惑星大気・プラズマシミュレーション

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2017年9月7日

STEシミュレーション研究会

Outline

- イントロダクション
  - 生命存在可能環境、水や大気の安定性
    - パラメータ：中心星(可視・紫外)放射強度、惑星サイズ、惑星大気組成・量、惑星磁場強度、等々 (今日は下線部分に特に着目)
    - 地球型惑星(過去含む)、系外惑星
  - （小天体、プラズマ-固体相互作用）
- 初期火星の磁気圏-電離圏MHDシミュレーション [S. Sakai et al.]
- 火星上層大気のDSMCシミュレーション [K. Terada et al.]

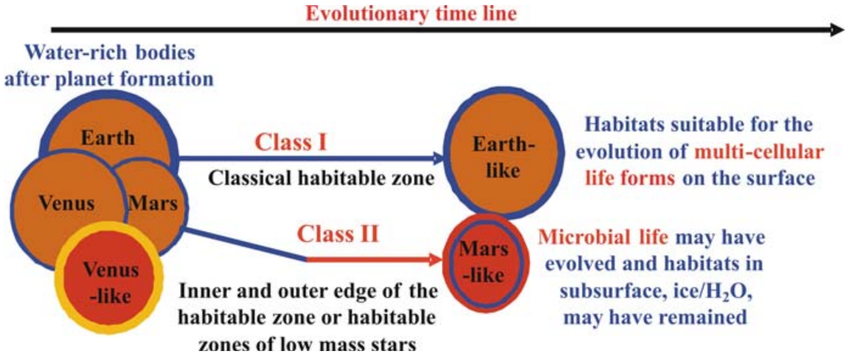
を中心に紹介

イントロダクション

- 生命環境の進化（生命圏の誕生・持続に至る条件の解明）は、惑星科学の中心課題となりつつある。

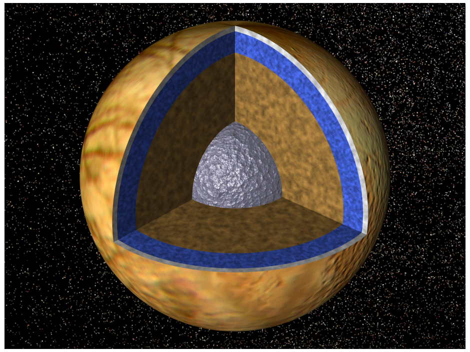
- 生命存在可能領域（HZ）
  - Class I
    - 地球類似惑星（古典的HZ）
  - Class II
    - 初期はClass Iと類似。その後の進化が異なる。
  - Class III
    - 地下海
  - Class IV
    - 表層＆地下海

水や大気の安定性



[Lammer et al., 2009]

氷衛星探査：
JUICE, Europa Clipper,
Ocean Worlds



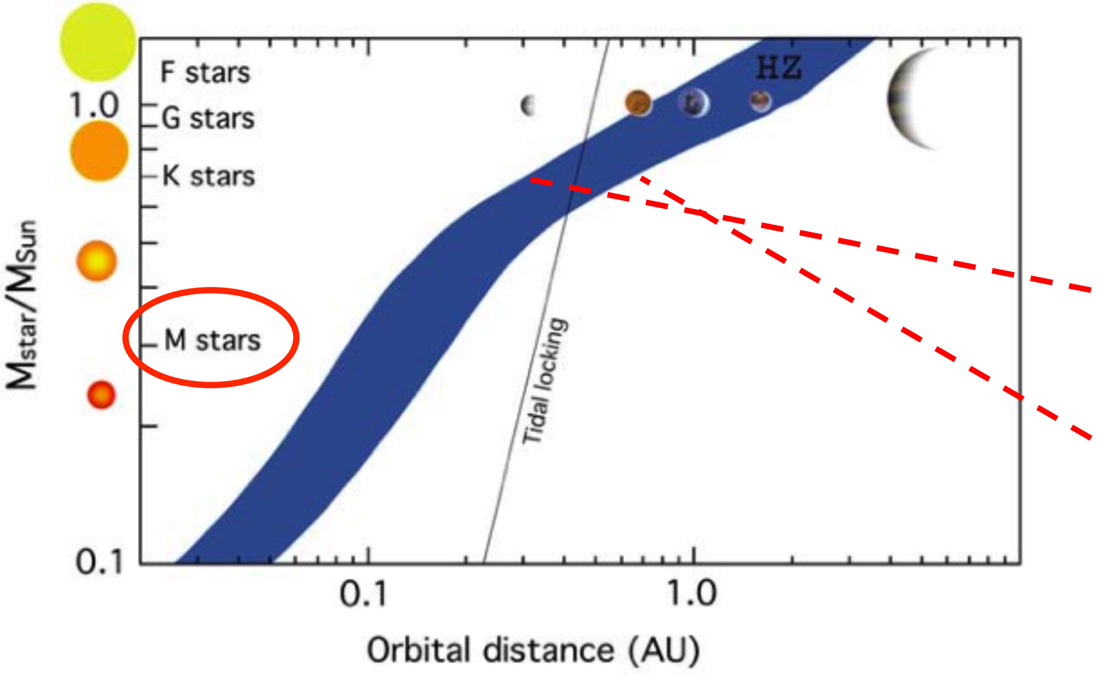
水や大気の安定性

- 鍵となるパラメータは
  - 中心星(可視・紫外)放射強度、惑星サイズ、惑星大気組成・量、惑星磁場強度、等々

連続的生存可能領域(CHZ)の古典的定義:

地球類似の惑星が、表面に液体の水を保持できる領域。

現在の太陽系では0.95-1.37 AU

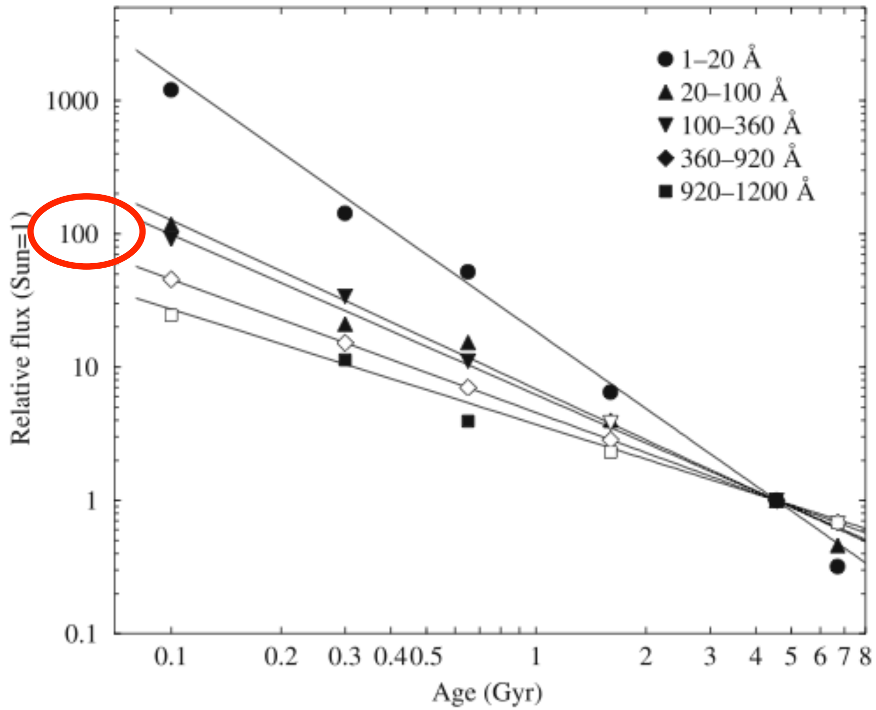


内側限界:
宇宙空間への流出(暴走温室状態)

外側限界:
CO_2の凝結で温室効果が維持不可

水や大気の安定性

- 鍵となるパラメータは
  - 中心星(可視・紫外)放射強度、惑星サイズ、惑星大気組成・量、惑星磁場強度、等々

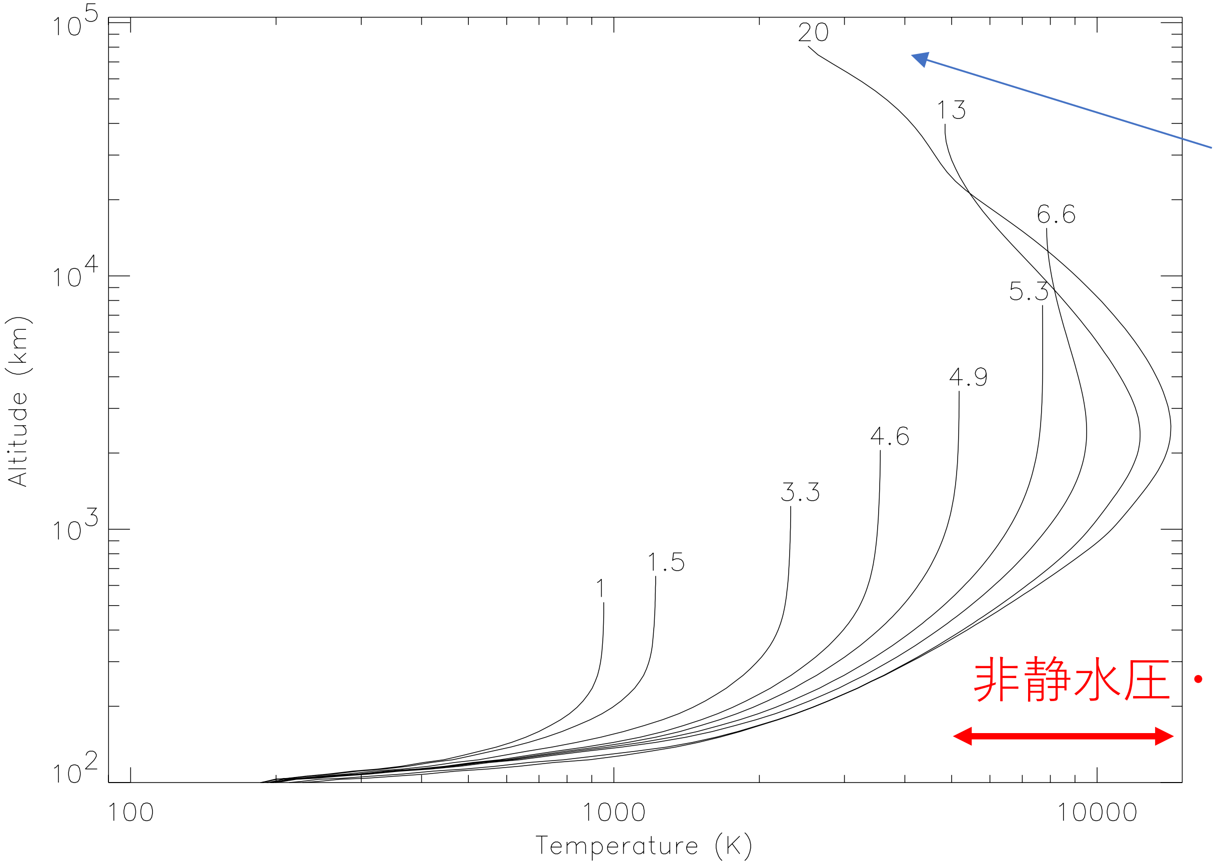


様々な年代のG型主系列星における
X線〜紫外放射 [Ribas et al., 2005]

過去の太陽紫外放射、太陽風は強かった。

- 自転速い⇒内部の差動回転大
  ⇒磁場生成大⇒表面活動大
  ⇒激しいコロナ、フレア、太陽風

初期地球大気は大膨張？

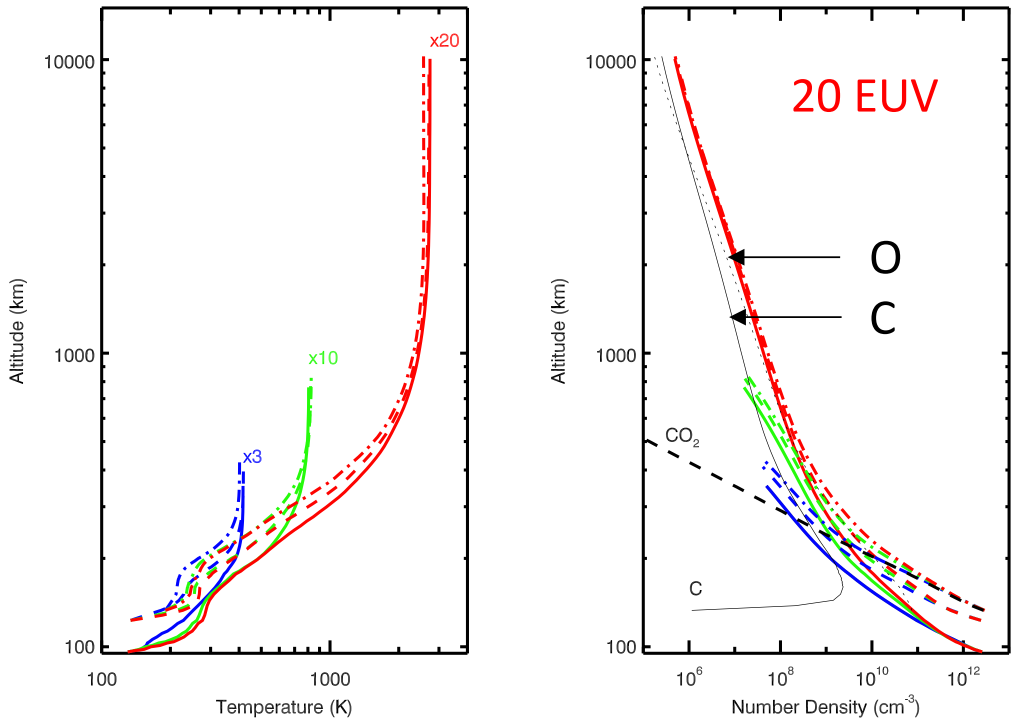


外圏底高度
（上側境界でジーンズ散逸速度を仮定）

非静水圧・膨張

- 地球熱圏モデル [Tian et al., 2008]
  - 太陽EUV放射が6倍（約35億年前）で外圏底が10,000kmに？
  - 太陽EUV放射が20倍（約41億年前）で外圏底が100,000kmに？？
  - 膨張、断熱冷却が重要となる

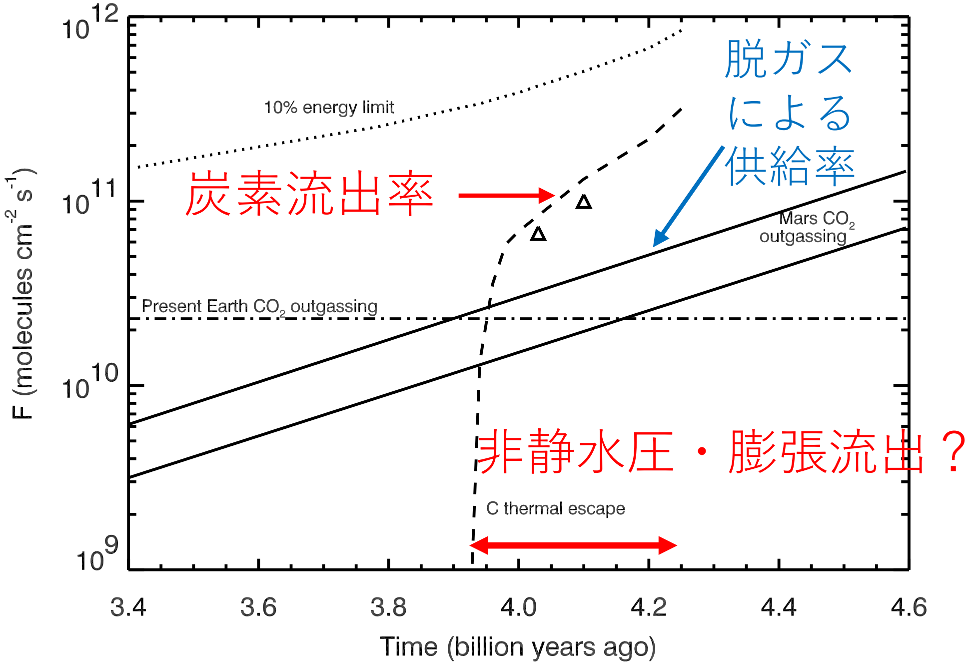
火星は初期数億年間、大気を保持できなかった？



20 EUV

O

C



脱ガスによる供給率

炭素流出率

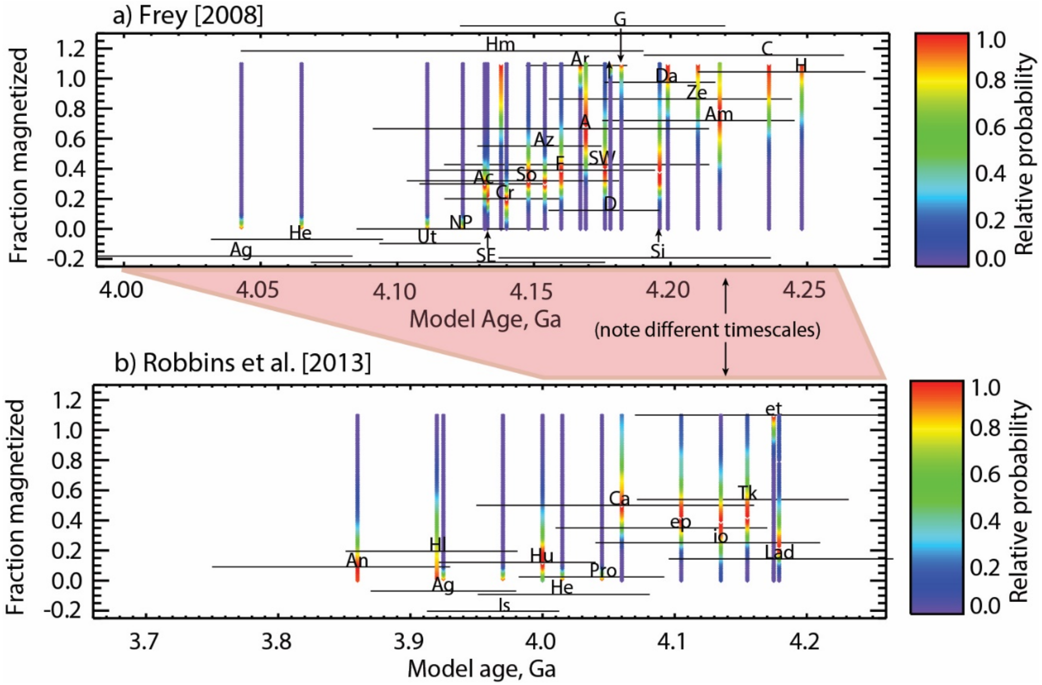
非静水圧・膨張流出？

Tian et al. [2009]

