km [6]. The 1.31-μm window is the weakest one. It was reported that the 1.28-μm maximum intensity varied from 0.05 to 0.1 $W/m^2/\mu m/ster$ with slightly higher values in the north hemisphere than in the south one [7]. The modeling allowed to conclude that these variations are determined by opacity changes in lower clouds.
The current work is analyzing the whole dataset of SPICAV observations to retrieve the cloud parameters changes and water abundance at the same time. Synthetic spectra of the night emissions were built according to multiple scattering radiative transfer model. The spherical harmonic discrete ordinate method [8] for plane parallel geometry adopted for the Venus night-side observations in [4, 9] is realized in the SHDOMPP program. We take an assumption that aerosol droplets are spherical and the H_2SO_4 solution is 75%. An optical depth, single scattering albedo and asymmetry parameter are computed using the Mie theory for the cloud distribution described by Haus et al. (2016) [10].
J.-L. Bertaux, D. Evdokimova, A. Fedorova and O. Korablev acknowledge the support from the Ministry of Science of Russian Federation grant #14.W03.31.0017.

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Retrieval of upper haze aerosol properties from SPICAV-UV and -IR data

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Introduction. Venus is covered by a thick layer of clouds extending from 40 to 70 km with tenuous upper haze layer lying above. Particles at the cloud top are spherical and consist of sulfuric acid droplets [1]. Clouds are stratified into three layers, the upper cloud region is populated by mode 1 (~0.2 μm) and mode 2 (~1 μm) particles. Before Venus Express, the upper haze was believed to consist of only mode 1 [1].

Early independent study of three channels of SPICAV/SOIR instrument with data set from three selected orbits showed presence of bimodality in size distribution [2]. Analysis of aerosol properties from single SPICAV−IR spectrometer for the whole data set obtained from May 2006 till November 2014 has proved it [3]. In this work, we report retrieval of upper haze aerosol properties from SPICAV−UV and −IR solar occultation observations for the whole data set.

Observations. 71 simultaneous solar occultation observations from SPICAV−UV and −IR instruments were processed from orbit #339 (February 2008) to #2464 (April 2011). Aerosol properties are determined using 6 wavelengths in 200−300 nm range from SPICAV−UV and 10 wavelengths in 650−1550 nm range for SPICAV−IR.

Method of analysis. The first step in retrieval procedure is calculation of aerosol extinction. Inversion method for SPICAV−UV is identical to the one used for SO_2 abundance retrievals [4]. Aerosol extinction retrieval of SPICAV−IR data was described in [3].

The second step is retrieval of particle size distribution by fitting spectral dependence of experimental normalized aerosol extinctions to their corresponding theoretical values. The aerosol extinction is modeled according to Mie theory, adopting refractive indices for 75% H_2SO_4 sulfuric acid aqueous solution. In our retrieval procedure unimodal and bimodal lognormal size distributions were considered independently.

The final step is to calculate aerosol number density as a ratio of experimental extinction coefficient to modeled extinction cross section.

Results. Examples of fitted normalized extinction at altitudes 89 and 92 km of orbit #444 are shown in Fig. 1. At 89 km, bimodality provides the best fit with effective radius r_{eff} = 0.13±0.02 μm and 0.81±0.1 μm and number density n = 13±3 cm^{-3} and (5.4±0.5)·10^{-3} cm^{-3} for mode 1 and mode 2 respectively. At 92 km, unimodal distribution is chosen with r_{eff} = 0.15±0.1 μm and n = 4±2 cm^{-3}.

Overall, aerosol size distributions have been retrieved at 127 altitudes from 71 solar occultation sessions mostly in the altitude range 86–96 km; bimodality has been observed 68 times most frequently in the altitude range 86–92 km, unimodality has been observed 59 times (Fig. 2c).

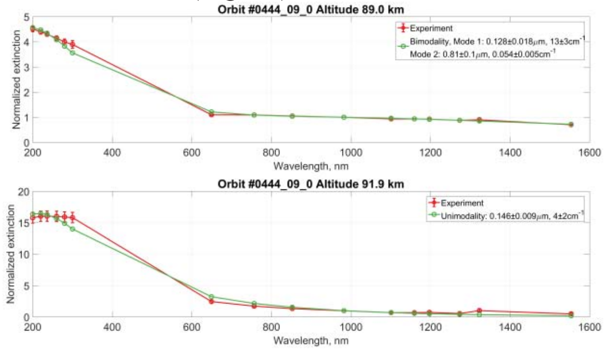

Fig. 1. Examples of fitted spectral dependence of aerosol extinction at altitudes 89 and 92 km of orbit #444.

All values of r_{eff} and n are averaged in 1 km altitude bins and plotted as vertical profiles in Fig. 2a and b. In addition, we have calculated mean values of r_{eff} and n, which are presented in Table 1.

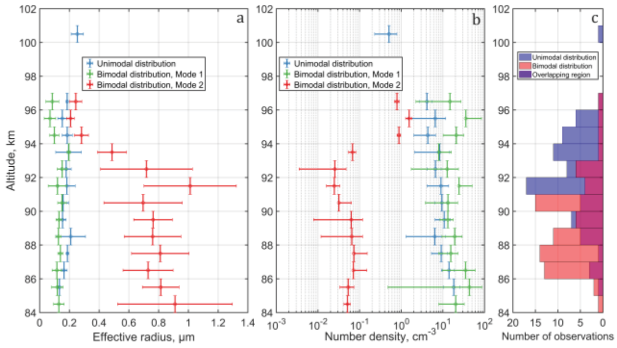

Fig. 2. Profiles of r_{eff} (a) and n (b) for unimodal and bimodal cases. (c) Altitude distribution of all observations.

Table 1. Mean values of r_{eff} and n.

	Unimodality	Bimodality	
		Mode 1	Mode 2
r_{eff}, μm	0.18 ± 0.05	0.13 ± 003	0.8 ± 0.2
n, cm^{-3}	8 ± 5	20 ± 14	0.05 ± 0.04

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Session 10

Atmospheric Dynamics (2)

Session Chair: Aymeric Spiga
Session Chair: Toru Kouyama

Organization of the convection in the Venusian cloud layer.

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Abstract

1. Introduction

Venus hosts a global sulfuric acid cloud layer between 45 and 70 km which has been investigated by the Venus Express and Akatsuki mission. One of the main questions that remains unclear about the dynamics of the Venusian atmosphere is how this convective cloud layer mixes momentum, heat, and chemical species and generates gravity waves. Gravity waves emitted by the convection have been proposed to promote a significant contribution to the maintenance of the super-rotation [1]. However, these waves develop from regional to local scales and cannot be resolved by global circulation models (GCM) developed so far to study Venus' atmospheric dynamics.

