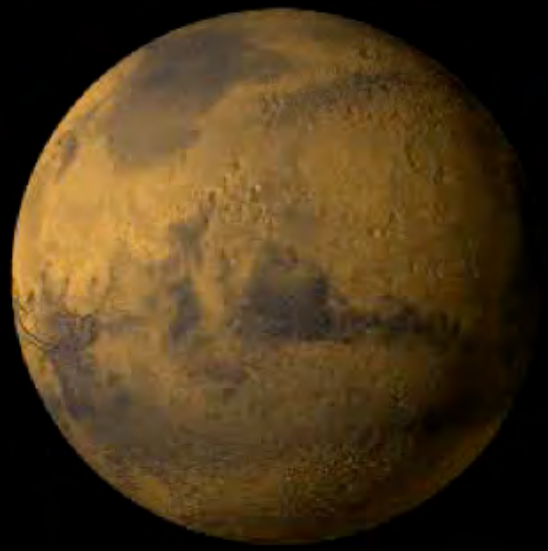
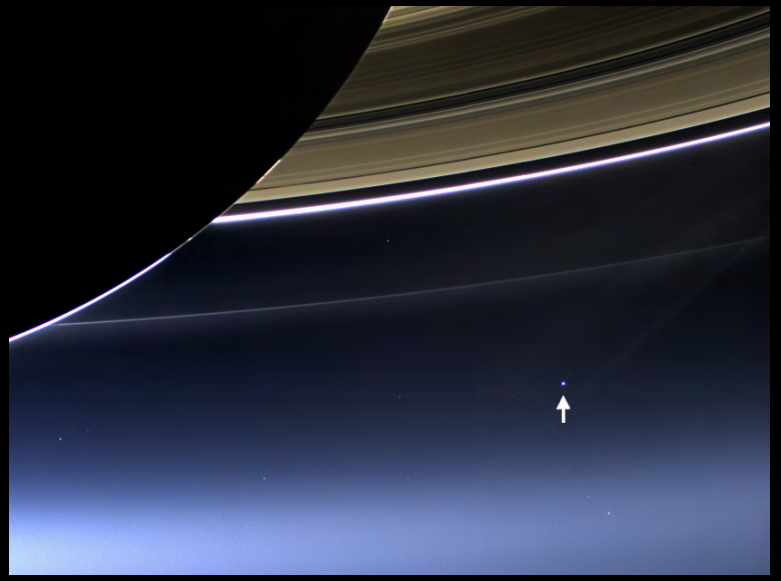
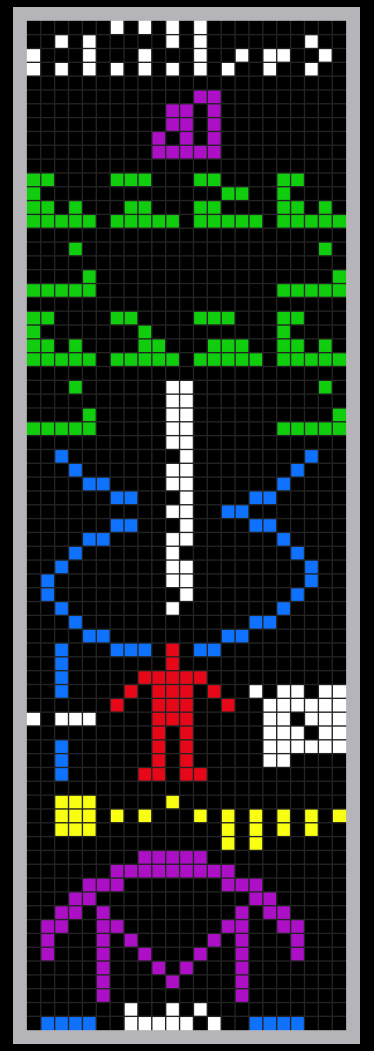
Lessons from Mars and Earth for future explorations of bio-signatures from earth-like planets







Yasushi Suto Department of Physics and Research Center for the Early Universe, the University of Tokyo

ABC project/CPS workshop "*Climates of Terrestrial Planets in Various Solar Systems*" @17:30-18:30 February 11, 2020

1 Introduction

Nobody can deny that there's something there
I will be there, and everywhere

— The Beatles "Here, there and everywhere"

Are we alone ?

a Pale Blue Dot or pale blue dots ?