- 約40億年前（~20 EUV）以前に酸素や炭素が大規模流出？
- 初期数億年間は大気を保持できず、その後に大気を形成？？

初期火星の磁場

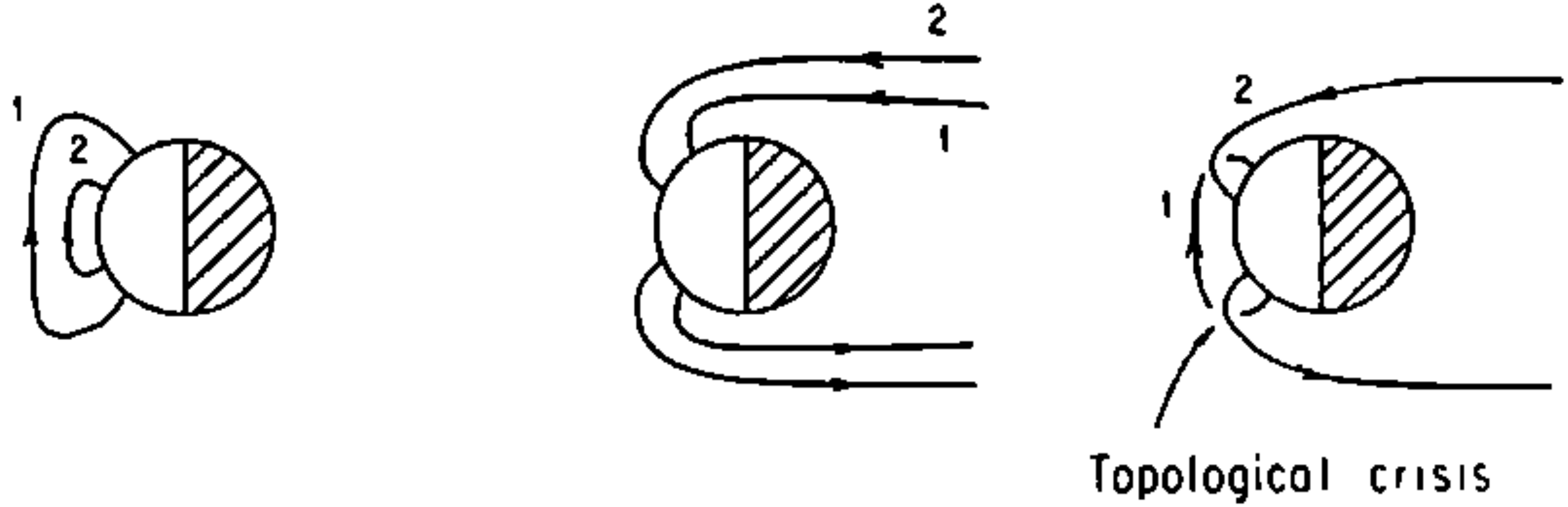
- クレータ磁場より、火星のダイナモは40-41億年前に停止 [Lillis et al., 2013]
- 表面磁場強度は~5000nT?? [Weiss et al., 2008]
- 磁気圏は大気を守ったのか？
- それとも大気の流出を促したのか？



[Lillis et al., 2013]

初期火星磁気圏

- そもそも火星は、地球のような磁気圏を持てるのか？
  - 厚い大気（電離圏）と弱い磁場を持つ惑星では、電離圏側の対流を駆動しにくく、磁力線が交差してしまう？



[Kennel and Coroniti, 1989]

初期火星磁気圏

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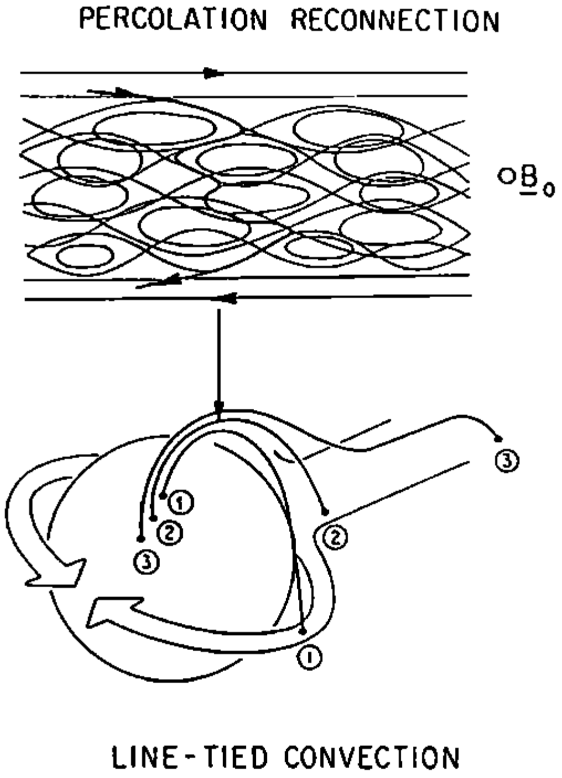


電離圏の応答時間は

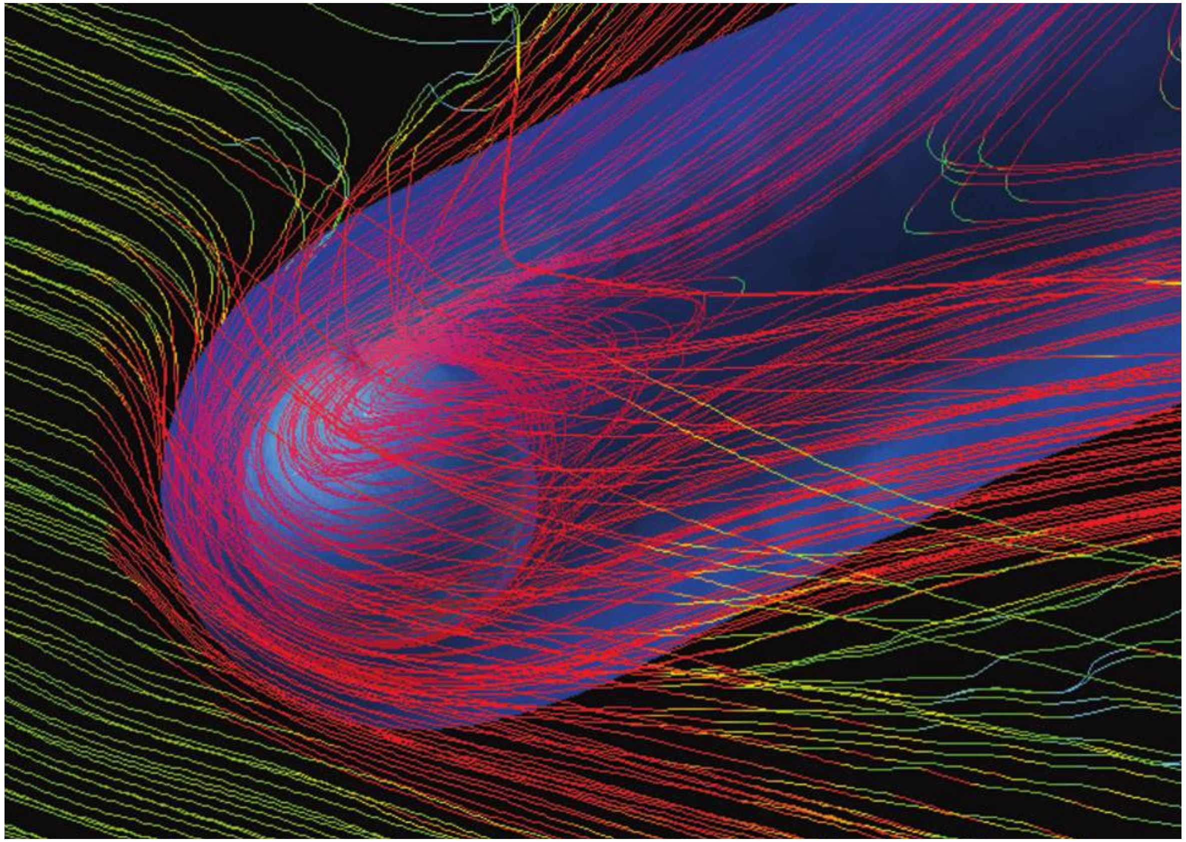
$\Delta=16\pi^2(\gamma+2)\mu\lambda\Sigma_P/c^2D^2\Lambda(\Delta B_{CF})$

地球では Δ=20分（Σ_P=10 mho）、
火星でB_{surf}=60nTでは Δ~6日（Σ_P=3000 mho）

[Kennel and Coroniti, 1989]

初期火星の磁気圏-電離圏MHD シミュレーション [S. Sakai et al.]

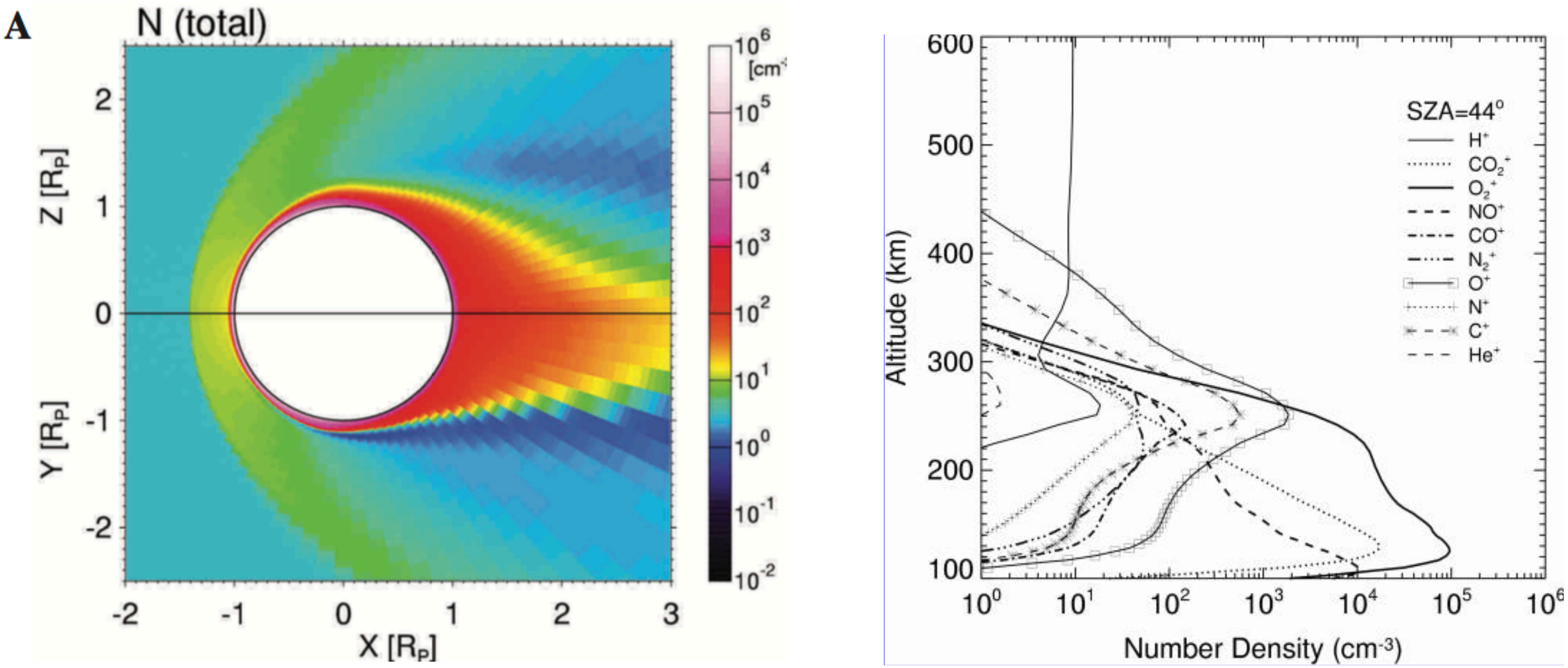
- Terada et al. [2009]の太陽風-火星電離圏MHDシミュレーションに、固有磁場を与える



100 EUV ~ 45億年前の火星。双極子磁場無し [Terada et al., 2009]

初期火星の磁気圏-電離圏MHDシミュレーション [S. Sakai et al.]

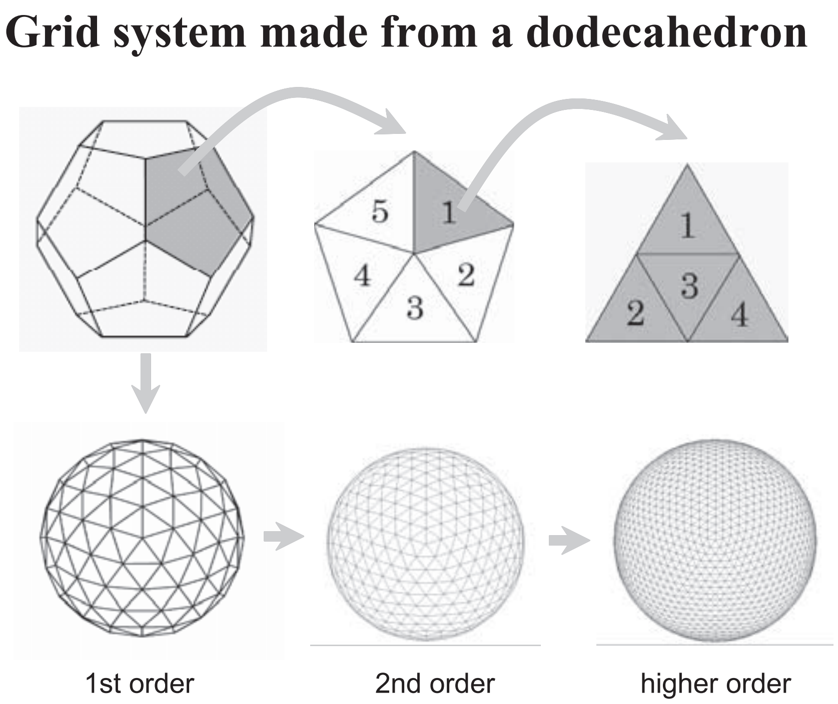
- Terada et al. [2009]の太陽風-火星電離圏MHDシミュレーションに、固有磁場を与える
  - 第一ステップとして、電離圏パラメータは現在の火星と同一



現在の火星。双極子磁場無し [Terada et al., 2009]

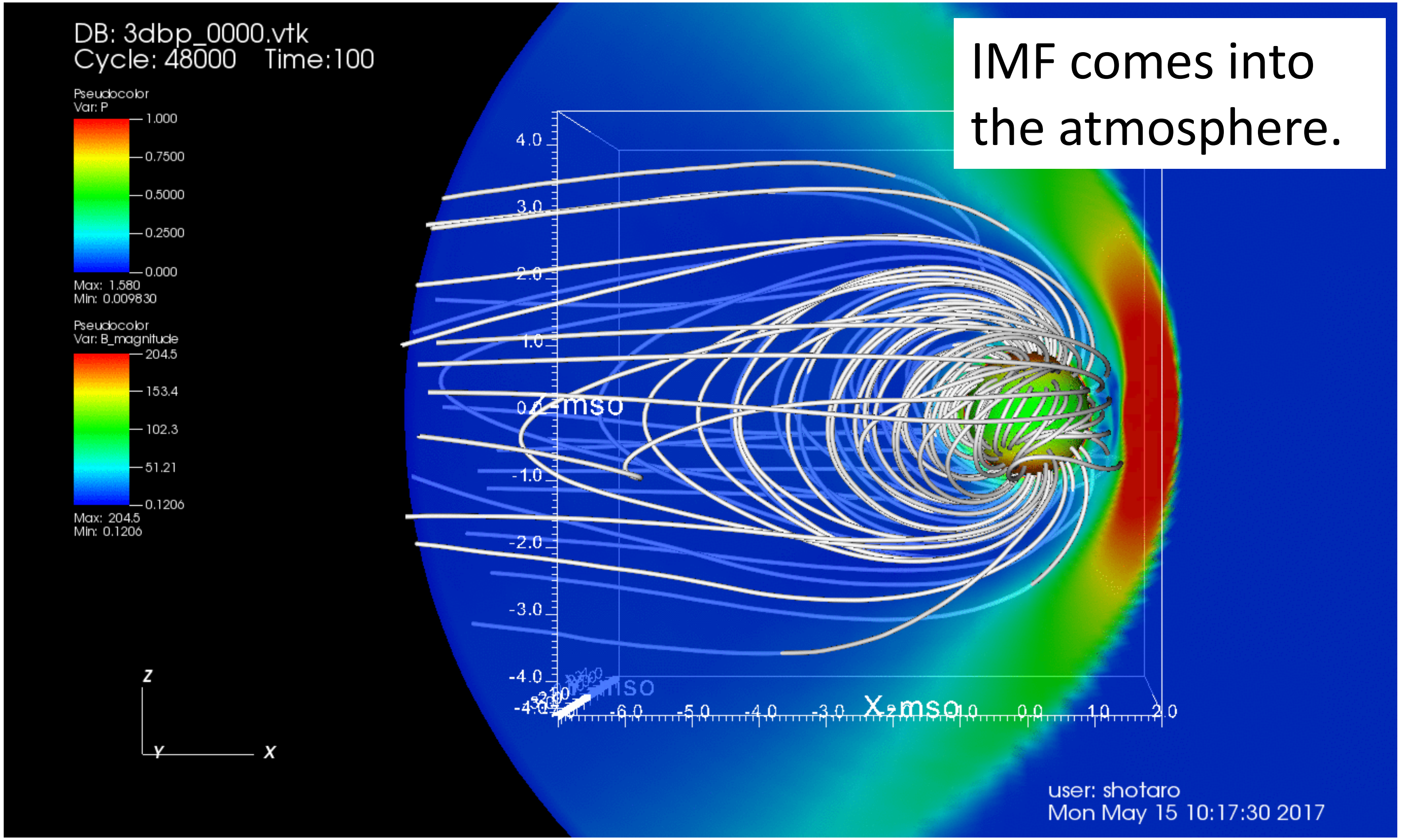
初期火星の磁気圏-電離圏MHD シミュレーション [S. Sakai et al.]