2. Model

Following the idealized LES model [2] using prescribed vertical profile of heating rates extracted from GCMs runs, we coupled the Venus LMD physics to the dynamical core [3]. The calculation of the solar and IR heating rates are done with LMD physics radiative scheme from the surface to ~100 km. The solar rate is computed with short waves radiation fluxes from Haus et al [4]. The radiative transfer is based on Eymet et al [5], using NET matrix with latitudinal varying cloud model from Haus et al [3]. As in the previous model, a third heating rate is added with an interpolated vertical profile from the LMD Venus GCM [6].

3. Results

The results shown here are for the Equator at noon with no wind shear.

The main results of this coupled LES model are the better agreement with observations of vertical extension and variability of the convective layer [7] and past modeling effort [8]. The presence of wind shear has a strong impact on the propagation of gravity waves as well as on the generation with the so-called ``obstacle effect´´. Convective activity at cloud top is also present in the model while Venus Express and Akatsuki radio occultation measured stable atmosphere [9].

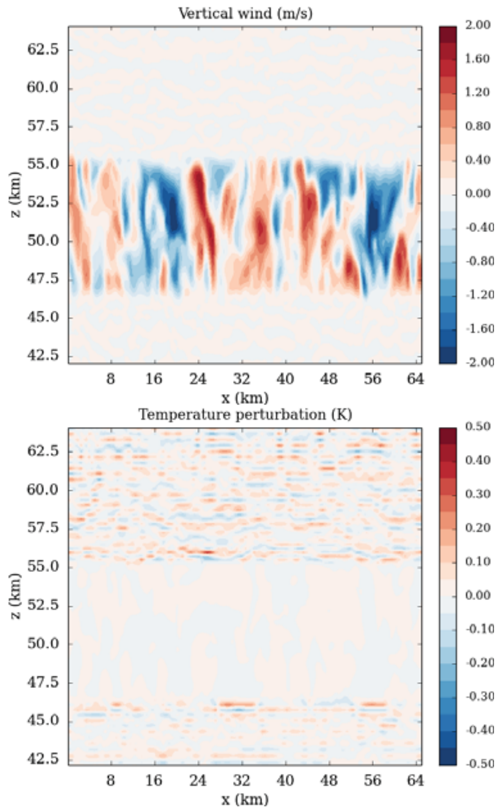

Figure 1: Top : vertical cross-section of the vertical wind (m/s). Bottom : vertical cross-section of temperature perturbation (K).

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Comparison of horizontal distributions of temperature and UV absorbers at the Venus cloud-tops

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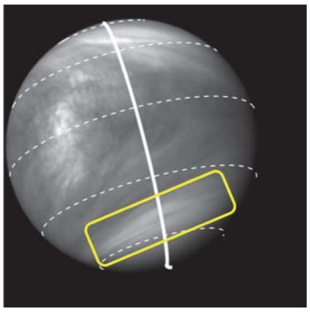
Venus is the nearest neighbor planet, which has a size similar to that of the earth. However, unlike the earth, Venus is covered with thick H_2SO_4-H_2O clouds floating at 45-70 km altitudes (Nakamura et al. 2011). It is considered that the clouds are photochemically generated by oxidation of SO_2 and H_2O. In the visible region, light reflected by the clouds are poorly absorbed and few structures are noticeable. On the other hand, in the ultraviolet (UV) region, inhomogeneity of albedo has been identified to be inhomogeneous distribution of UV absorbers above the layer of UV scattering. It has been identified that SO_2 in the Venusian atmosphere absorbs light in the wavelength region between 200 nm and 320 nm, but chemical species responsible for the absorption in the wavelength region longer than 320 nm is still unidentified. S_2O and $OSSO$ are candidates (Perez et al. 2018). The UV absorbers play an important role in the atmospheric dynamics, controlling vertical thermal stability by heating at the top of convection layer. The dynamics may feedback the distribution of the UV absorbers by transport of them from the lower atmosphere. Details of the chemical and dynamical coupling are still unknown.

We analyzed images obtained by the Longwave Infrared Camera (LIR) and Ultraviolet Imager (UVI) onboard the Venus orbiter Akatsuki. LIR takes images of thermal radiation in the wavelength range of 8-12 μm emitted from the cloud-tops (Fukuhara et al., 2011). Temperature distributions are derived from the images. Disturbances seen in the temperature distributions are thought to be caused by atmospheric waves and tides, changes in the cloud-top altitude and adiabatic heating and cooling due to convection, direct heating by the UV absorbers, and so on. UVI takes images of the solar radiation reflected by the clouds with narrow bandpass filters centered at the 283 and 365 nm wavelengths, which correspond to the absorption bands of SO_2 and unknown absorbers (Yamazaki et al., 2018).

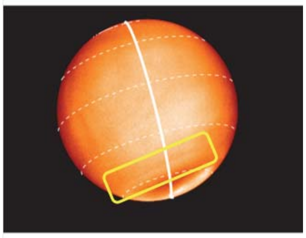
Observations at 365 nm often find clouds with a little radiation in the middle latitudes. Such clouds with low radiation (bright) are covering on the clouds with high radiation (dark). The bright clouds are hard to receive the supply of UV absorbers from the lower layer (Titov et al., 2008). We found such bright distributions in the middle latitudes of images taken by LIR and UVI. Examples (on January 26, 2017) are shown in figures. The fact that we can see the similar distributions at different wavelengths means that two cameras observe clouds almost the same altitude. Therefore, we are studying of the dynamics of cloud top distributions at middle latitudes to use data taken by LIR and UVI.

We converted the UV radiation obtained into the absorption rate. Furthermore, we compared by combining the absorption rate and the temperature. The combined image is displayed more reddish when the temperature is higher and it is displayed more blueish when UV absorption rate is higher. Example are shown in figures. The figure is displayed blackish in the equatorial region and whitish in the polar region. In the middle latitudes where we pay attention, the temperature is high and the amount of absorption is small, so it is displayed reddish. In this presentation, we will introduce some examples like this, and will present relationships between temperature and SO_2, temperature and unknown absorbers.