Sciences with exoplanets

- the ***final*** question: ***Are we alone ?***
  - origin of the earth
  - origin of the Solar System
  - ***habitable*** planets ⇒ origin of life
  - signature of extra-terrestrial life

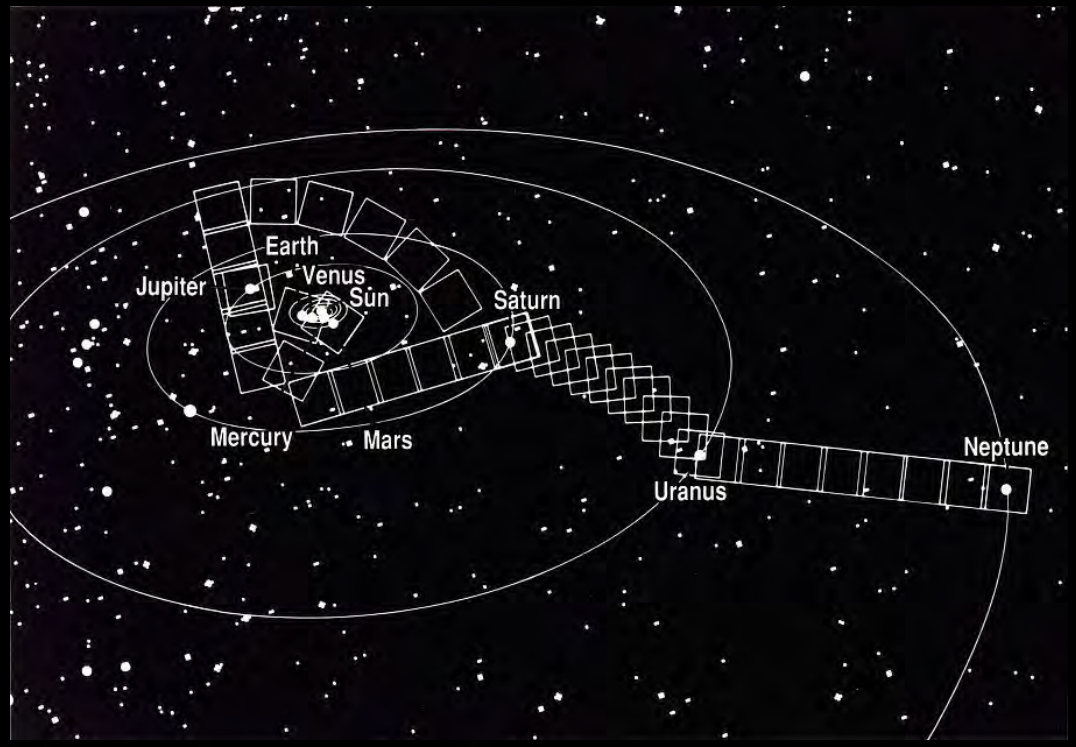
    and/or extra-terrestrial intelligence ?