- 3次精度TVDスキーム[Tanaka, 1994]を用いた3次元多成分MHDシミュレーション。
- CO_2^+, O_2^+, O^+, H^+などの14イオンの光化学反応を含む。
- 赤道表面で100 nTの双極子磁場を与えた。



シミュレーションで
用いた非構造格子
[Moriguchi et al., 2008]

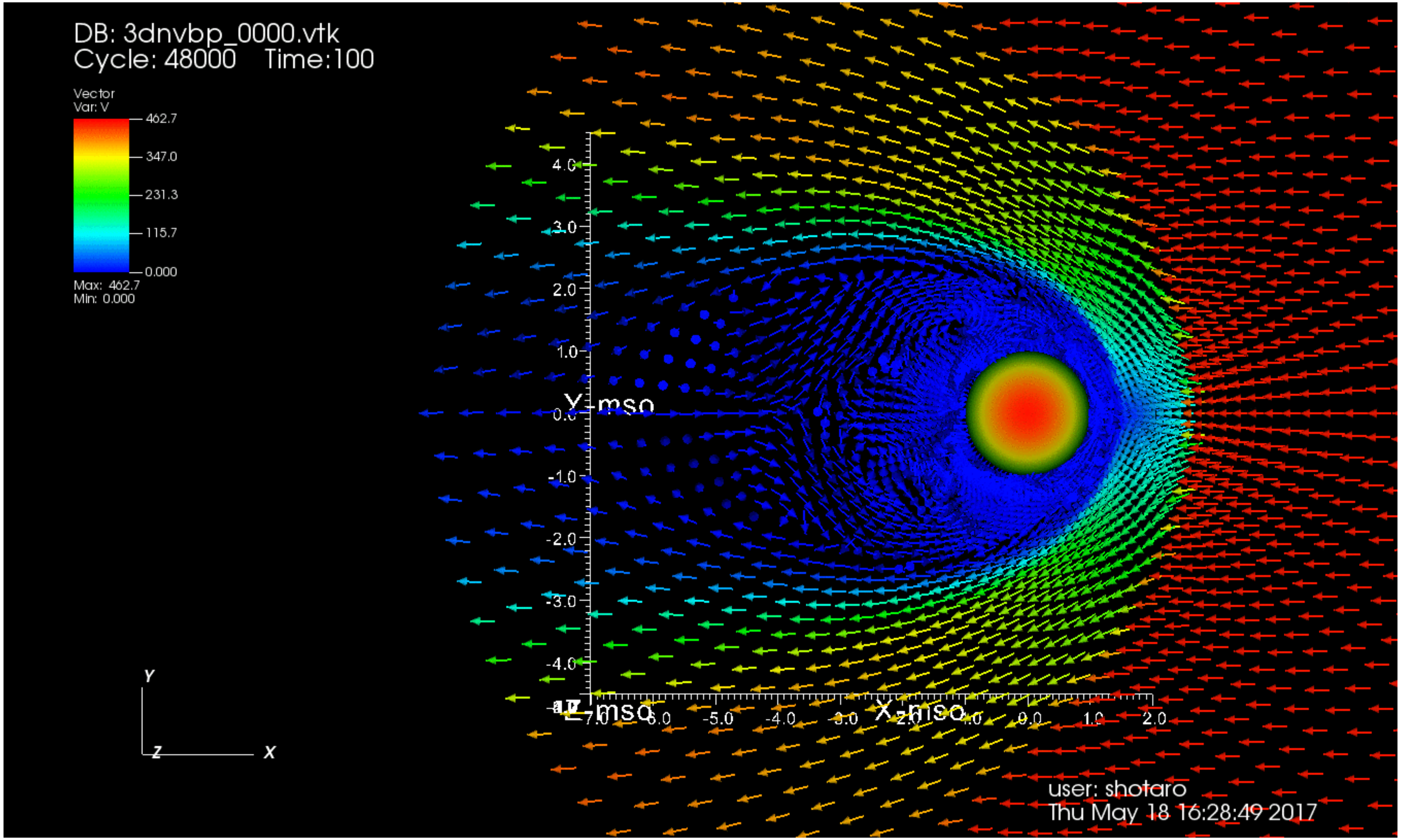
初期火星の磁気圏-電離圏MHD シミュレーション [S. Sakai et al.]



IMF comes into the atmosphere.

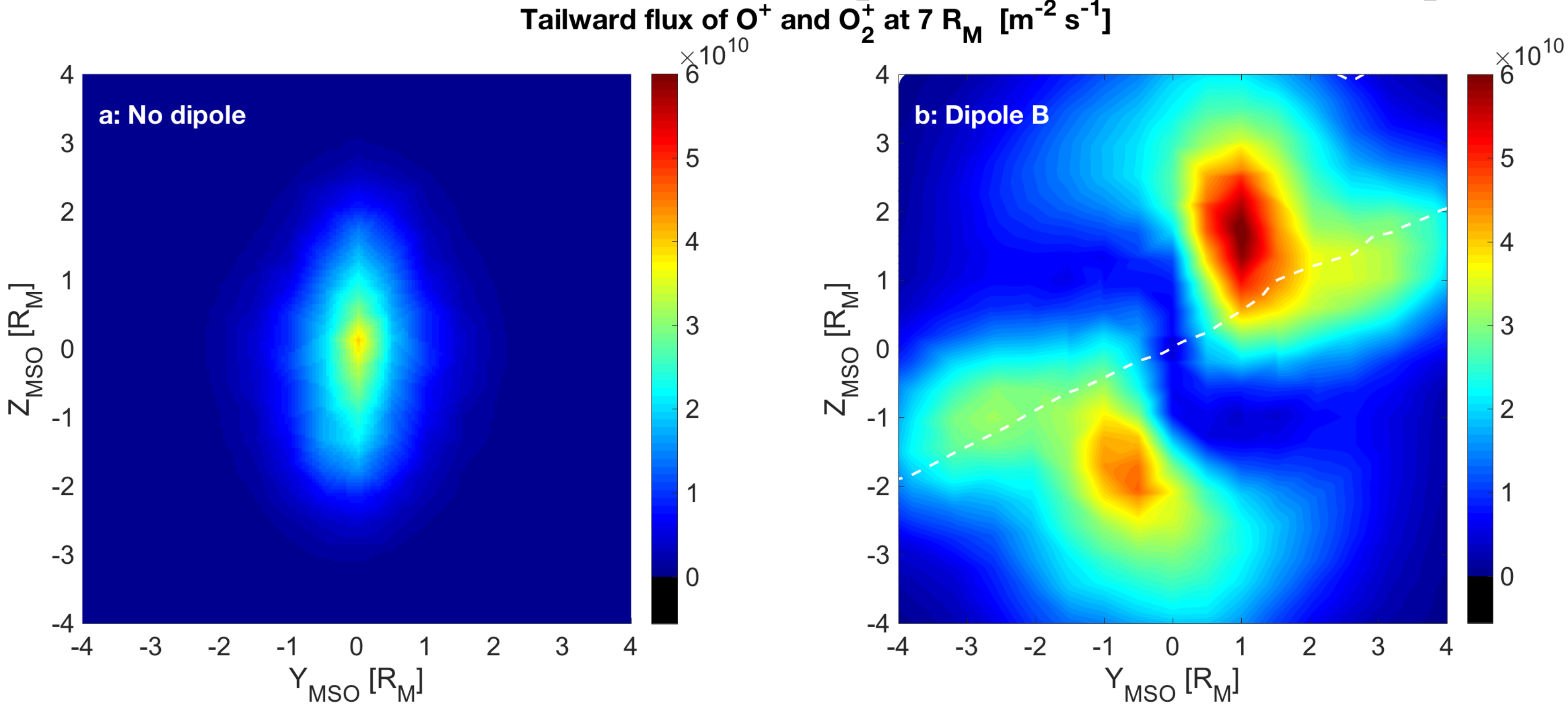
赤道表面で100 nTの双極子磁場。IMFはパーカースパイラル。
磁力線と圧力の図 [S. Sakai et al., JpGU 2017]

初期火星の磁気圏-電離圏MHD シミュレーション [S. Sakai et al.]



x-y面での速度ベクトル

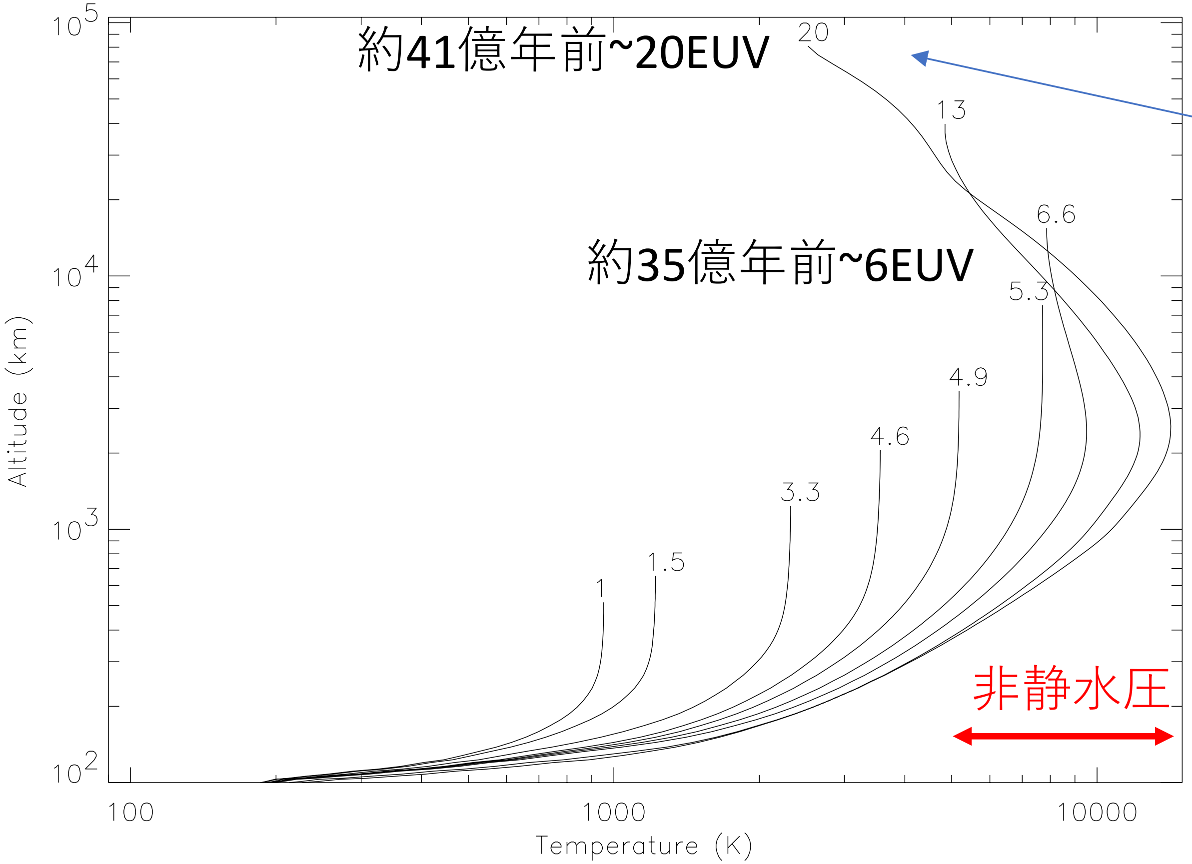
初期火星の磁気圏-電離圏MHD シミュレーション [S. Sakai et al.]



- 反太陽向き$O^+ + O_2^+$フラックス（$X=-7R_M$）
  - 双極子磁場なし（左図）
    - 火星の影にピークが1つ
  - 双極子磁場あり（右図）
    - 高緯度側にピークが2つ。より多くのイオンが流出。少なくとも本計算では、磁場は大気を守っていない。

初期地球の膨張熱圏モデルは妥当か？

初期地球の膨張熱圏モデル



約41億年前~20EUV

約35億年前~6EUV

外圏底高度
（上側境界でジーンズ散逸速度を仮定）

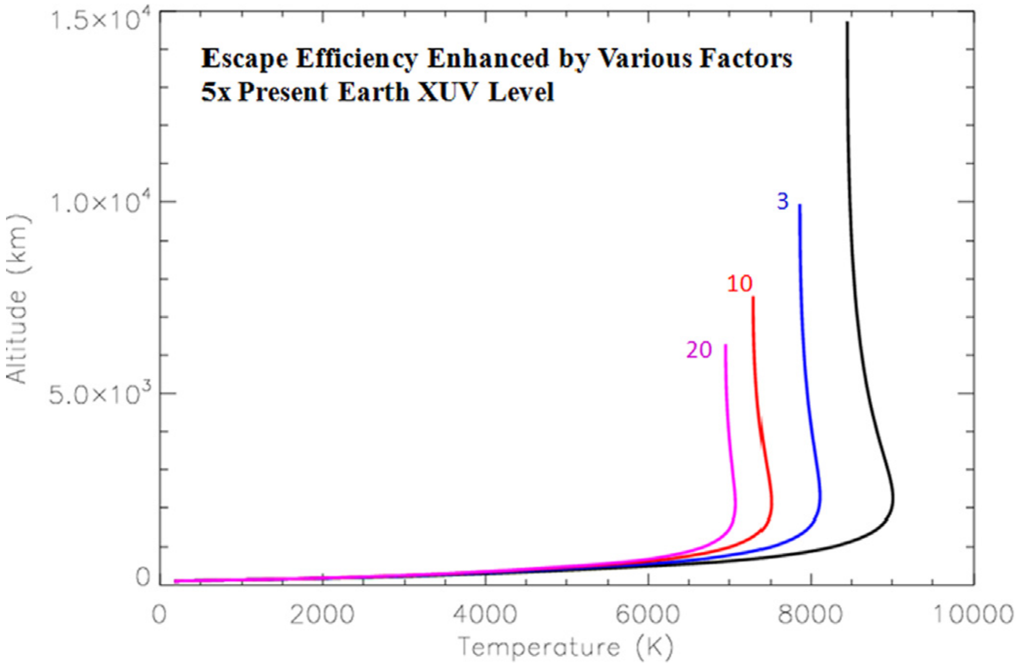
非静水圧・膨張

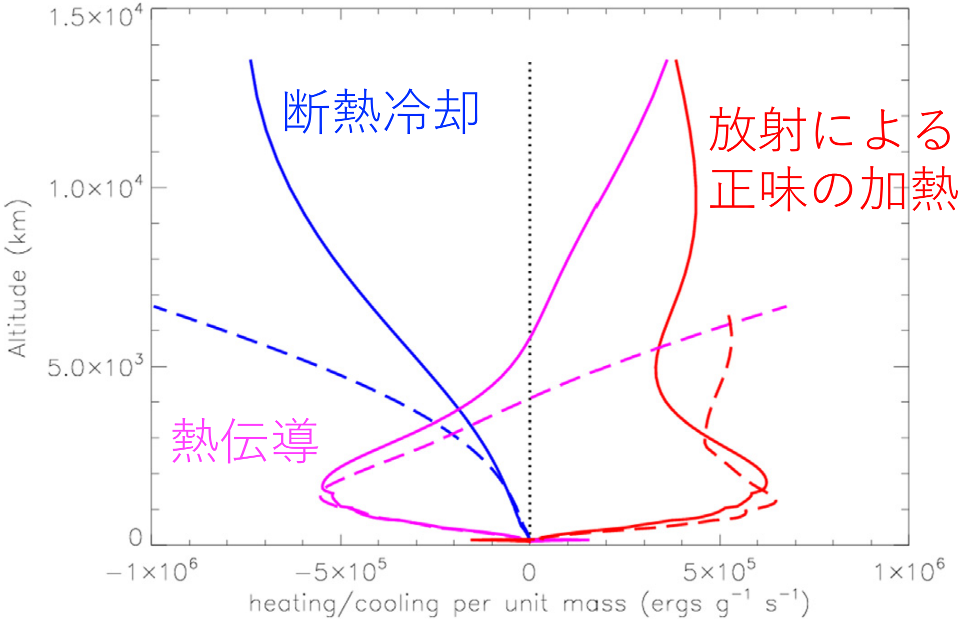
[Tian et al., 2008]