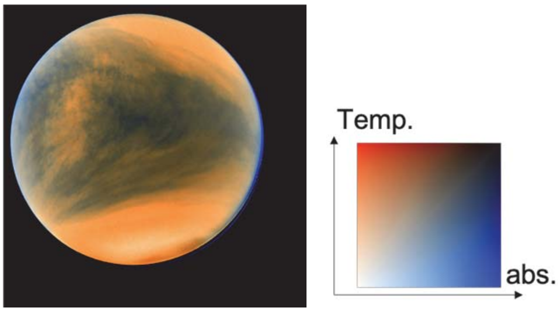
As a next step, we will further study the relationship between temperature and UV absorbers for each latitude and local time, and will clarify what atmospheric dynamics is occurring at the cloud top.



Unknown UV absorber distribution observed by UVI (365 nm)



Brightness temperature distribution observed by LIR (10 μm)



Distribution combined by the temperature distribution and the UV absorption rate distribution

Towards a (GCM-based) Venus Climate Database

E. Millour*, S. Lebonnois, A. Spiga, F. Forget
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Introduction

Over the past twenty year, our team, with support from the European Space Agency and CNES (French space agency) and collaboration with other European partners, has successfully developed, maintained and distributed the Mars Climate Database (MCD) [1] to the international community. This database is derived from dedicated Global Climate Model (GCM) developed by our consortium.

The Venus atmosphere is also studied by our planetary atmospheres team, using a state of the art Venus GCM [2-4]. Based on our experience with Mars, we feel that the best means to share these results with the international community, both for users wanting to compare with their models or analyze observations and users planning future missions, would be with the creation of a Venus Climate Database (VCD).

Overview of the Venus Climate Database contents and access modes

Based on our experience with the MCD, the VCD would:

- Be based on the latest validated outputs of our Venus GCM.
- Provide an interface routine (e.g. Fortran, but also with interfaces in other languages such as C, Python, etc.) so that a user could easily retrieve atmospheric fields (temperature, wind, pressure, …) at any sought coordinate in space and time.
- Provide an online interface (similar to the MCD one: http://www-mars.lmd.jussieu.fr/) for users interested in obtaining a quick look at the data.
- Provide some access to the VCD as a virtual observatory in the frame of the Virtual European Solar and Planetary Access (VESPA) [5] Europlanet 2020 Research Infrastructure program (http://www.europlanet-vespa.eu/).

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Numerical modeling of the Venus atmosphere

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It has been revealed by recent space-craft and ground-based observations that various atmospheric activities such as thermal tides, polar vortex, and Kelvin- and Rossby-type waves occur in the Venus atmospheric superrotation in the cloud layer. In order to elucidate generation mechanisms of these activities and their dynamical effects on the superrotation, we have developed a general circulation model (GCM) for the Venus atmosphere named AFES-Venus, which is based on AFES (AGCM for Earth Simulator) (Ohfuchi et al., 2004; Enomoto et al., 2008). Recently, AFES-Venus has been extended for the data-assimilation (Sugimoto et al., 2017). Results we have obtained so far are summarized as follows:

- Superrotating winds consistent with the observations (e.g., Machado et al., 2017) have been reproduced in the AFES-Venus simulations.
- Baroclinic instability appears in mid-latitudes in the cloud layer (Sugimoto et al., 2014a; 2014b). The Rossby waves and the Y-shape pattern observed at the cloud top might be explained by the baroclinic instability waves.
- A cold band encircling the warm polar region called "cold collar" is attribute to the residual mean meridional circulation enhanced by the thermal tide (Ando et al., 2016).
- Vertical temperature structures and their temporal variations in the polar atmosphere observed by radio occultation measurements are interpreted as neutral barotropic Rossby waves related to barotropic instability in the polar region (Ando et al., 2017).
- Three-dimensional structures of the thermal tide indicate a strong circulation between the subsolar and antisolar (SS-AS) points in the cloud layer superposed on the superrotation (Takagi et al., 2018). The SS-AS circulation can contribute to the material transport, and its upward motion might be related to UV dark clouds observed near the subsolar region in low latitudes.
- Streak features of the lower cloud observed in night side images of Akatsuki IR2 camera, reproduced for the first time, are related to baroclinic instability in the cloud layer (Kashimura et al., 2019).

At the conference, we will discuss more recent results including short-period disturbances and zonal-mean meridional circulation.

Investigations below the clouds of Venus with the IPSL Venus GCM.

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Thanks to the various space missions that investigated Venus's atmosphere since the 70's, and in particular the recent Venus-Express (Europe, 2006-2014) and Akatsuki (Japan, 2015-) missions, the atmosphere of Venus above roughly 45 km altitude including the clouds (~48-70 km) has been thoroughly investigated. This vast amount of data helps to understand how this complex atmospheric system works, in particular with the help of advanced Global Climate Models (GCMs). However, data from below the clouds are sparse, despite the importance of the deep atmosphere in the global behavior of Venus's atmospheric system: peak of angular momentum content, interactions between surface and atmosphere (including angular momentum exchange, volcanism, weathering). A better knowledge of the region is also needed for specific mission planning purposes, such as aerial platforms or landers. To investigate this region while planning new missions, GCMs are valuable tools and we review here all the studies conducted on this region with the IPSL Venus GCM developed in Paris (Lebonnois et al., 2016; Garate-Lopez & Lebonnois, 2018).

To model the temperature profile in the deep atmosphere, it is crucial to investigate the radiative transfer and the opacity sources below the clouds. Lebonnois et al. (2015) studied how the solar energy absorbed below the cloud may be balanced with infrared energy heating the base of the cloud, convecting up to the middle cloud to escape finally to space mostly in the 20-30 micron region. Using recent solar flux calculations (Haus et al., 2015) and up-to-date datasets for IR gaseous opacities and collision-induced absorptions, the temperature profile in our GCM is tuned through assumptions on the haze below the cloud to fit the observed temperature profile between the cloud base and the surface.

Though we obtain realistic superrotation in the upper cloud, the vertical profile of zonal wind observed below 60 km is not fully understood. Around the cloud base (40-60 km), wave activity obtained in our most recent simulations contributes to angular momentum convergence in the equatorial region (Garate-Lopez & Lebonnois, 2018). In previous simulations (Lebonnois et al., 2016), large-scale gravity waves were transporting angular momentum equatorward and downward, improving the distribution of zonal wind below 40 km. As both wave activities are not obtained in the same simulations, we are investigating the conditions for the development of each of these wave groups and will detail our most recent conclusions in this talk.

Near the surface, the IPSL Venus GCM was also used to investigate the behavior of the Planetary Boundary Layer (PBL), in particular diurnal convective activity (Lebonnois et al., 2018). The deepest 10 km above the surface are neutrally stable in our simulations, a peculiar environment for the diurnal cycle of the PBL. A nocturnal stable layer is obtained due to cooling of the surface during nighttime. In daylight hours, convection develops in mid- to low-latitude regions, with a maximum around noon and a convective layer mostly limited to just over 1 km thickness. Strong slope winds are obtained in the simulations, with a diurnal cycle: downslope katabatic winds at night, upslope anabatic winds during daytime. The convergence of anabatic winds at noon over the western slopes of topographic features induces a large increase in the vertical extension of the convective activity, reaching higher than 5 km thickness in some of these regions.

The interactions between the near-surface flow and the topography are also explored with the IPSL Venus GCM (Navarro et al., 2018). A parameterisation of the drag due to orographic gravity waves generated by topographic features is now implemented and can help interpret the stationary bow-shape waves observed at cloud-top by the Akatsuki spacecraft.

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Acknowledgements

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Session 11

Atmospheric Dynamics (3)

Session Chair: Helen Parish
Session Chair: Javier Peralta

Detection of large stationary gravity waves over ten Venusian solar days seen in LIR images

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Abstract:

The existence of large stationary gravity waves was discovered during Akatsuki's first observation sequence in December 2015 (Fukuhara et al., 2017). Since the discovery, large stationary gravity waves have been detected periodically in not only mid-infrared images by LIR (Kouyama et al., 2017), but also ultraviolet images by UVI and near infrared images by IR2 onboard Akatsuki. The waves appeared mostly above four specific highland regions in the low latitudes (Aphrodite Terra, Thetis Regio, Atla Regio, and Beta Regio), and they always became significant when the locations passed in local afternoon. Numerical studies have successfully reproduced the clear dependence of stationary waves on location and local time (Navarro et al., 2018; Lefevre et al., 2019).

In this study, we will report the further detection of the stationary gravity waves seen in LIR images over ten Venusian solar days (2015 Dec. – 2018 Dec.). As described in Kouyama et al. (2017), the waves appeared again and again above the four highlands when they were in local afternoon. Figure 1 shows examples of large stationary waves on Aphrodite Terra. The clear periodicity of the wave appearance indicates that lower atmosphere steadily repeats a certain atmospheric condition which is suitable for excitation of stationary waves. In addition to the large-scale waves, small stationary features have been identified which sometime appeared surrounding the large waves. There has been no detection of a stationary wave signature above Ishtar Terra, which has the highest mountain in Venus, Maxwell Mons, but locates in higher latitudes (> 60°).

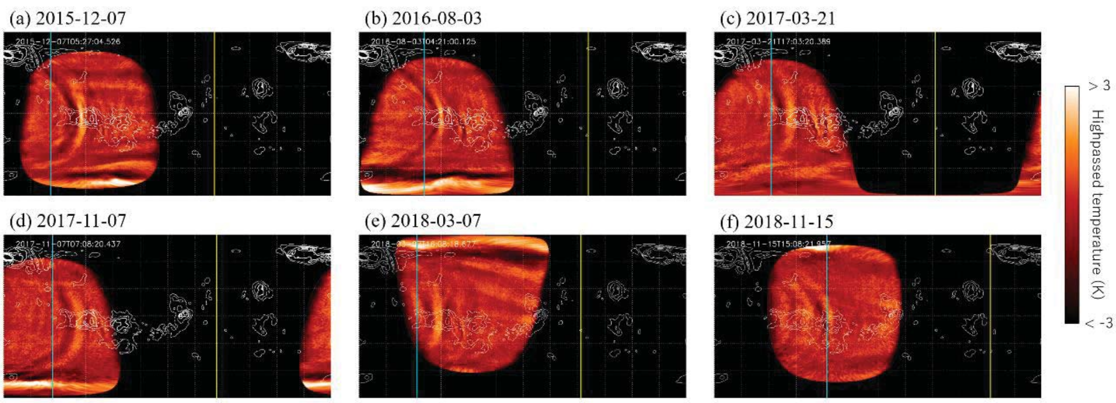

Figure 1. Stationary gravity waves above Aphrodite Terra in LIR images from 2015 to 2018. Orange and blue lines indicate morning and evening terminator, respectively.

A new mesoscale model for Venus' atmosphere and its application to the bow-shaped structures discovered by Akatsuki

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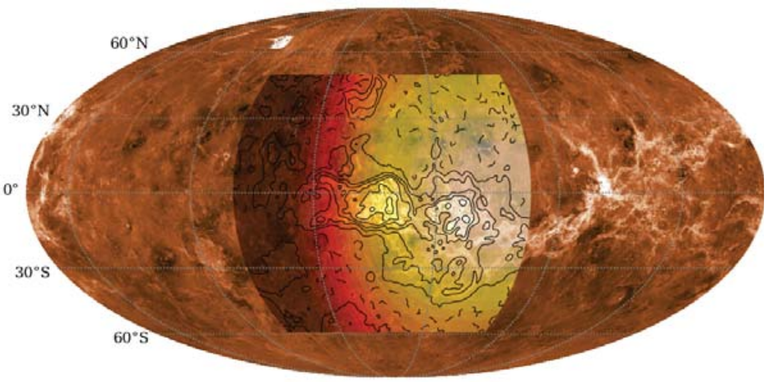

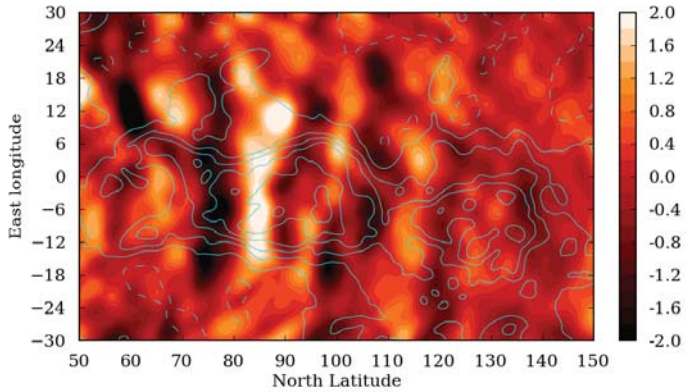

[Left figure] Incoming sunlight shown on the domain set for the Aphrodite Terra simulation with our Venusian mesoscale model, superimposed on a Magellan radar image. [Right figure] Equivalent brightness temperature at cloud top (65-72 km) as simulated by our Venusian mesoscale model at the local time shown on the left, after applying high-pass filtering as for the published Akatsuki LIR images (Fukuhara et al. 2017, Kouyama et al. 2018).