膨張熱圏モデルの問題点:
上側境界条件の影響

Tian [2013]
非熱的散逸などの効果を考慮して、
上側境界からの散逸速度を3, 10, 20倍に

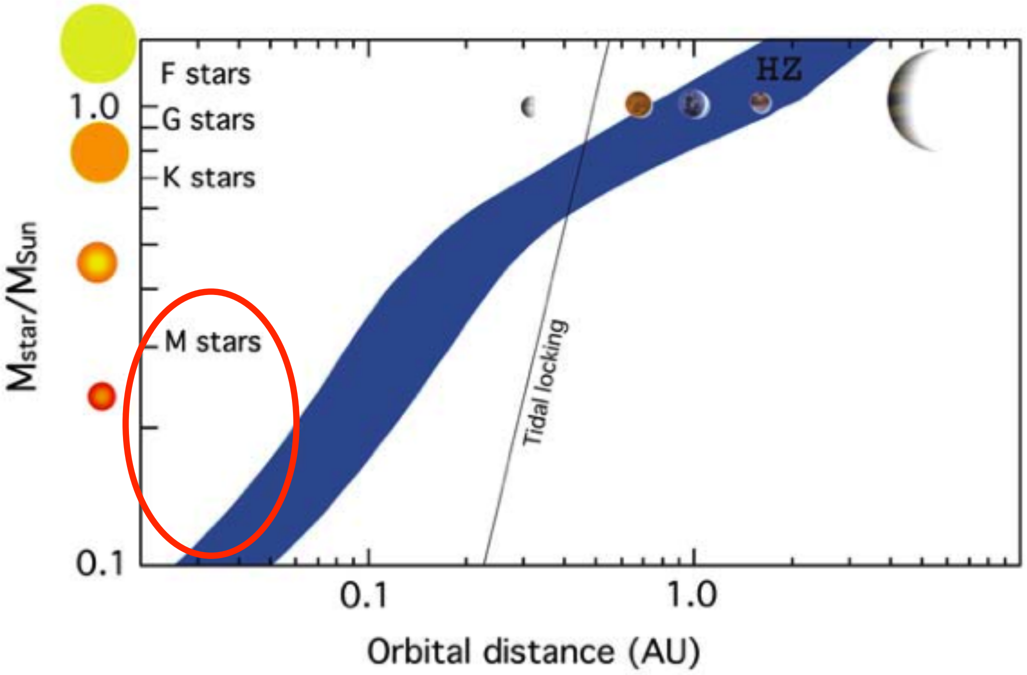
加熱・冷却項
実線は非静水圧時（左図の黒線）





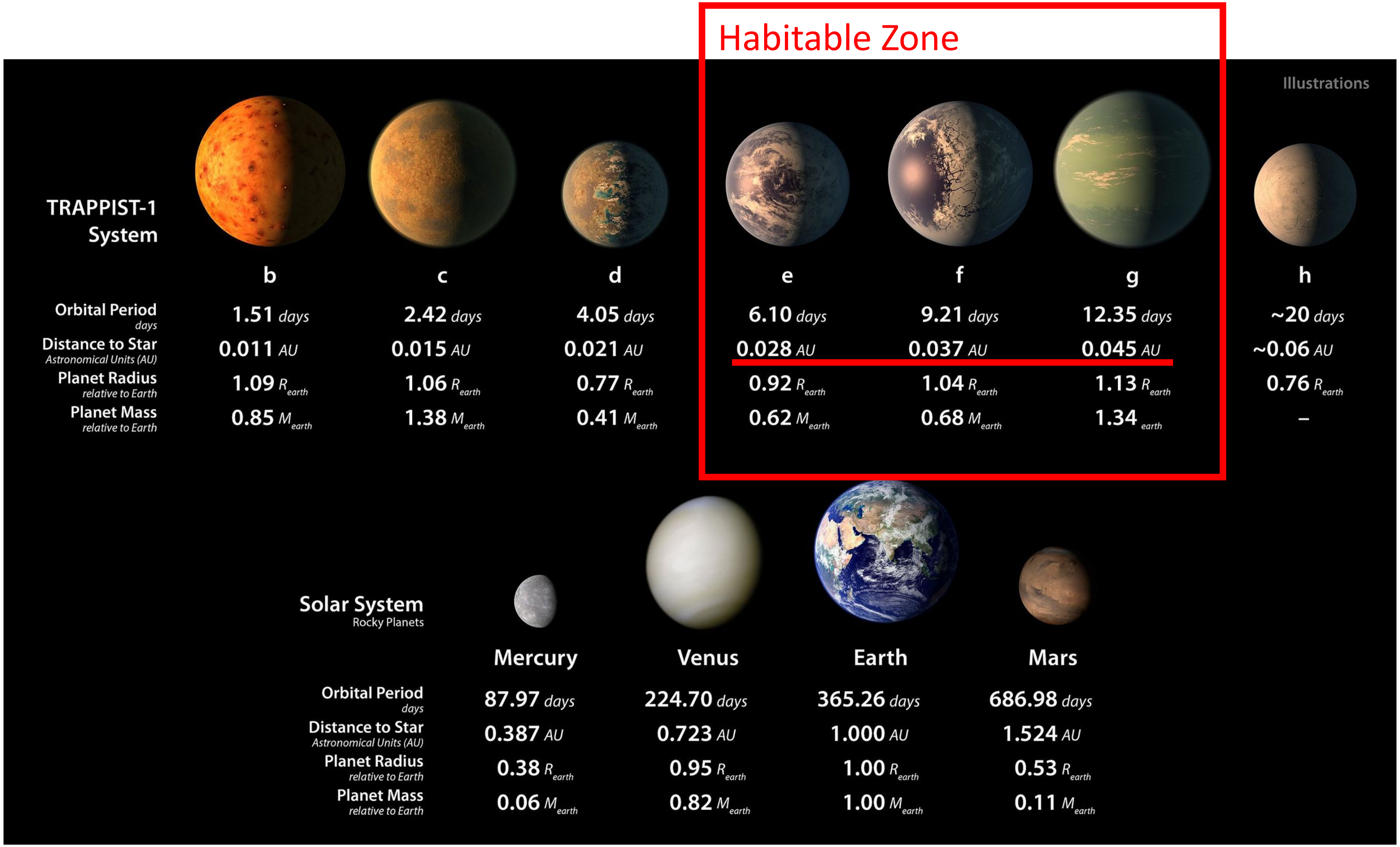
境界条件を変えると、
大気はあまり膨らまない？

膨張熱圏モデルの問題点



- 実はこれは大きな問題。
- ハビタブルゾーンに入る惑星が見つかりつつあるが、その殆どがM型星周りの惑星。
- 中心星に近く、相対的に紫外放射が強い場合が多い。
- 同様に大気が膨張している可能性がある。

TRAPPIST-1 system



Habitable Zone

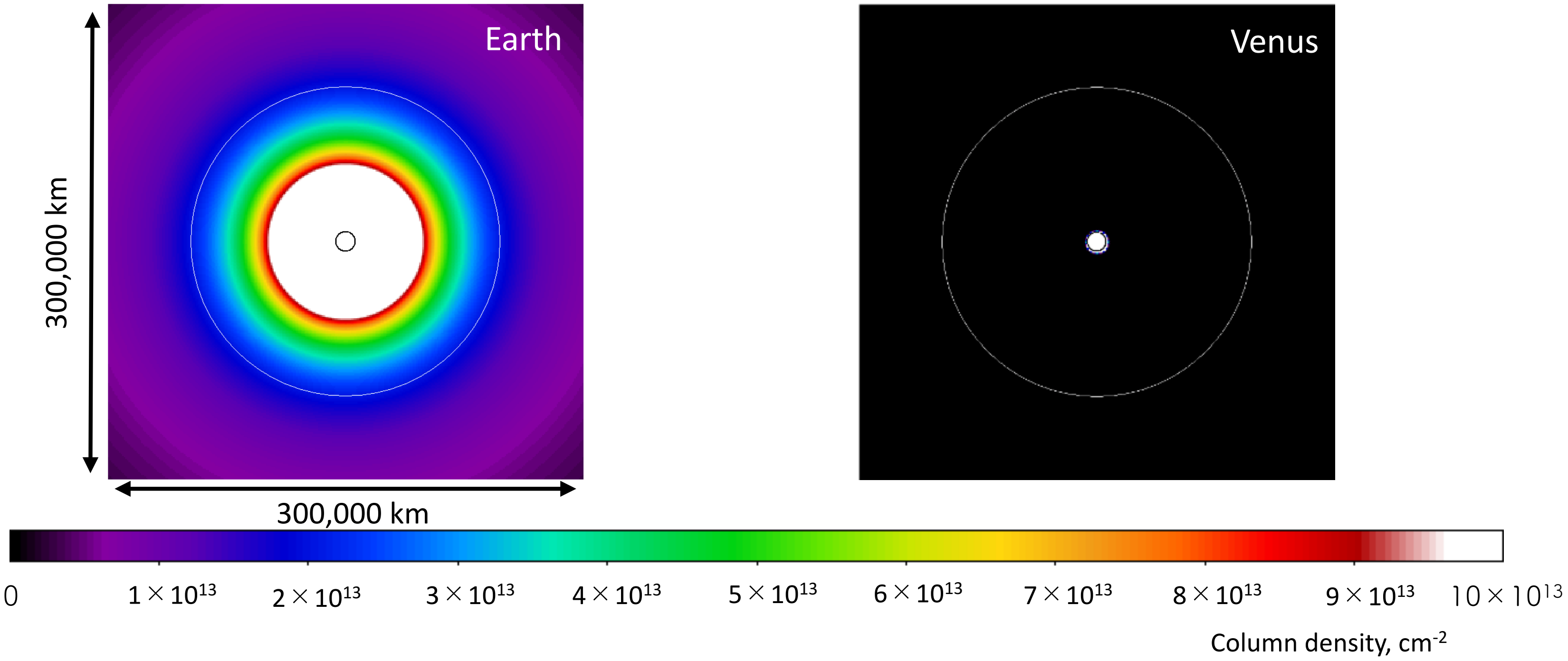
TRAPPIST-1 System

	b	c	d	e	f	g	h
Orbital Period *days*	1.51 *days*	2.42 *days*	4.05 *days*	6.10 *days*	9.21 *days*	12.35 *days*	~20 *days*
Distance to Star *Astronomical Units (AU)*	0.011 *AU*	0.015 *AU*	0.021 *AU*	0.028 *AU*	0.037 *AU*	0.045 *AU*	~0.06 *AU*
Planet Radius *relative to Earth*	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}	0.92 R_{earth}	1.04 R_{earth}	1.13 R_{earth}	0.76 R_{earth}
Planet Mass *relative to Earth*	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}	0.62 M_{earth}	0.68 M_{earth}	1.34 $_{earth}$	–

Solar System Rocky Planets

	Mercury	Venus	Earth	Mars
Orbital Period *days*	87.97 *days*	224.70 *days*	365.26 *days*	686.98 *days*
Distance to Star *Astronomical Units (AU)*	0.387 *AU*	0.723 *AU*	1.000 *AU*	1.524 *AU*
Planet Radius *relative to Earth*	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass *relative to Earth*	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}

Oxygen thermosphere/exosphere (10 EUV)



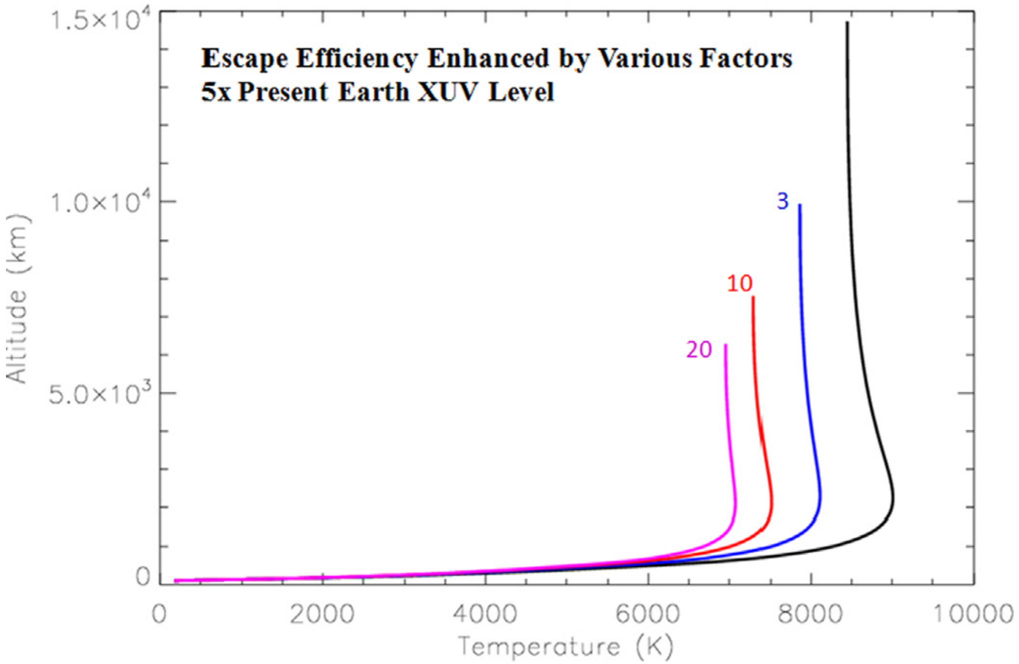
- Black circle : Planet,　White circle : Star (Proxima Centauri)
- Earth-like case : Optically thick oxygen to ~8R_e（1×10^{14} cm^{-2} ~ τ=1）

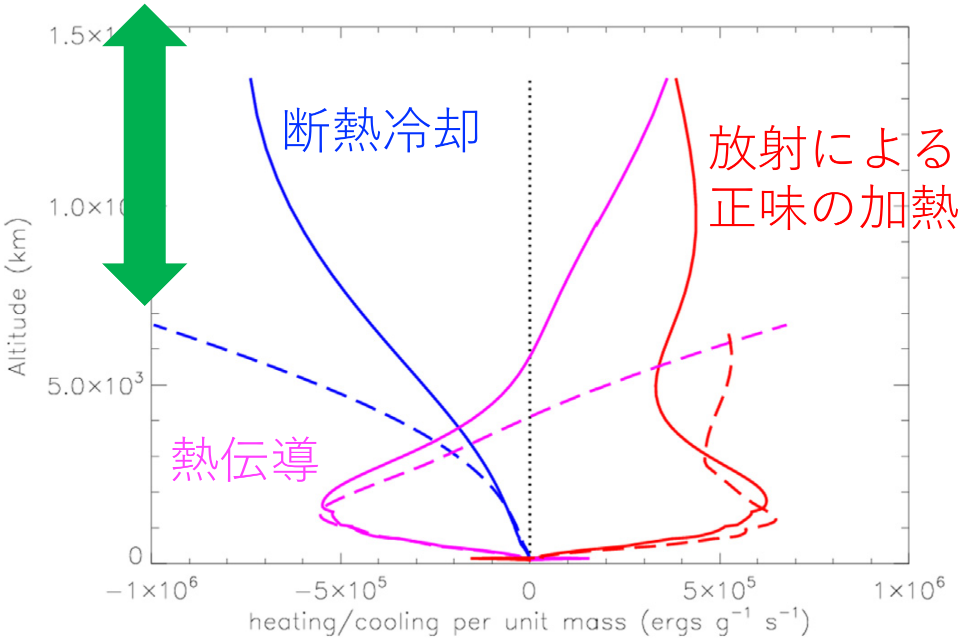
（亀田 et al. 系外惑星紫外分光WG資料より）

膨張熱圏モデルの問題点:
上側境界条件の影響

Tian [2013]
非熱的散逸などの効果を考慮して、
上側境界からの散逸速度を3, 10, 20倍に

衝突大気から無衝突大気に遷移。
流体近似が成り立たなくなる。

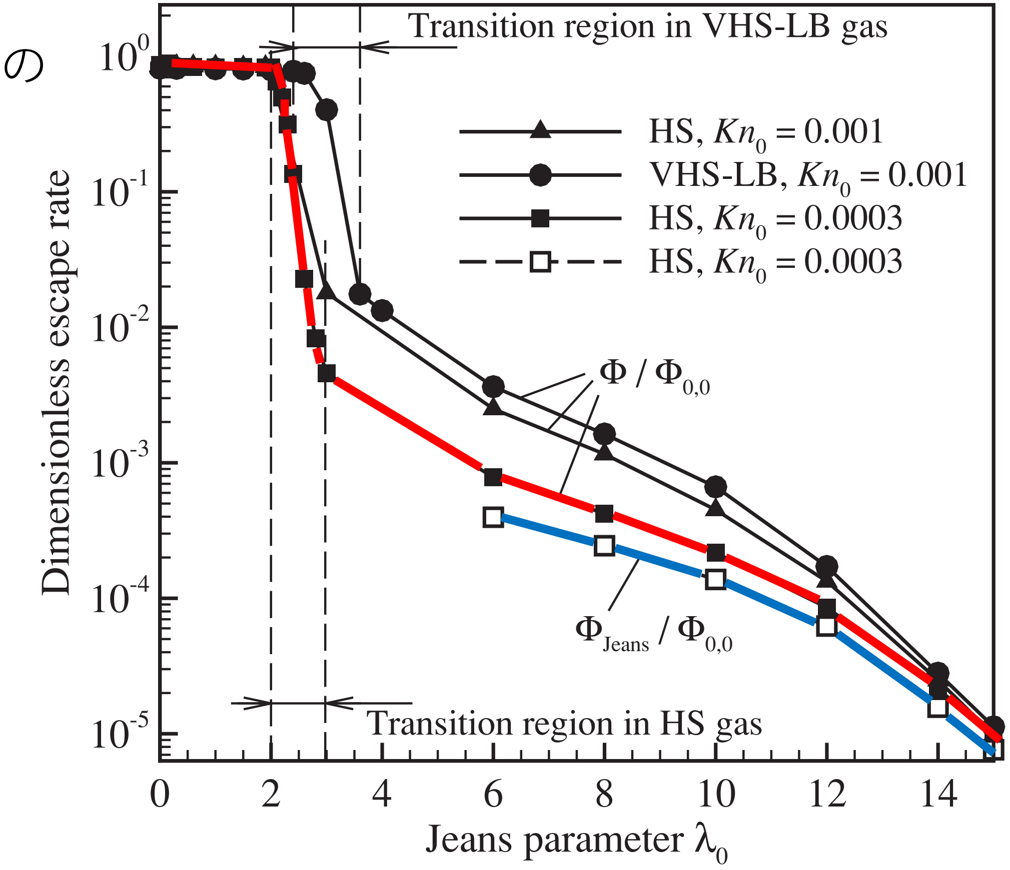




境界条件を変えると、
大気はあまり膨らまない？

全粒子(DSMC)モデル

Volkov et al. [2011]の
DSMCモデル



HS : Hard Sphere原子モデル
VHS : Variable Hard Sphere分子モデル

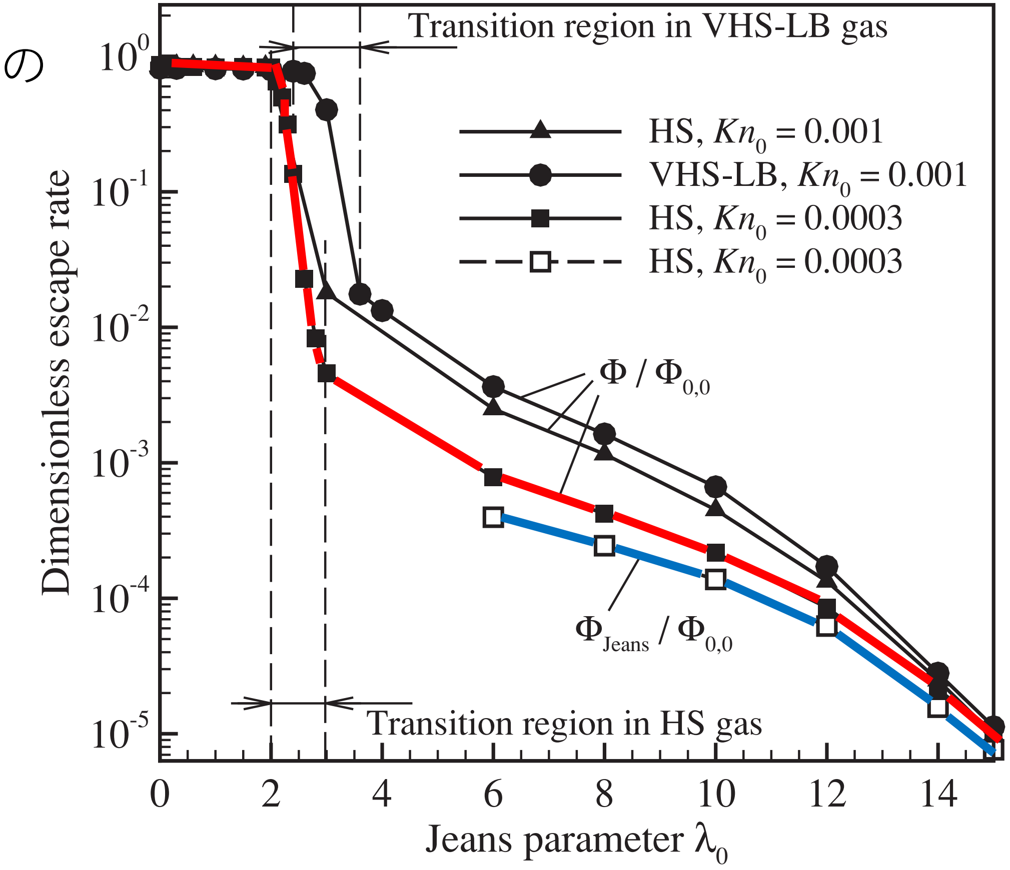
DSMCモデル

膨張しない場合の解析解

- 膨張しない状態（hydrostatic状態）が続く
  - 膨張状態（slow hydrodynamic escape）はほとんど起こらない？
  - Hydrodynamic escapeへの切り替えは急激