The aim of mesoscale modeling is to complement Global Climate Modeling by resolving, in a specific region of interest, the meteorological phenomena arising at spatial scales lower than a couple hundreds kilometers. Mesoscale models developed for the terrestrial atmosphere have been adapted to Mars to study the numerous small-scale perturbations evidenced by orbiting and in-situ spacecraft. To date, mesoscale modeling on Mars has been used to study slope winds, katabatic jumps, polar transients, gravity waves, dust-induced convection.

Apart from a few idealized studies, there is no mesoscale model existing for the Venus atmosphere. Results from Venus Express and the prospect of the Akatsuki mission led us three years ago to start the development of a mesoscale model for Venus. Following the same logic as the Martian mesoscale model developed in our team at Laboratoire de Météorologie Dynamique (LMD), we have now built a complete mesoscale model for Venus by coupling the dynamical core from the terrestrial Weather Research and Forecast (WRF) model with the complete physical packages developed for the Venus LMD GCM, notably the latest version of the radiative transfer. Limited-area domains can be set anywhere on Venus for our Venusian mesoscale model. High-resolution Magellan topography is used in the model. Idealized large-eddy simulations are also possible with this model and presented in a separate abstract.

Akatsuki provided the first scientific case to study with our new Venusian mesoscale model, by enabling the discovery of bow-shaped stationary structures at the cloud tops above Venus' major topographical obstacles. We will present simulations with our Venusian mesoscale model that reproduce both those signatures and their local time phasing. Our modeling study supports the interpretation of bow-shaped signatures as orographic gravity waves undergoing vertical propagation modified by the successive stability gradients they experience when propagating upwards. We will discuss the case of Atla Regio, Beta Regio and Aphrodite Terra, and detail model-observation differences and remaining challenges. Other possible modeling studies with our model (polar simulations, slope winds, ...) will be discussed and ideas of mesoscale simulations suggested by the community will be welcome.

Venus atmosphere dynamics revealed by cloud tracking using images from Akatsuki

T. Horinouchi*[1], T. Fukuhara[14], Y.-Y. Hayashi[2], T. Imamura[3], H. Kashimura[2], T. Kouyama[4], Y. J. Lee[3], S. S. Limaye[5], K. McGouldrick[6], S. Murakami[7], K. Nakajima[8], M. Nakamura[7], K. Ogohara[9], J. Peralta[7], T. M. Sato[7], T. Satoh[7], M. Taguchi[14], M. Takagi[10], S. Watanabe[11], M. Yamada[12], A. Yamazaki[7], and E. F. Young[13]

*: presenting, 1: Hokkaido Univ., 2: Kobe Univ., 3: Univ. Tokyo, 4: AIST, 5: Univ. Wisconsin-Maddison, 6: Univ. Colorado, 7: JAXA/ISAS, 8: Kyushu Univ., 9: Univ. Shiga Prefecture, 10: Kyoto Sangyou Univ., 11: Hokkaido Information Univ., 12: Chiba Inst. Tech., 13: Southwest Research Inst, 14: Rikkyo University.

Since its orbit insertion in December 2015, Akatsuki has been providing new discoveries on the Venusian atmosphere, which is known for thick clouds and the intense super-rotation. This presentation will focus on dynamical aspects revealed largely from cloud tracking by using images at multiple wavelengths from Akatsuki. Venus is covered with clouds that extend from about 45 to 70 km altitude, and the super-rotation is maximized around the cloud top.

Images at the near-infrared “atmospheric window” wavelengths visualize the silhouette of lower-to-middle layer clouds. From Akatsuki’s near-infrared images, it was found that a jet-like feature emerged and lasted over several months near the equator, which had not been observed before. Also found are large-scale vortices presumably due to dynamical instability. These results suggest that winds in the lower and middle cloud layers are much more variable than have been thought.

Ultraviolet imaging has long been used to measure winds at the cloud top. However, with Akatsuki’s novel two-wavelength imaging and a new cloud tracking method with high accuracy, major advances have been achieved. Results from the two wavelengths suggested vertical shear near the cloud top. Observations over the past ~3years revealed the long-term variability of the cloud-top winds, which includes that of their hemispheric asymmetry. Solar-longitude dependent tidal features are well elucidated, but geographically fixed features are very obscure if any.

Recently, we have been studying the maintenance of the super-rotation and the meridional circulation. We have successfully evaluated the horizontal transport of angular momentum by thermal tides and transient disturbances. We have also obtained meridional tidal heat flux. Combining the estimates from Akatsuki with knowledge from past studies, we can draw a consistent view of the super-rotation maintenance and meridional circulation in the cloud layer of Venus.

Akatsuki (cloud-tracking) and TNG/HARPS-N (Doppler velocimetry) coordinated wind measurements of cloud top Venus' atmosphere.

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Abstract

We present wind velocity results based in the measurements of the horizontal wind field at the cloud top level of the atmosphere of Venus, near 70 km altitude, in the visible range on the dayside. At this altitude the wind circulation is dominated by the retrograde zonal superrotation (RZS).

The cloud-tracking space observations were carried out, between 26-31 January 2017, by the "Ultra Violet Imager" (UVI) onboard Akatsuki's Venus Climate Orbiter (VCO), using the 365 nm filter. The cloud-tracking technique we used was evolved from a phase correlation method between images developed by Peralta et al. 2007. The use of UVI images to track cloud features from the unknown UV absorber has already provided important results in the constrain of zonal and meridional wind at cloud-top (Horinouchi et al. 2018).

The ground observations were carried out, on the 28th and 29th of January 2017, at the 3.58-meter "Telescopio Nazionale Galileo" (TNG) using the "High Accuracy Radial velocity Planet Searcher" spectrograph (HARPS-N) in the visible range (0.38-6.9 µm). It was the first use of this high-resolution (R≈115000) spectrograph to study the dynamics of a solar system atmosphere. The sequential technique of visible Doppler velocimetry is based on solar light scattered by cloud top particles in motion. This technique was developed over the last decade (Widemann et al. 2008, Machado et al. 2012, 2014) and has proven to be a reference technique in the retrieval of instantaneous zonal and meridional winds (Machado et al. 2017). In this work we successfully adapt this technique to the HARPS-N fiber-fed spectrograph with consistent results.

The Akatsuki/UVI observations provided 3 high-quality images per observation day, separated by ~2h interval. Due to its low inclination orbit (<10º), Akatsuki's images offer a great range in Venus' dayside, allowing us to track cloud features from 60º N to 70º S latitude and from 7:30 to 17:00 local time. This has enabled a study of spatial and time variability of both zonal and meridional wind. The HARPS-N ground observations focused on the meridional wind field between 60° S and 55° N latitude and zonal wind field near equator (latitudes between 10° S and 10° N). HARPS-N results present an unprecedented high-precision meridional wind latitudinal profile.

The Akatsuki results show a North-South asymmetry on zonal wind velocity, as well as an opposite asymmetry on meridional wind velocity, consistent with the results from Horinouchi et al 2018. A thermal tide is also detected from both space and ground observations, where zonal velocities are higher near the evening terminator

This work intends to contribute to the characterization of Venus' cloud top zonal and meridional wind by studying latitudinal behavior on hour and day timescales as well as wind temporal and spatial variability. Similar studies have proven the relevance of both space-based cloud tracking observations (Sánchez-Lavega et al. 2008, Hueso et al. 2012, Hourinouchi et al. 2018) and ground-based doppler velocimetry (Machado et al. 2014, 2107), as well as the usefulness of coordinated observations in the cross validation of both technique results.

Meridional and Zonal winds at Venus' atmosphere from Cloud-tracking, Doppler techniques and comparison with modelling

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We present final results of the meridional wind in both Venus' hemispheres and spatial and temporal variability of the zonal wind, based on coordinated observations at Venus cloud-tops based with two complementary techniques: Ground-based Doppler velocimetry and cloud-tracked winds using ESA Venus Express/VIRTIS-M imaging at 0.38 µm. Cloud-tracked winds trace the true atmospheric motion also responsible for the Doppler-Fizeau shift of the solar radiation on the dayside by super-rotating moving cloud-tops with respect to both the Sun and the observer (Machado et al., 2014). Based on this complementarity, we performed a new coordinated campaign in April 2014 (Machado et al., 2017) combining both Venus Express observations and ground-based Doppler wind measurements on the dayside of Venus' cloud tops at Canada-France-Hawaii telescope at a phase angle $\Phi = (76 \pm 0.3)^{\circ}$. Venus Express cloud top wind measurements based on tracking using images taken with the VIRTIS instrument indicate nearly constant zonal winds in the Southern hemisphere between 0 and 55º S. The analysis and results show (1) additional confirmation of coherence, and complementarity, in the results provided by these techniques, on both spatial and temporal time scales of the two methods; (2) first-time estimation of the meridional component of the wind in other planet using the Doppler velocimetry technique, with evidence of a symmetrical, poleward meridional Hadley flow in both hemispheres; (3) spatial and temporal variability of the zonal flow with latitude and local time, with a significant increase of wind amplitude near morning terminator.

We also present final results based on observations of Venus' bottom of the cloud deck, carried out with the Near Infrared Camera and Spectrograph (NICS) of the Telescopio Nazionale Galileo (TNG), in La Palma, on July 2012. We observed for periods of 2.5 hours starting just before dawn, for three consecutive nights. We acquired a set of images of the night side of Venus with the continuum K filter at 2.28 microns, which allows to monitor motions at the lower cloud level of the atmosphere of Venus, close to ~ 48 km altitude. Our objective is to measure the horizontal wind field in order to characterise the latitudinal zonal wind profile, to study variability, to help constrain the effect of large scale planetary waves in the maintenance of superrotation, and to map the cloud distribution.

We will present results of cloud tracked winds from ground-based TNG observations and winds retrieved from coordinated space-based VEx/VIRTIS observations. The observational results will be compared with the ground-to-thermosphere 3D model developed at the Laboratoire de Meteorologie Dynamique in Paris (Gilli et al. 2017), whose zonal wind predictions above 60 km seem to be consistent with available measurements (Peralta et al.2018).

Session 12

Aeronomy and Plasma Environment

Session Chair: Masato Nakamura

Session Chair: Amanda Susanne Brecht

Understanding the impact of waves on Venus' Upper Atmosphere through General Circulation Model Simulations

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The upper atmosphere of Venus has been observed for many decades by multiple means of observations (e.g., ground-based, orbiters, probes, fly-by missions). The European Space Agency Venus Express (VEX) orbiter and more recently the Japanese mission, Akatsuki, have been providing illuminating observations of the Venusian atmosphere. From past and present observations there is evidence of wave activity contributing to Venus' atmospheric dynamics and variability. Systematic studies with theoretical models can help better understand the underlying physical processes.

The Venus Thermospheric General Circulation Model ((VTGCM), e.g. Brecht et al., 2011) has improved upon the already existing constraints by including more chemistry (OH nightglow, SOx, $[SO]_2$), modern energy budget calculations (near-IR and aerosol heating, NLTE 15-μm cooling), and wave specification and parameterizations (planetary-scale waves and small scale gravity waves).

The presented work will focus on VTGCM simulations and their comparisons with published observations in regards to wave-induced variability within the circulation and nightglow emissions. Small-scale gravity waves, incorporated into the VTGCM by a whole atmosphere gravity wave parameterization (Yiğit et al., 2008), along with specified internal waves (Kelvin and Rossby waves) impact the background atmosphere. The effects of these subgrid-scale waves and large-scale internal waves on atmospheric circulation will be discussed. The O_2 IR nightglow emission and the NO UV nightglow emission are great features to observe and help constrain circulation. The location (spatial and temporal), intensity, and variability of these emissions provide information (model constraints) on temperature, winds, and density. These emissions have been observed and their averaged behavior has been documented (Soret et al., 2012; Steipen et al., 2013). However, the emission variability (and the wave processes responsible) has not been studied in detail. The impacts the wave specification and parameterizations have on these emissions and their variability will also be presented.

The Venus Ionosphere as seen by the Akatsuki Radio Science Experiment

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The radio science experiment on the japanese Venus orbiter Akatsuki is sounding the ionosphere of Venus in the one-way radio link mode at X-band (8.4 GHz). The radio link is stabilized by an on board Ultrastable Oscillator (USO). Because of the geometry of the Earth/Venus/Akatsuki constellation, Earth occultations occur in seasons. Akatsuki will have finished its third season at the time of this conference. The locations of the occultation ingress and egress positions during a season are confined in a band within the mid-latitudes on both hemispheres. Ingress and egress local times are at night to early morning and afternoon to early night, respectively. This work will present the ionospheric electron density profiles from the first seasons of Akatsuki radio sounding and will compare those directly with VEX-VeRa ionospheric electron density profiles at similar locations, local times and solar zenith angles but from different phases of the solar cycle.