全粒子(DSMC)モデル

Volkov et al. [2011]の
DSMCモデル



HS : Hard Sphere原子モデル
VHS : Variable Hard Sphere分子モデル

DSMCモデル

膨張しない場合の解析解

ただし、Volkovモデルは、

- 加熱は下端のみ
- 放射冷却や光化学反応は考慮せず

→　これらを考慮したDSMCモデルが必要 [K. Terada et al., 2016]

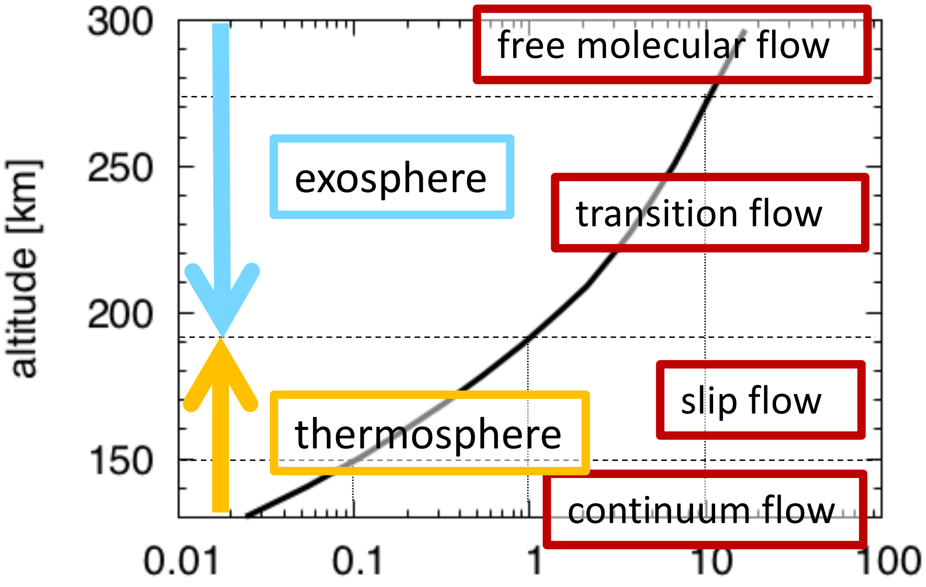
熱圏・外圏DSMCモデルの開発 [K. Terada et al., 2016]と、衛星観測との比較

Full-particle DSMC simulations

Boltzmann equation

$$\frac{\partial}{\partial t}(nf) + c\frac{\partial}{\partial r}(nf) + F\frac{\partial}{\partial c}(nf) = \int_{-\infty}^{\infty}\int_{0}^{4\pi} n^2(f*f_1*-ff_1)c_r\sigma d\Omega dc_1$$

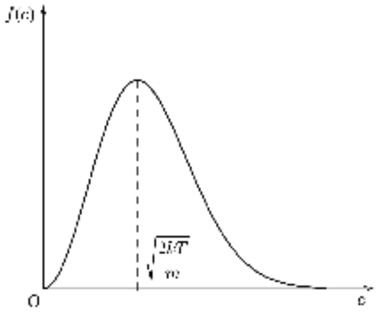
n : number density, *f* : velocity distribution function, *c* : molecular velocity, c_r : relative molecular speed, *F* : external force per unit mass, subscript * : post-collision values, *f* and f_1 : distribution functions of two different types of molecules of class *c* and c_1, respectively, σ : collision cross-section, *t* : time, *r* : physical space, *Ω* : solid angle



Knudsen number
(mean free path/scale height)

continuum flow

- Energy of molecules are distributed according to Maxwell distribution

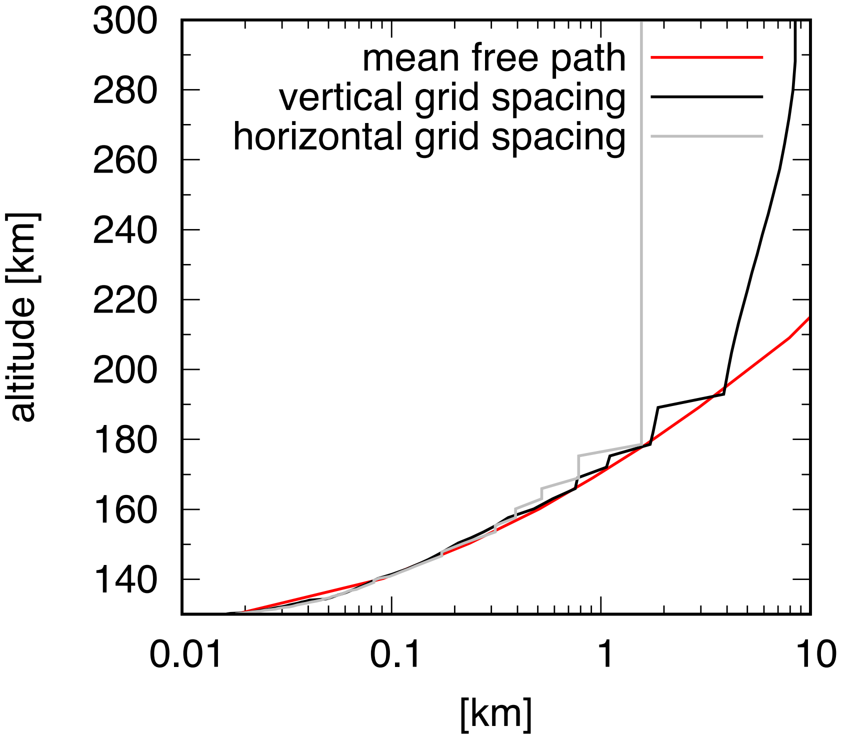


Navier-Stokes equations

- The first order moment of *f*

Full-particle DSMC simulations

- A thermosphere-exosphere DSMC model [K. Terada et al., 2016]
  - A full-particle code
  - 2-D version is used in this study
- Grid spacing
  - Δx = 10m ~ 1km
  - Δz = 10m ~ 10km
  - (l_{mfp} = 10m ~ 10km)
- No. of particles in a cell
  - >~100 particles/cell



MD simulation

numerical integration scheme

Verlet algorithm

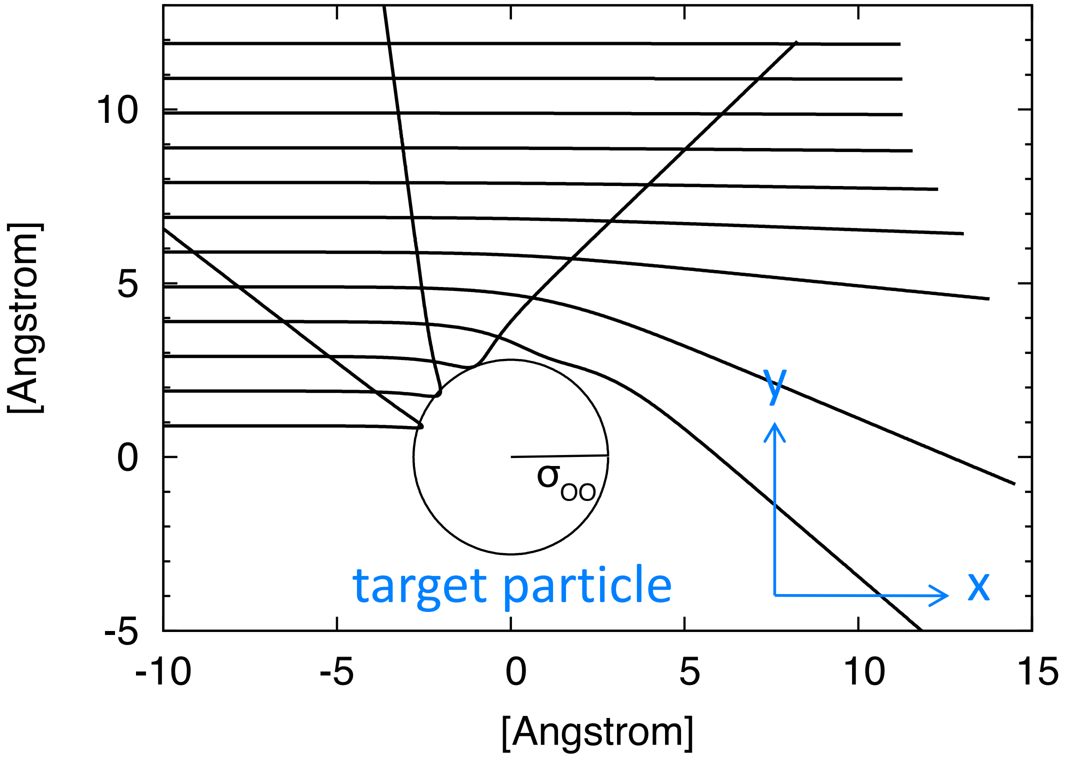
interval of time

$\Delta t = 3 \times 10^{-18} \sim 1 \times 10^{-17}$ s

cutoff point

$F \leq 1.0 \times 10^{-19}$ N

Calculated orbit of O interacting with O
(collision energy = 0.03 eV)



deflection angle

$$\chi = \cos^{-1}\left(\sqrt{\left(v_x - v_{xGC}\right)^2} \Big/ \sqrt{\left(v_x - v_{xGC}\right)^2 + \left(v_y - v_{yGC}\right)^2}\right)$$

$v_x, v_{xGC}, v_y, v_{yGC}$:
value at cutoff point

diffusion cross section

$$\sigma_M \equiv 2\pi \int_0^{\infty} \left(1 - \cos\chi\right) b\,db \approx 2\pi \sum_{b=0}^{15\times10^{-10}} \left(1 - \cos\chi\right) b\Delta b$$

viscosity cross section

$$\sigma_\mu \equiv 2\pi \int_0^{\infty} \left(1 - \cos^2\chi\right) b\,db \approx 2\pi \sum_{b=0}^{15\times10^{-10}} \left(1 - \cos^2\chi\right) b\Delta b$$

$\Delta b = 1.0 \times 10^{-13}$ m

DSMC collision model

Variable sphere model [Matsumoto, 2002]

$$\chi = \begin{cases} \chi_0 & (b \leq d) \\ 0 & (b > d) \end{cases}$$

$$\begin{pmatrix} \chi_0 & : \text{ scattering angle} \\ b & : \text{ impact parameter} \end{pmatrix}$$

$$\sigma_M = 2\pi \int_{\chi=0}^{\chi=\infty} (1 - \cos\chi) b\,db = (1 - \cos\chi_0)\pi d^2$$

$$\sigma_\mu = 2\pi \int_{\chi=0}^{\chi=\infty} (1 - \cos^2\chi) b\,db = (1 - \cos^2\chi_0)\pi d^2$$

This collision model is simple and efficient, are both diffusion and viscosity cross-sections are consistent with those of the intermolecular potential.

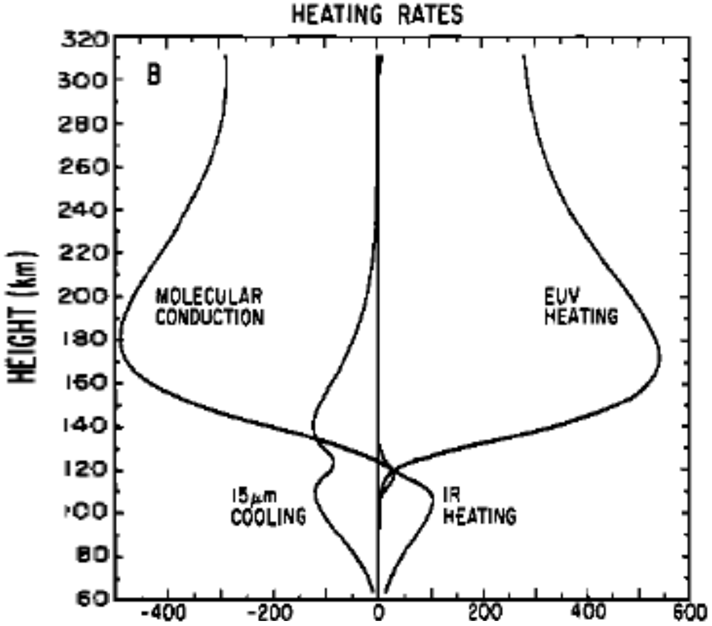
For intermolecular potential (Lennard-Jones(6-12) & Universal potentials), solar EUV heating, CO_2 15 μm radiative cooling, etc.,
see K. Terada et al. [2016].

加熱過程と冷却過程

<u>Heating mechanism</u>
dissociative recombination of O_2^+
other minor heating sources are included using a macroscopic heating efficiency

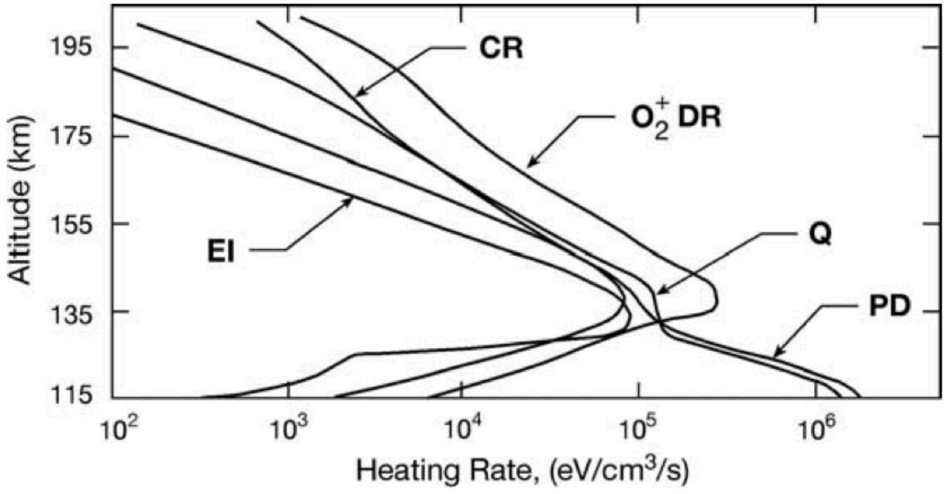
<u>Cooling mechanism</u>
molecular conduction
CO_2 15-μm cooling [Gordiets et al., 1982]

Heat budget of the Martian atmosphere



DEGREES PER DAY [K/day]
[Bougher et al., 1988]

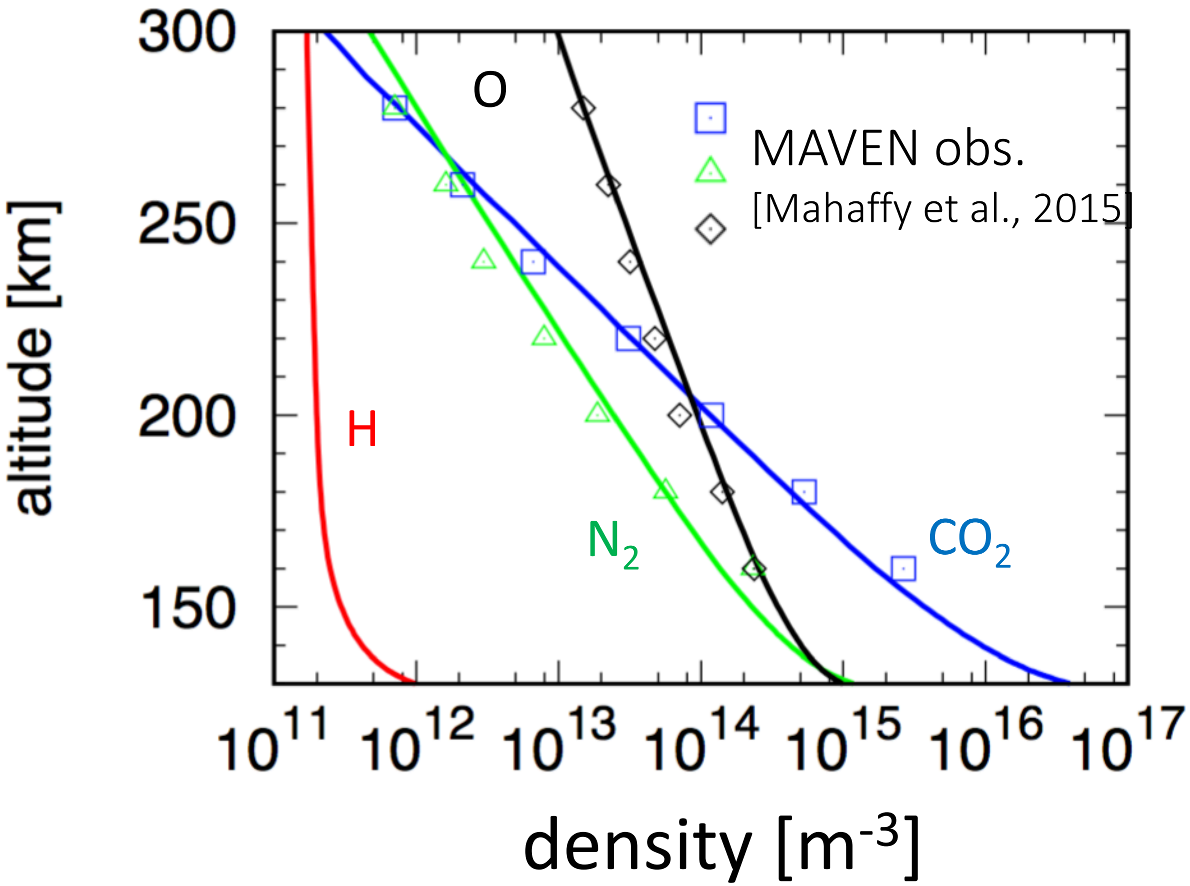
Heating rates in the Venus thermosphere



[Fox et al., 2008]