Upper atmosphere of Venus and impact from solar wind plasma: What we have learned from Venus Express

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Abstract

Venus is nicknamed "Earth's twin" due to its similarities in size, gravity, and distance from the Sun. However, Venus is significantly different from the Earth in terms of the space environment, mainly due to the lack of the dipole magnetic field. The lack of a magnetic dipole directly exposes the upper atmosphere and ionosphere to the solar wind plasma, the momentum and energy of which are injected into the Venusian upper atmosphere. Thus the momentum and energy inputs from the solar wind can erode the upper atmosphere and change its composition. The main component of interest has been water molecules. Such a loss of the water molecules at Venus over billion year scale is thought to be consistent with the high D/H ratio at Venus compared to that at the Earth.

In 2006, Venus Express (VEX) was inserted into a Venusian orbit. One of the scientific objectives of the VEX mission was to investigate the solar wind interaction in a context of the "fate of water". For this purpose, VEX was equipped with a magnetometer (MAG) and a plasma and energetic neutral atom (ENA) package (ASPERA-4). The VEX mission was operated for 8.5 years, and completed its mission in 2014. During the mission, MAG and ASPERA-4 were operated, and these instruments have updated our understandings of the near-space environment of Venus.

VEX measured the plasma environment in the polar, terminator and magnetotail regions of Venus. The ionosphere and near-tail regions host dynamic processes that energize plasma, leading to the loss of ionospheric ions to space with their composition of H^+ and O^+ in the ratio 2 to 1. This indicates that the water molecules are escaping now through the magnetotail due to the solar wind interaction. The VEX plasma measurements also have revealed the response of the structures and dynamics of the Venusian induced magnetosphere to the prevailing solar wind conditions with various time scales. We review what has been found by VEX in the context of the interaction between the upper atmosphere and the solar wind. We further will formulate the key open questions to extend our understandings about Venus for future missions; and more in general, to extend our understanding about other Solar System bodies, as well as exoplanets.

Circulation of Venusian atmosphere at 90-110 km based on apparent motions of the O_2 1.27 µm nightglow from VIRTIS-M (Venus Express) data

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In the atmosphere of Venus at 90-110 km altitudes in the transition region between the superrotation and the subsolar-antisolar circulation, tracking of the $O_2(a^1\Delta_g)$ 1.27µm nightglow is practically the only method of studying the dynamics. The nightglow images were obtained by VIRTIS-M on Venus Express from 2006 to 2008. The horizontal wind speed can be obtained by tracking the displacement of the bright morphological features at given pairs of images. The resulting global mean velocity vector field covers the nightside between latitudes 75°S – 0°N and local time 19 h – 5 h. The mean zonal and meridional components are asymmetrical between the morning and the evening side in terms of direction and magnitude. The zonal wind speed in the eastward direction from the morning side exceeds the westward (evening) by 20-30 m/s, and the streams “meet” at 22±1 h. The meridional component is predominantly poleward on the morning side, ranging from 0 to -50 m/s, and changes to equatorward at mid-latitudes. The influence of underlying topography was suggested in some cases: above mountainous regions flows behave as if they encounter an "obstacle" and "wrap around" highlands. Instances of circular motion were discovered, encompassing areas of 500-4000 km.

An Investigation of the Solar Wind Influence on the Venus Upper Atmosphere Structure and Dynamics

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Introduction and Motivation. This project addresses one of the outstanding questions of the dynamics of the Venus upper atmosphere, namely "What causes the retrograde super-rotating zonal (RSZ) flow of the Venusian upper atmosphere above ~110 km?" The primary goal of this research is to test the hypothesis first introduced by *Lundin et al.,* (2011) [1] that the Venus solar wind interaction drives asymmetric plasma winds that in turn drive neutral winds via ion-neutral collisions that when combined with the orbital motion of Venus lead to the observed RSZ flow. To accomplish this goal, two sophisticated and well established three dimensional simulation codes are utilized and coupled together. The neutral atmosphere is modeled (~70 to 220 km) with the Venus Thermospheric General Circulation Model (VTGCM) [2, 3, 4, 5, 6]. The Venusian solar wind interaction (~100 km to $4R_V$) is simulated using the HALFSHEL hybrid particle code (cf. HALFSHEL is used at Mars [7] and at Titan [8, and references therein]). Specifically, the HALFSHEL code is exercised to calculate ion particle motion consistent with its E and B fields. Both codes have all the necessary physical, chemical and energetics routines needed to successfully achieve this coupling. The "flat field" passage of 3-D gridded VTGCM neutral density fields to HALFSHEL, and the subsequent passage of newly calculated plasma momentum and energy terms from HALFSHEL back to VTGCM are implemented for this project. This paper focuses upon testing the impact of these plasma model momentum and/or energy terms within the VTGCM thermospheric domain, and examining whether RSZ neutral winds can be produced from ion-neutral drag processes.

Pioneer Venus (PVO) and Venus Express (VEx) Measurement Constraints. A detailed study of the VEx/ASPERA-4 IMA ion measurements demonstrates that the flow of solar wind (H^+) and ionospheric (O^+) ions near Venus is characterized by a marked asymmetry [1]. Accelerated O^+ has average velocities less than required for Venus escape. Hence, O+ gives rise to a high altitude zonal plasma wind at Venus. The nightside plasma wind is in the same direction as Venus super-rotation and RSZ neutral flow. In addition, statistical distributions of Venus upper atmosphere temperatures and densities as a function of latitude & local time (~100-200 km) have been mapped [9], using: (a) PVO (ONMS) densities and temperatures, (b) PVO (OUVS) NO nightglow distributions, (c) VEx VIRTIS-H dayside T and CO profiles, and (d) VEx (SPICAV UV) NO nightglow distributions. The underlying VTGCM processes maintaining these observed thermospheric distributions have been studied, especially the RSZ component of the highly variable global winds.