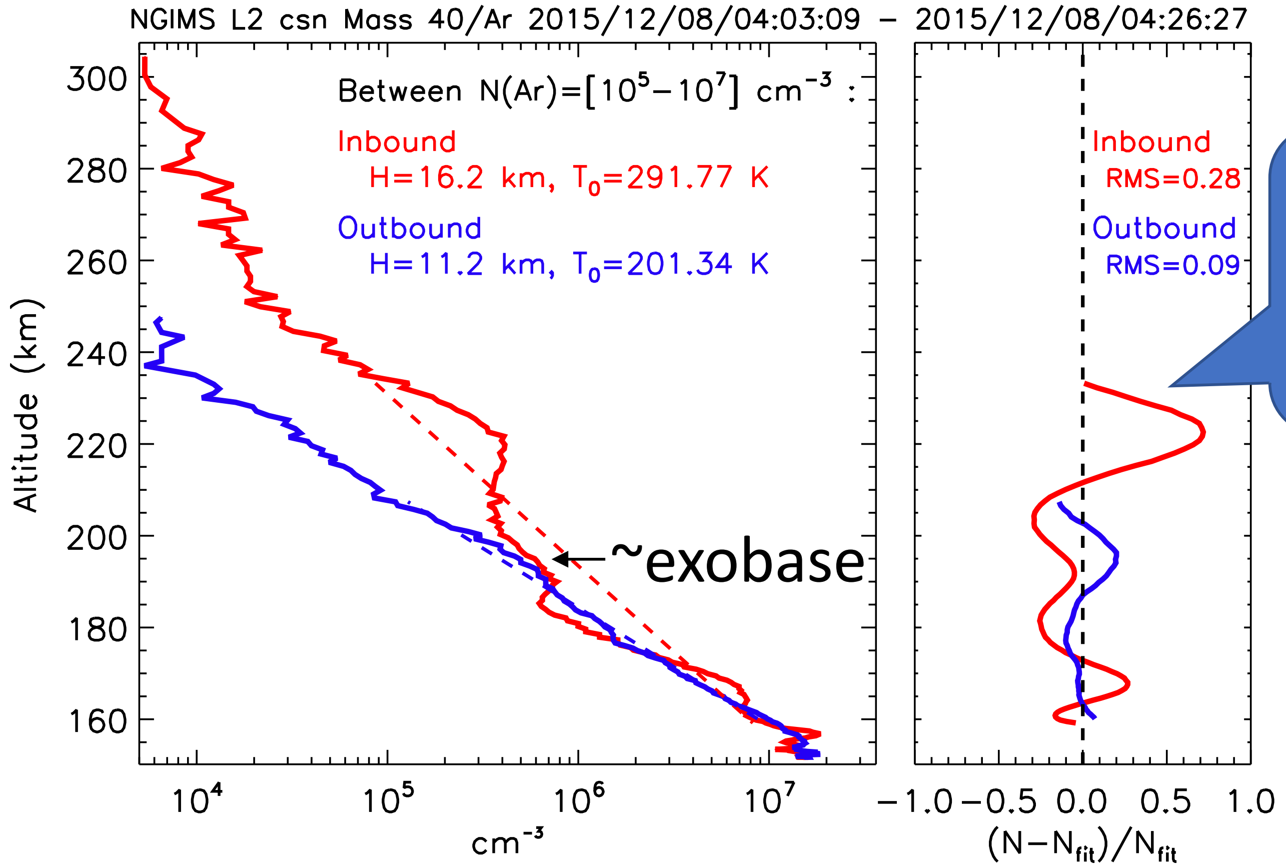
Full-particle DSMC simulations

(molecular diffusion and radiative damping included)



Quasi-steady state solution of our DSMC model agrees well with MAVEN observations.

An example of thermospheric perturbations
(MAVEN/NGIMS in-situ obs.)

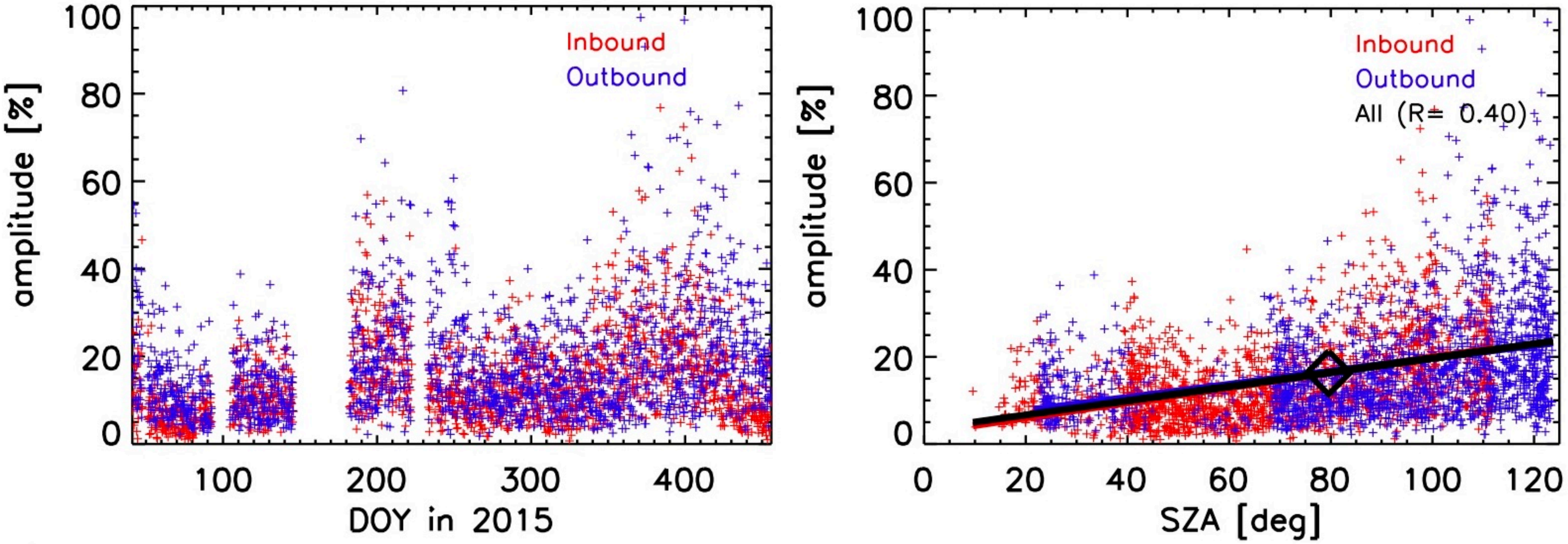


目標は、この無衝突領域での大振幅擾乱を説明すること

[Terada et al., 2017]

- Large-amplitude (~50%) and small-scale (λ_h~200 km) perturbations exist even above the exobase
- Why do they exist in the collisionless exosphere ?
  - Any perturbations should be quickly dissipated due to molecular diffusion

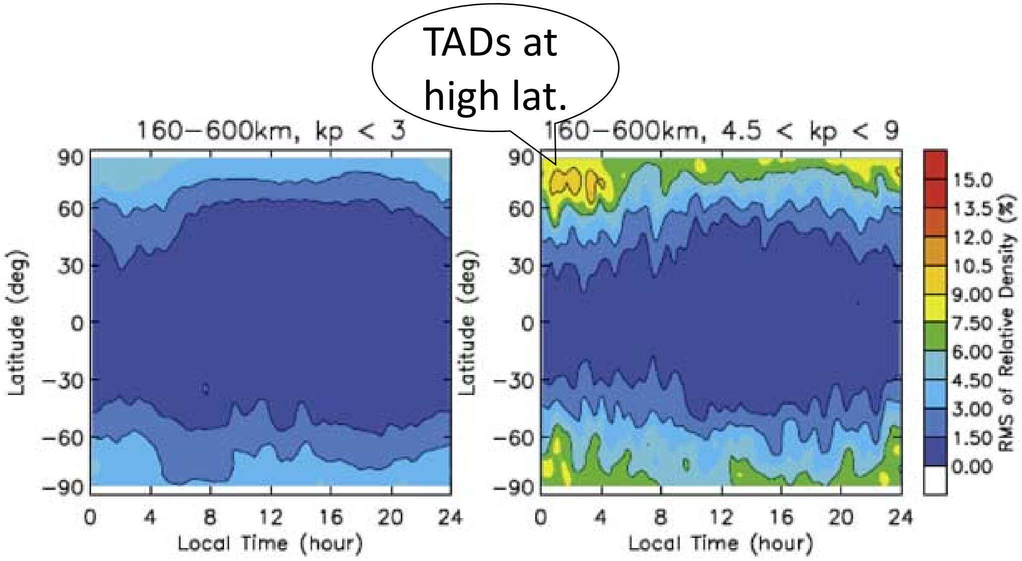
One-year observations of exospheric (above the exobase) perturbations



R = 0.7, if daily-averaged amplitudes are used.

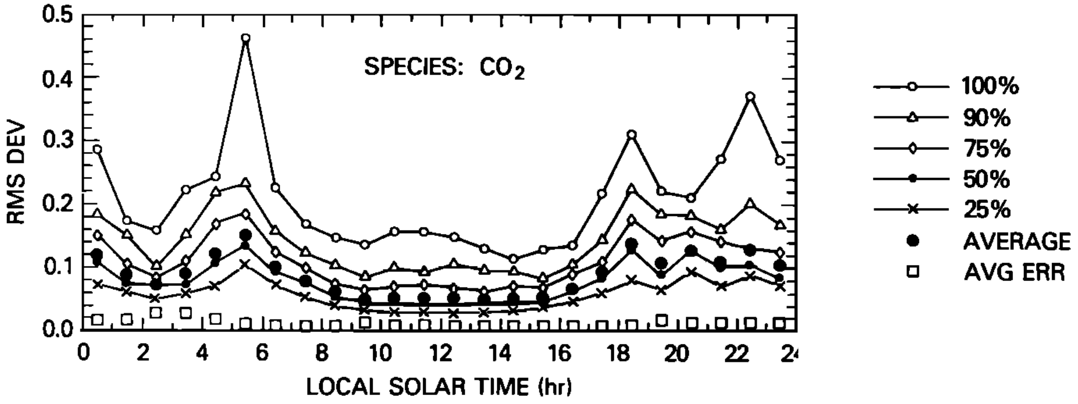
- Wave amplitudes in the Martian exosphere (> ~200 km alt.) are ~10-20 % on average, and sometimes > 50 %
- Higher amplitudes on nightside

Comparison among Earth, Venus, and Mars



Earth, CHAMP obs. at 370-450 km altitudes

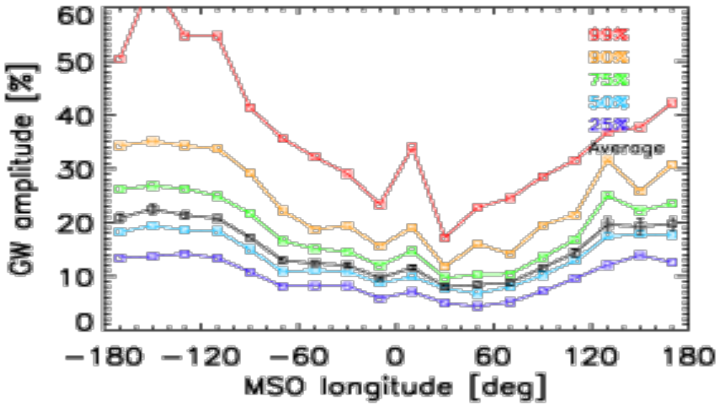
[Bruinsma and Forbes, 2008]



Venus, PVO obs. around the exobase

[Kasprzak et al., 1988]

- Around the exobases.
- Similar analysis methods are used.
  - Earth low lat. ~ 1%
  - (Earth high lat. ~ 3-8%) [Bruinsma and Forbes, 2008]
  - Venus ~ 5-10% [Kasprzak et al., 1988]
  - Mars ~ 10-20% [Terada et al., 2017]

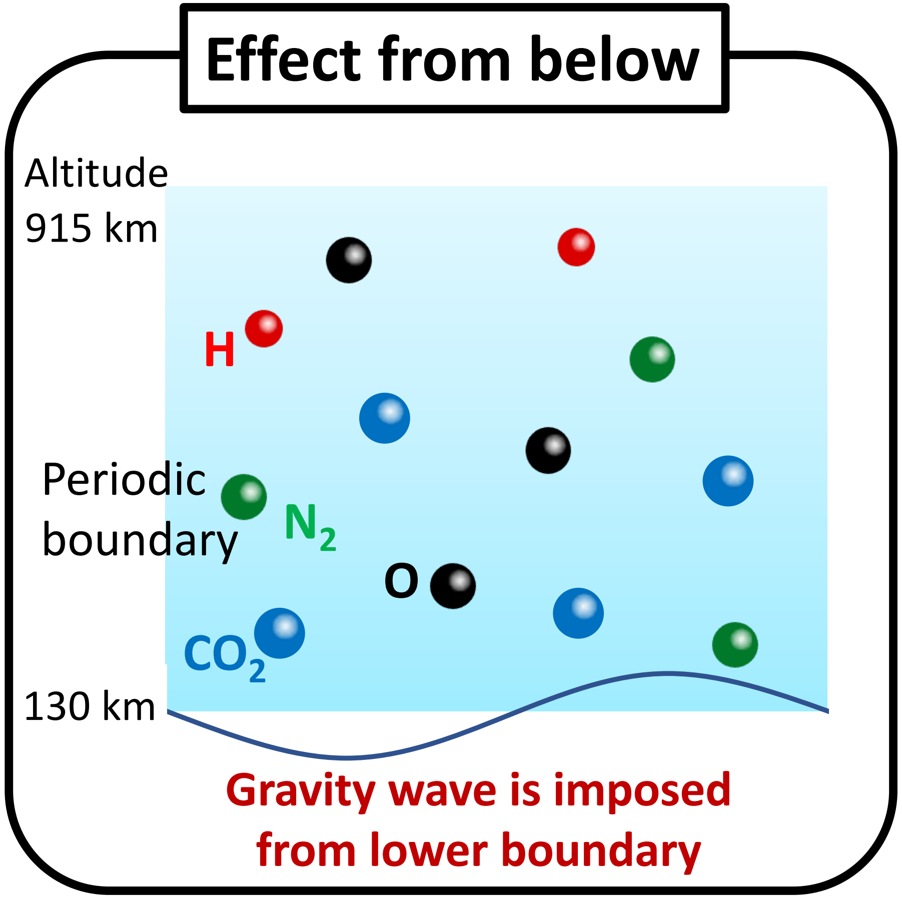


Mars, MAVEN obs. around the exobase

[Terada et al., 2017]

Full-particle DSMC simulations

- To understand excitation, propagation, and dissipation processes of thermospheric-exospheric perturbations, a full-particle DSMC (Direct Simulation Monte-Carlo) model is utilized



Effect from below

Altitude

915 km

H

Periodic boundary

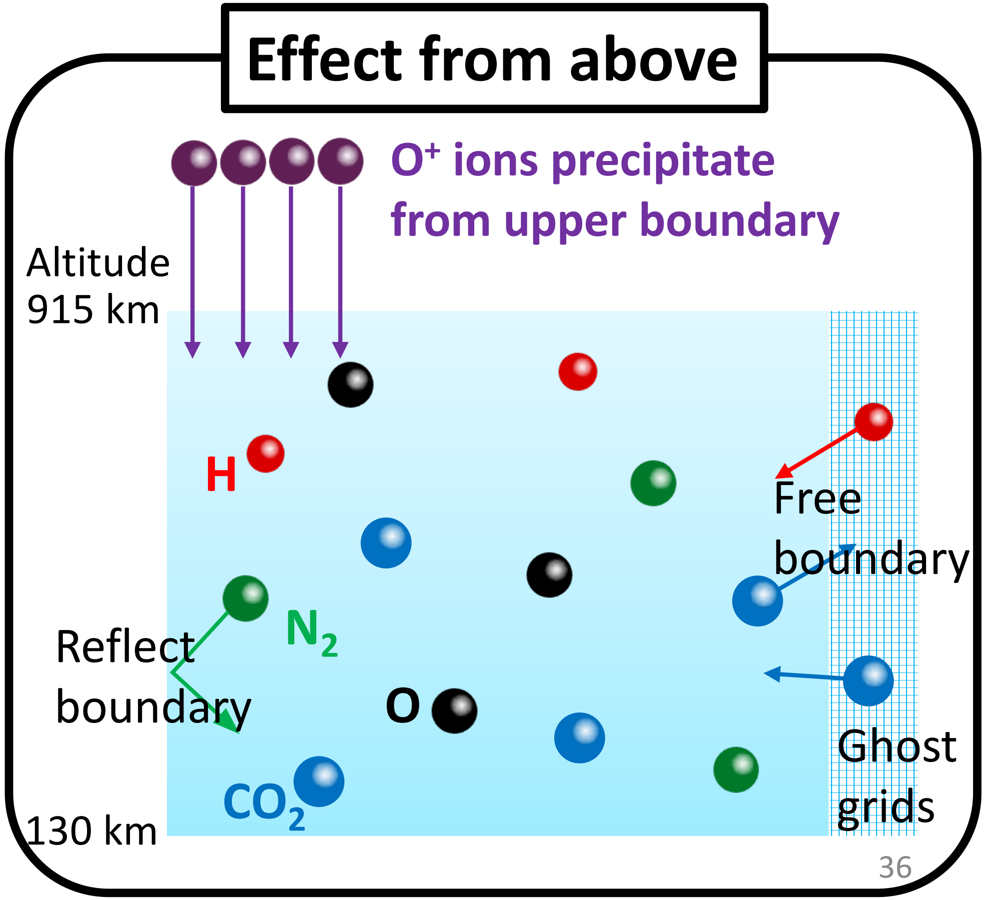
N_2

O

CO_2

130 km

Gravity wave is imposed from lower boundary



Effect from above

O^+ ions precipitate from upper boundary

Altitude

915 km

H

Free boundary

N_2

Reflect boundary

O

CO_2

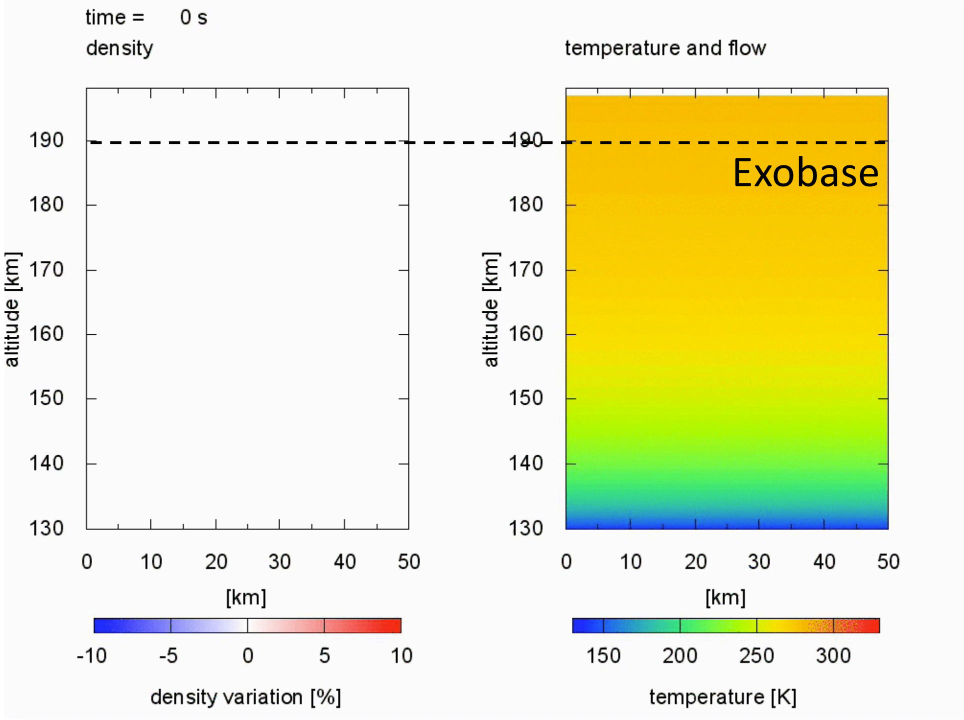
Ghost grids

130 km

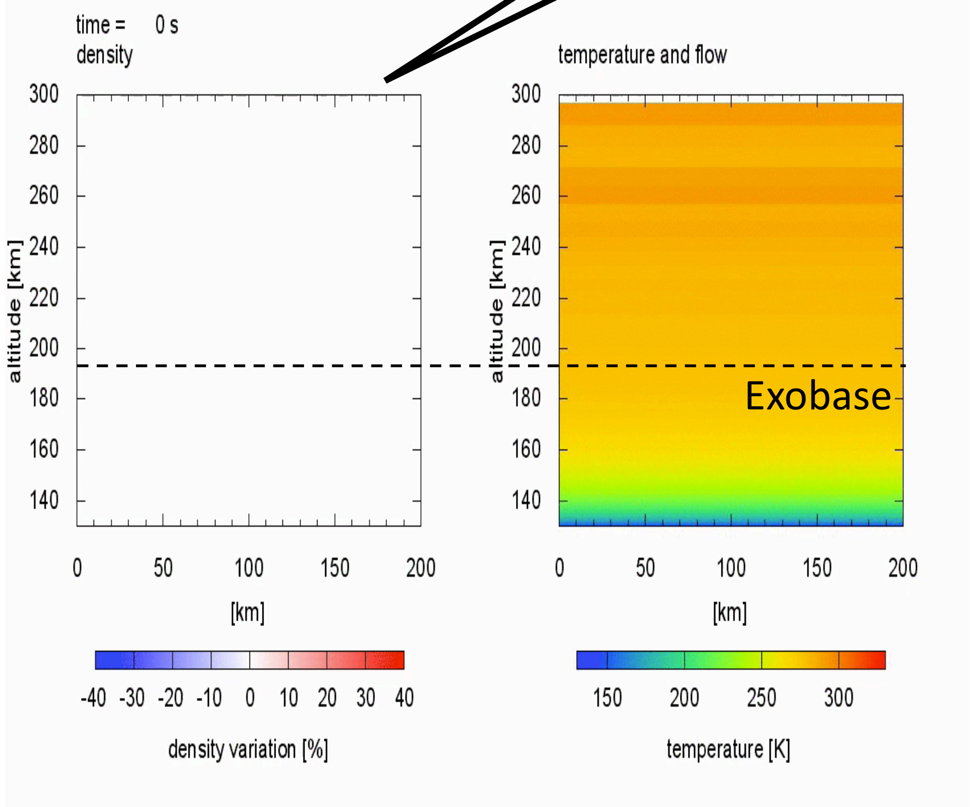
Full-particle DSMC simulations

(molecular diffusion and radiative damping included)

GWs with λ_z=30 km



GWs with λ_z=215 km



Ballistic motions above exobase

λ_z=200 km or more is required to explain exospheric (>200 km alt.) perturbations observed by MAVEN.

- Amplitude growth of GW (cf. Imamura and Ogawa [1995]):

$$\propto \exp\left(\underbrace{\boxed{\frac{1}{2H}}}_{\text{Growth with height}}-\underbrace{\boxed{\frac{\eta}{N_B}\frac{(k_z^2+k_x^2)^2}{k_x}}}_{\text{Damping due to molecular viscosity}}-\underbrace{\boxed{\frac{1}{\tau_{rad}N_B}\frac{(k_z^2+k_x^2)^{3/2}}{k_z k_x}}}_{\text{Damping due to radiative cooling}}\right)z$$

  - GW with a large λ_z (with a faster group velocity) has a higher amplitude at a higher altitude

- Amplitude growth of GW (cf. Imamura and Ogawa [1995]):

$$\propto \exp\left(\boxed{\frac{1}{2H}} - \boxed{\frac{\eta}{N_B}\frac{(k_z^2+k_x^2)^2}{k_x}} - \boxed{\frac{1}{\tau_{rad}N_B}\frac{(k_z^2+k_x^2)^{3/2}}{k_z k_x}}\right) z$$

Growth with height

Damping due to molecular viscosity

Damping due to radiative cooling

  - GW with a large λ_z (with a faster group velocity) has a higher amplitude at a higher altitude

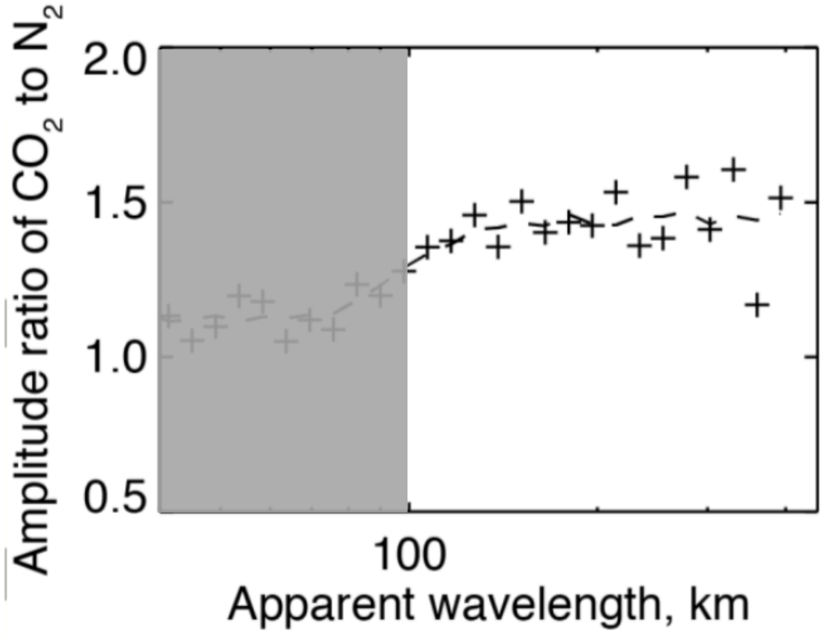
- Why larger amplitude at Mars than Venus and Earth ?
  - Difference in damping
    - **Radiative cooling** (CO_2 15 μm) is stronger at Venus (higher O/CO_2 ratio)
    - Damping due to **ion drag** is stronger at Earth
  - Difference in forcing (?)
    - Mars winter jet wind speeds would be much faster than Earth's [Fritts et al., 2006]

Full-particle DSMC simulations

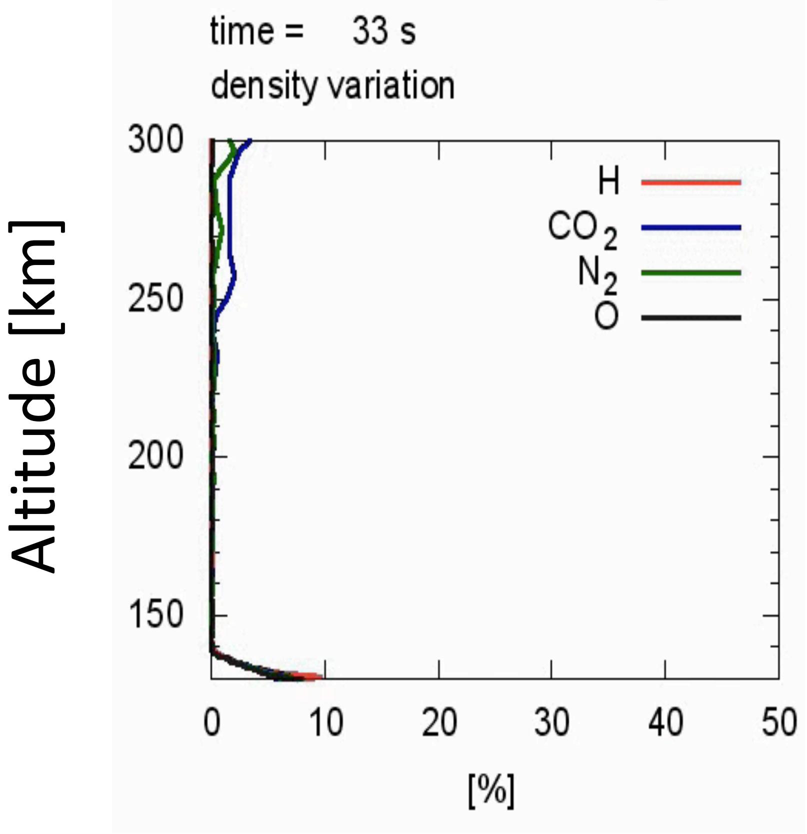
(molecular diffusion and radiative damping included)

MAVEN observation

[England et al., 2016]



DSMC simulation (λ_z=215 km)



Calculated amplitude ratio of CO_2 to N_2 perturbations qualitatively agrees with MAVEN observations.

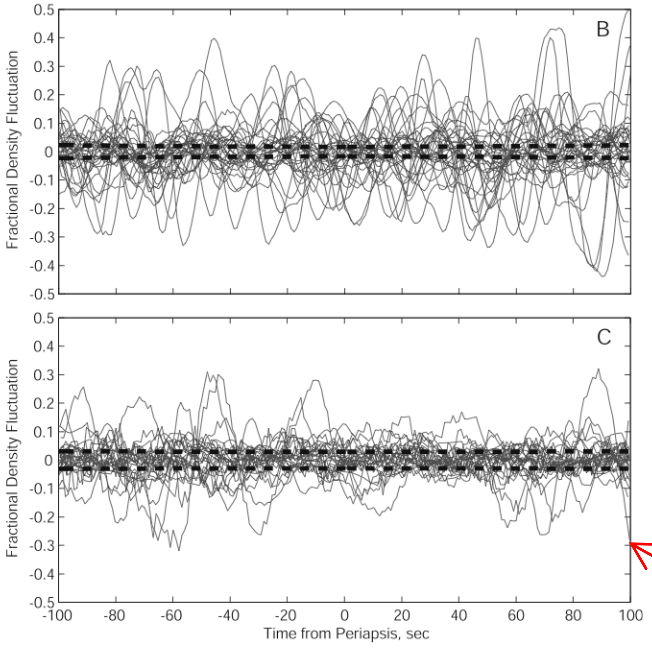
How such a long λ_z (λ_z>200 km) wave excited ?

A gap between lower and upper thermospheres

MGS observation in lower thermosphere [Creasey et al., 2006]

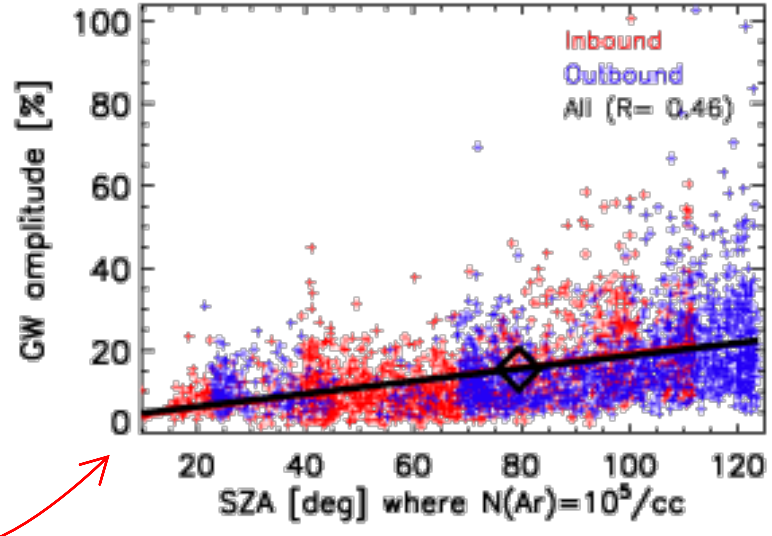
Dayside
1500 LT
~60°S
35 orbits

Nightside
0200 LT
~60°S
30 orbits



MAVEN observation in upper thermosphere >150 km alt. [This study]

1659 orbits

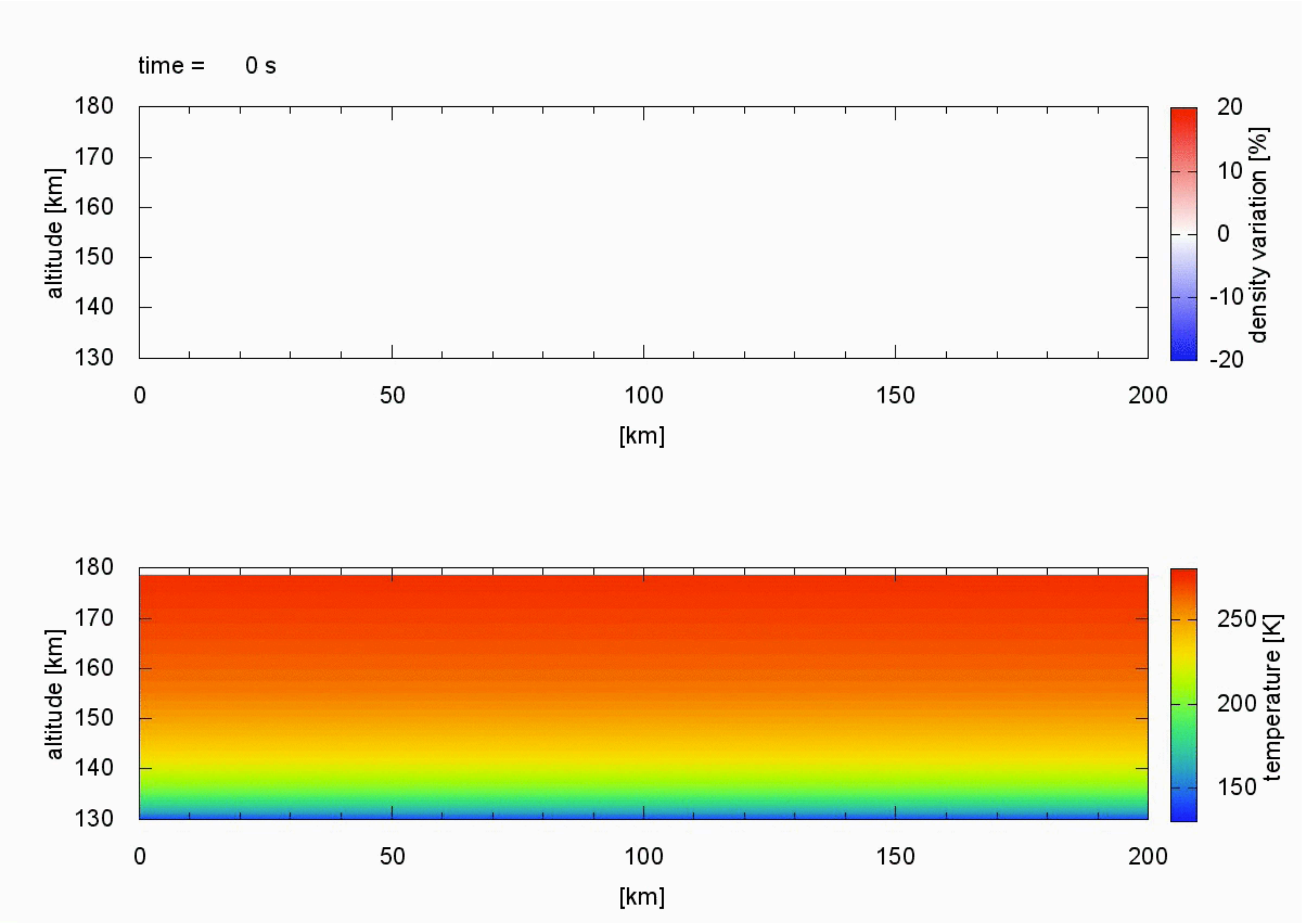


Day-night variation is opposite

Gap ?