Focus on VTGCM Modeling. The Venus Thermospheric General Circulation Model (VTGCM) has been continuously upgraded and utilized over the past 30+ years. It was recently improved [6, 10, 11] by including new chemistry (e.g. OH nightglow, SOx), modern heating and cooling formulations (near-IR and aerosol heating, NLTE 15-μm cooling), and wave parameterizations. For this study, the impacts of HAFSHEL ion particle precipitation (yielding atmospheric heating), and ion-neutral collisions (yielding momentum deposition) are examined within the VTGCM code to determined their relative importance upon thermospheric temperature and wind structures. The corresponding VTGCM heat and momentum balance terms are extracted and carefully examined to characterize the relative importance of these underlying processes. Ultimately, this enables us to examine the potential role that ion motion may play in the observed asymmetries observed in the Venus thermospheric structure and dynamics.

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H^+/O^+ escape rates in the Venusian magnetotail and their dependence on upstream conditions

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Venus has a continuous outflow of H^+ and O^+ ions from its upper atmosphere through the magnetotail [Futaana et al. 2017]. The ratio of the outflow flux between the H^+ and O^+ is important to characterise in order to predict the loss of water from the Venusian atmosphere through its history. However, the ratio between the H^+ and O^+ outflowing ions has only been investigated during solar minimum (2006-2009) using Venus Express (VEx) data [e.g. Barabash et al. 2007a, Fedorov et al. 2011]. The ratio was found to be close to 2, which is the stoichiometric ratio of a water molecule. In this study, we extend the analysis of the H^+/O^+ flux ratio in the magnetotail using all available data from the Ion Mass Analyser (IMA), part of the ASPERA-4 instrument package [Barabash et al., 2007b], onboard VEx during 2006-2014 [Svedhem et al. 2007]. The 24-hour polar orbit of VEx gave more than 3000 orbits, making the mission suitable for long term Venus atmospheric escape studies.

We create average velocity distribution functions of H+ and O+ in the Venusian magnetotail, separately for two periods of high/low solar activity. These average distribution functions are used to calculate the total flux and subsequently the total escape rates of H^+ and O^+ through the Venusian magnetotail. The results show that the H^+ and O^+ escape fluxes are strongly correlated with solar activity. The escape flux during solar minimum ($7.6 \cdot 10^{24}$ s^{-1} for H^+ and $2.9 \cdot 10^{24}$ s^{-1} for O^+) is larger than that during solar maximum ($2.1 \cdot 10^{24}$ s^{-1} for H^+ and $2.0 \cdot 10^{24}$ s^{-1} for O^+). The decreases of the fluxes in the solar maximum are mainly due to strong return flows toward Venus. As a result, the escape rate ratio decreases from 2.6 at solar minimum to 1.1 at solar maximum [Persson et al., 2018].

Further, we formulate escape fluxes of O^+ and H^+ as functions of the upstream parameters (solar wind density and velocity, and solar EUV flux). As the solar wind and solar EUV flux are known to have been stronger in its earlier history [Ribas et al., 2005, Airapetian and Usmanov, 2016], the formulation is essential to extrapolate atmospheric loss rates ~4 Gyr backwards in time. The formulation also provides important characteristics of the Venusian atmosphere when comparing with similar studies made for Mars [Ramstad et al., 2015] and Earth [Schillings et al., 2017], to understand the effects of an intrinsic magnetic field, atmospheric content and gravity on the escaping oxygen flux.

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Variability of the Venusian and Martian nightside ionosphere after solar storms

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1. Introduction

Interactions between planetary atmospheres and the solar wind can be observed via atmospheric emission and ion/electron density profiles. The interaction of the solar wind with Venus and Mars is unique given that both planets lack an intrinsic magnetic field (or, in the case of Mars, only posesses a weak crustal field) and have similar atmospheric composition (95% CO_2).

The Venusian and Martian nightside ionospheres have two distinct electron density peaks: the V1 and V2 peaks for Venus (located near 125 and 150 km), and the M1 and M2 peaks for Mars, (located near 100 and 150 km). These peaks are known to be be highly variable for both planets but the chemical pathways and processes, particularly for the V1 and M1 layers, are not well understood.

Both the V1 and M1 layers exhibit increases in density after intense solar storms, such as coronal mass ejections (CMEs) and solar flares [1, 2]. These increases in density are observed almost immediately and are present on the deep nightside. While ions are transported from the dayside to the nightside of the planet, the time for this process to occur is much longer then the response seen in the electron density profiles. Thus, proton and/or electron precipitation must play a key role in the variability of these ionospheres. Here, we study the variability of the Venusian and Martian nightside ionosphere and its connection to the solar wind, particularly after solar storms.

2. Observations

Using the Venus Radio Science Experiment (VeRa) instrument on Venus Express (VEX), Mars Radio Science Experiment (MaRS) on Mars Express (MEX), and Langmuir Probe and Waves (LPW) instrument on the Mars Atmosphere Volatile and EvolutioN (MAVEN) spacecraft, we compare electron density profiles of the Venusian and Martian nightside before and after solar storms. Additionally, we compare nightside ion density profiles observed by Neutral Gas and Ion Mass Spectrometer (NGIMS) onboard MAVEN.

3. Discussion

The MAVEN spacecraft is able to observe low ionsphere composition directly. [3] and [4] Giazian et al. 2017 shows that NO^+ is the dominate ion at the M1 level on the Martian nightside. NO^+ was predicted to be the source of the nightside V1 layer on Venus as well as a possible chemical pathway to the observed auroral emission of OI 5577.7 “oxygen green line” [5]. We propose that the the V1 and M1 layers are dominated by NO^+ and that production is sensitive to electron precipitation on Venus.

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Small-scale disturbances in the lower dayside ionosphere of Venus

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The Venus Radio science Experiment VeRa on board Venus Express sounded the ionosphere and lower neutral atmosphere of Venus from 2006 to 2014. More than 800 vertical profiles of the ionospheric electron density, neutral atmospheric pressure/density and temperature were derived from occultation ingress and egress observations. A subset of the VeRa ionospheric dayside observations contains small-scale ionospheric excess electron densities in and below the secondary ionospheric layer (Pätzold et al., 2009). A similar feature was identified in the Mars dayside ionosphere (Pätzold et al., 2005). Certain aspects of the Martian excess electron densities indicate that the ionization of the locally available neutral atmospheric species by shorter solar X-ray radiation seems to play a key role in their formation (Peter 2018). This work provides a statistical evaluation of the occurrence rates of the small-scale ionospheric features in the dayside ionosphere of Venus. Correlations between the occurrences of the excess electron densities and observational/environmental parameters (e.g. solar zenith angle, solar X-ray proxies) should reveal if a formation process similar to that in the Martian ionosphere is possible.

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