Secondary waves may be excited by dissipation of GWs ?

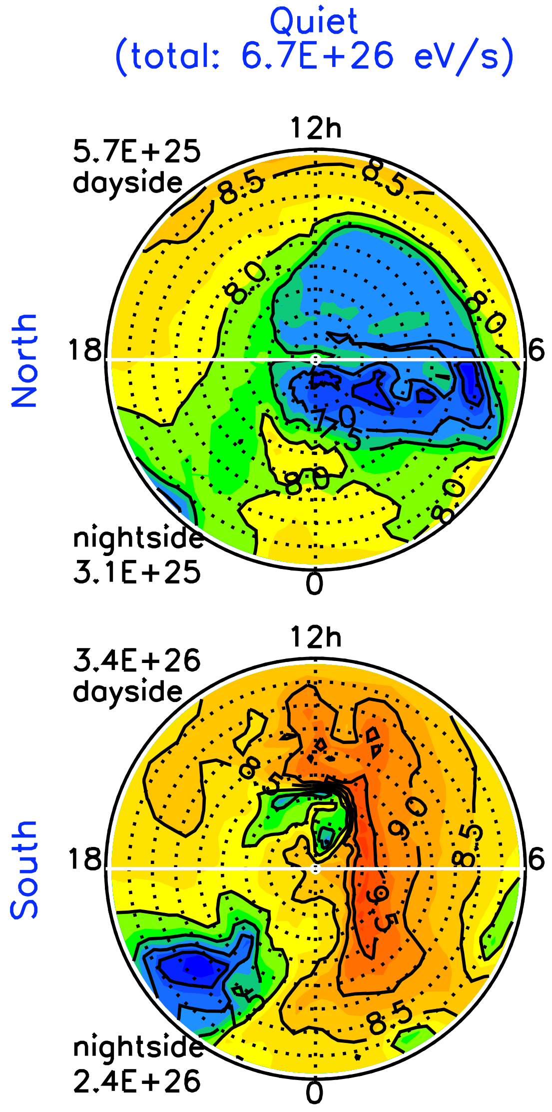
Excitation of secondary GWs ??



- ローカライズした波が必要？

Effects from above

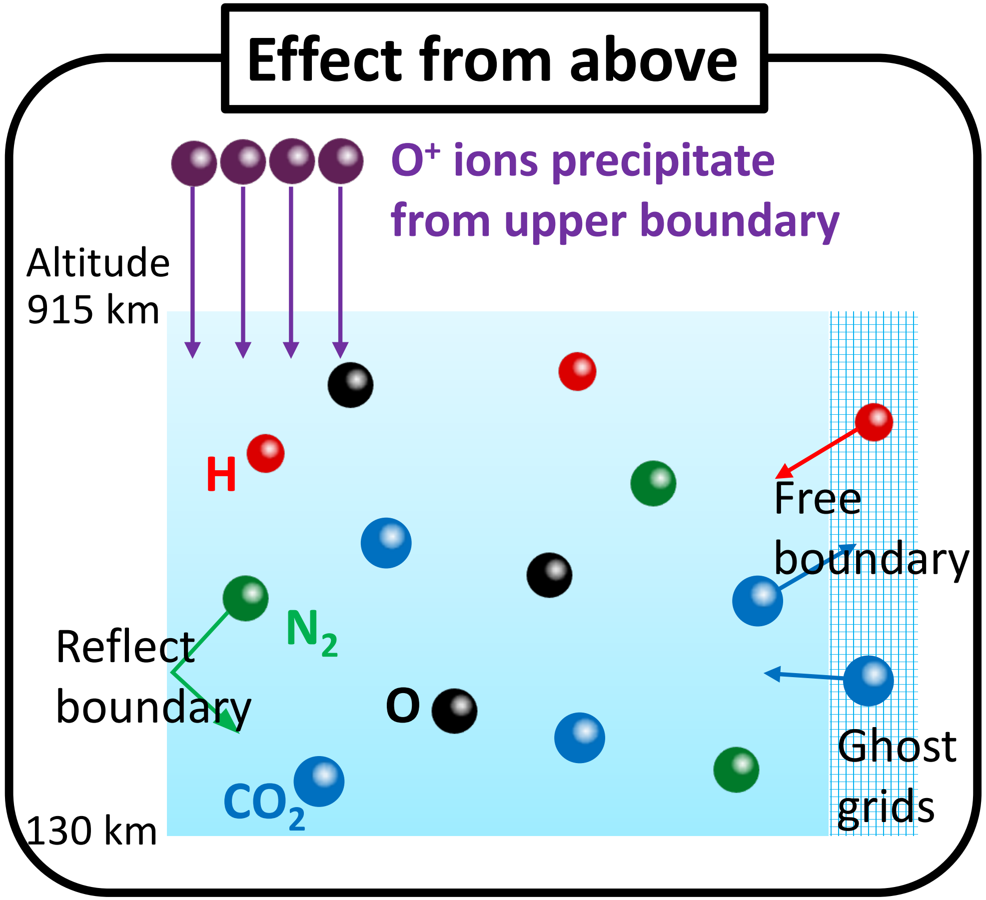
- Precipitating ions
  - Pickup O^+ ions at Mars (and Venus)
  - They may produce larger amplitude waves at higher latitudes [e.g., Fang et al., 2013]
  - Total precipitating O^+ energy is ~0.1-1 Giga Watt at Mars
  - (cf. in the polar region of Earth, Joule heating and particle precipitation ~100 Giga Watt [Knipp et al., 2004])



Estimate of precipitating O^+ energy flux [Fang et al., 2013]

Full-particle DSMC simulations

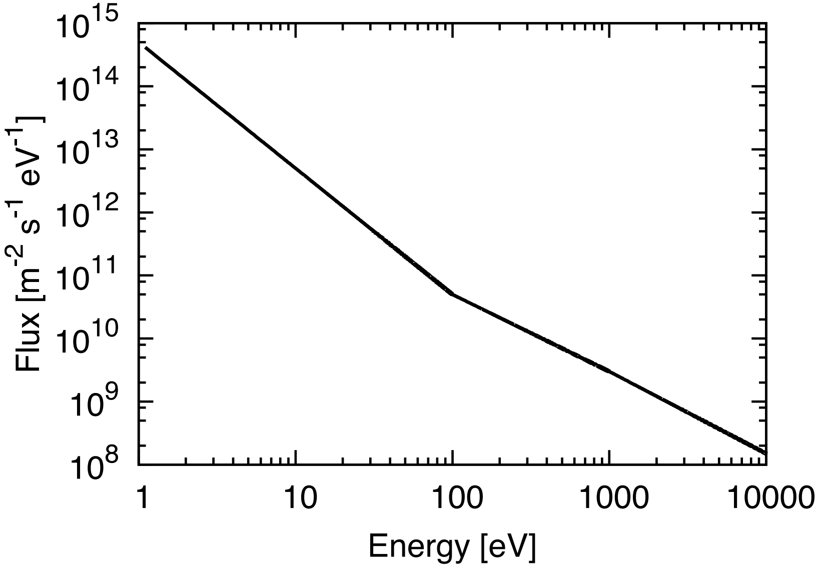
(effect of precipitating O^+ ions)



Energy spectrum

of precipitating O^+ ions

Impacting for only first 3 minutes

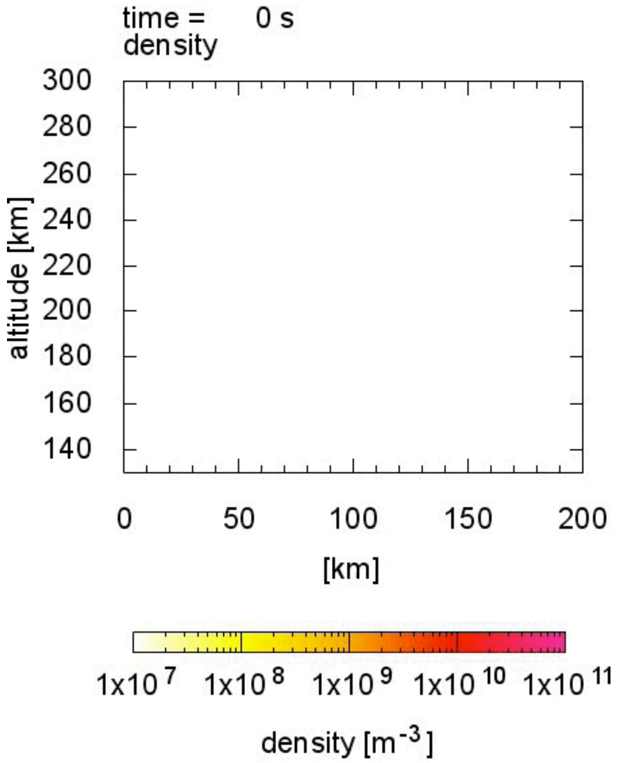


About 3-4 orders larger flux than Chaufray et al. [2007] and Leblanc et al. [2015]

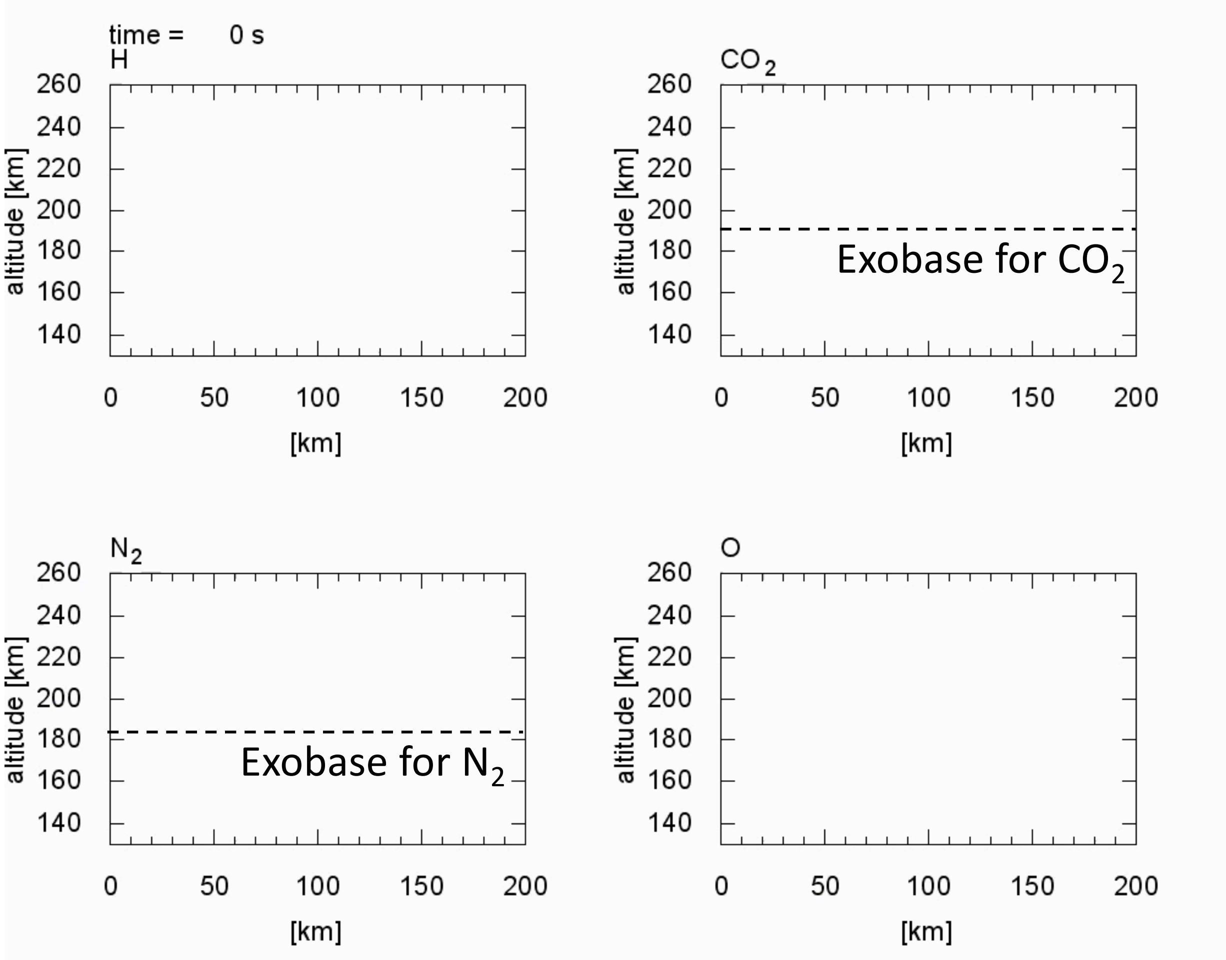
Full-particle DSMC simulations

(effect of precipitating O^+ ions)

Precipitating O^+ ions

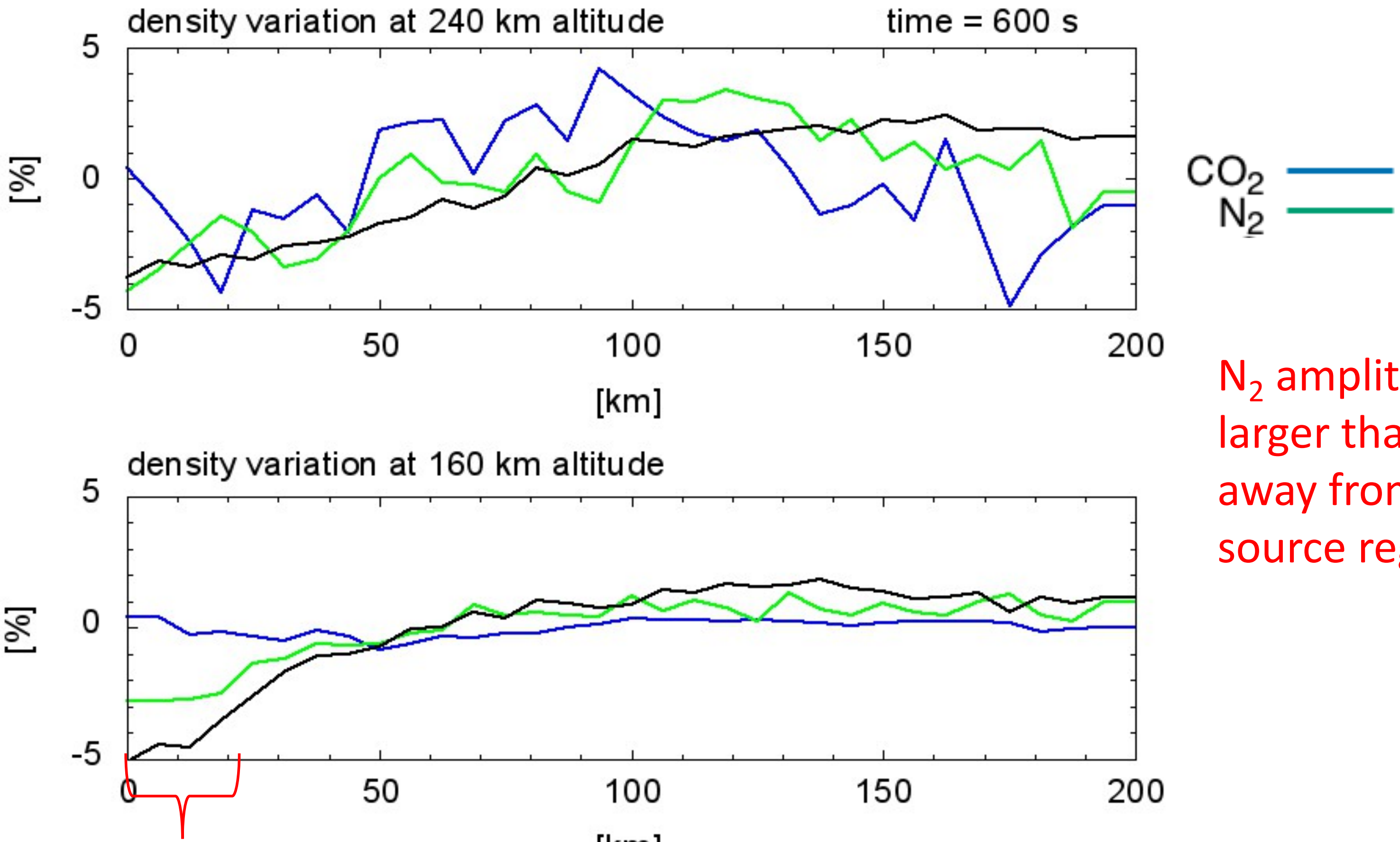


Density perturbations in the Martian thermosphere-exosphere



Full-particle DSMC simulations

(effect of precipitating O^+ ions)



N_2 amplitude is larger than CO_2 away from the source region

Source region

Amplitude ratio of CO_2 to N_2 may be opposite to MAVEN observations. Even more, a very large precipitating flux of O^+ ions is required.

Conclusions

- The average amplitudes of small-scale perturbations around exobase are ~10-20% at Mars, ~5-10% at Venus, and ~1% at low latitude region of Earth (~3-8% at high latitude region of Earth).

- DSMC simulations suggest that perturbations around Mars exobase are produced by GWs with a very long λ_z (λ_z >200 km).
- However, excitation mechanism of such a long λ_z mode, and a gap between the lower and upper thermospheres (opposite day-night variations) are still to be explained.

- In the polar region of Earth's thermosphere, solar wind forcing (Joule heating and particle precipitation, ~100 Giga Watt) sometimes generates large-amplitude perturbations.
- However, in the Martian (and probably Venusian) thermosphere, solar wind forcing (~0.1-1 Giga Watt) seems to be less important.