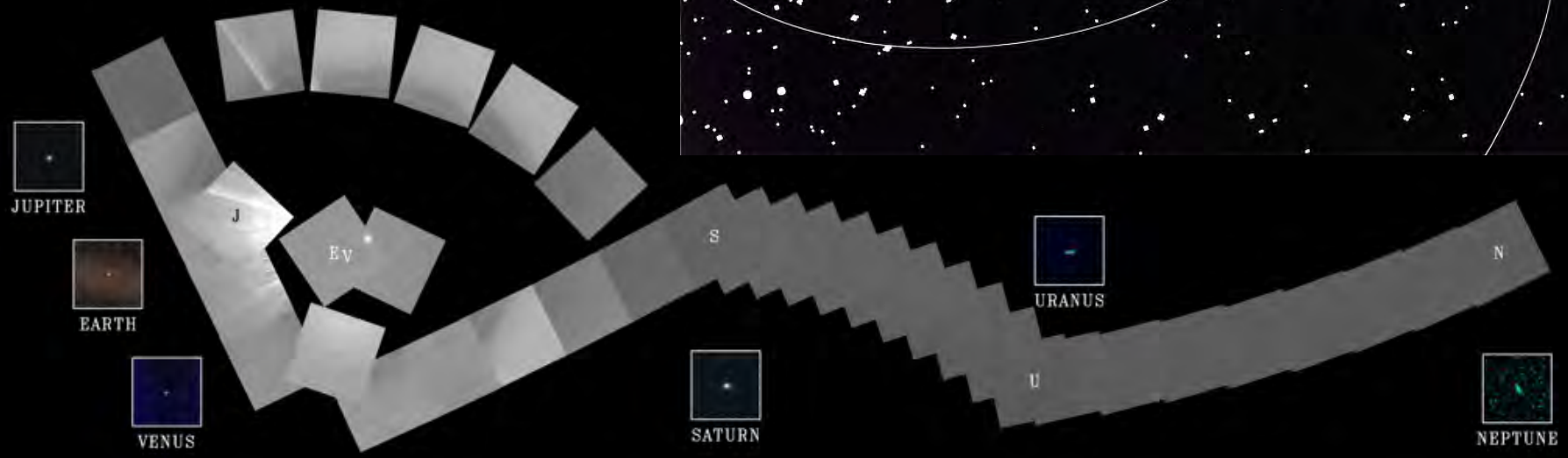
    ⇒ origin of consciousness/intelligence

"Where are they ?" E.Fermi (1950)

Solar planets imaged by Voyager 1 (February 4, 1990)

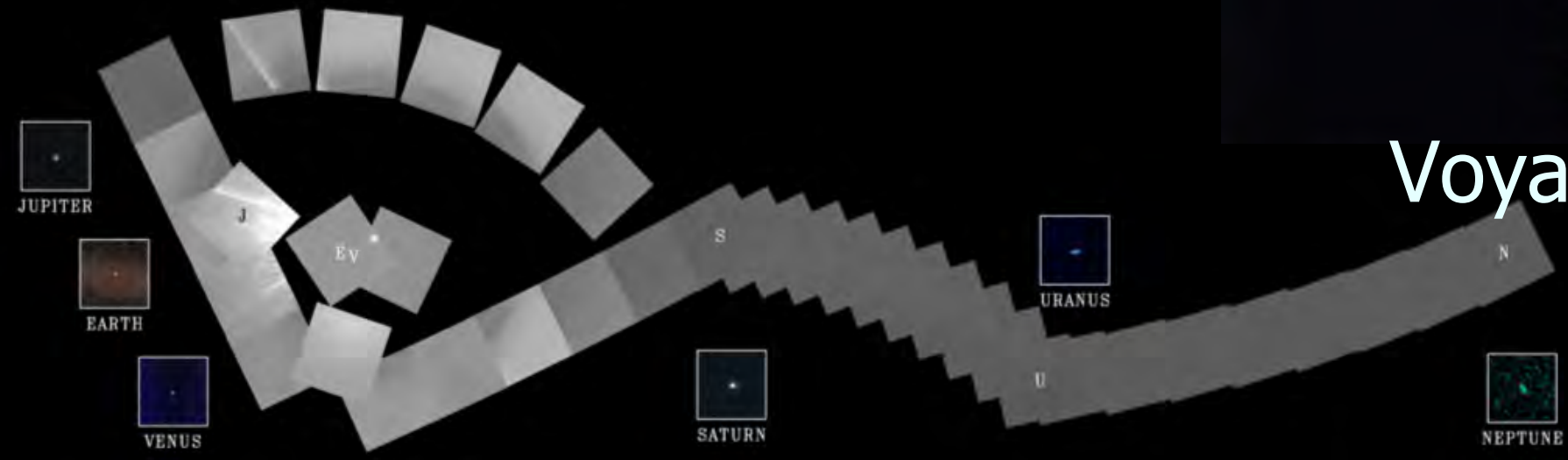
- Earth imaged at distance of 40 au away
- A Pale Blue Dot (Carl Segan)





A Pale Blue Dot

Voyager 1



Earth and Moon viewed from Saturn

- Viewed from *Cassini* on July 20, 2013
  - about 20,000 happy Americans are waving their hands towards Cassini, but *how can we know that ?*

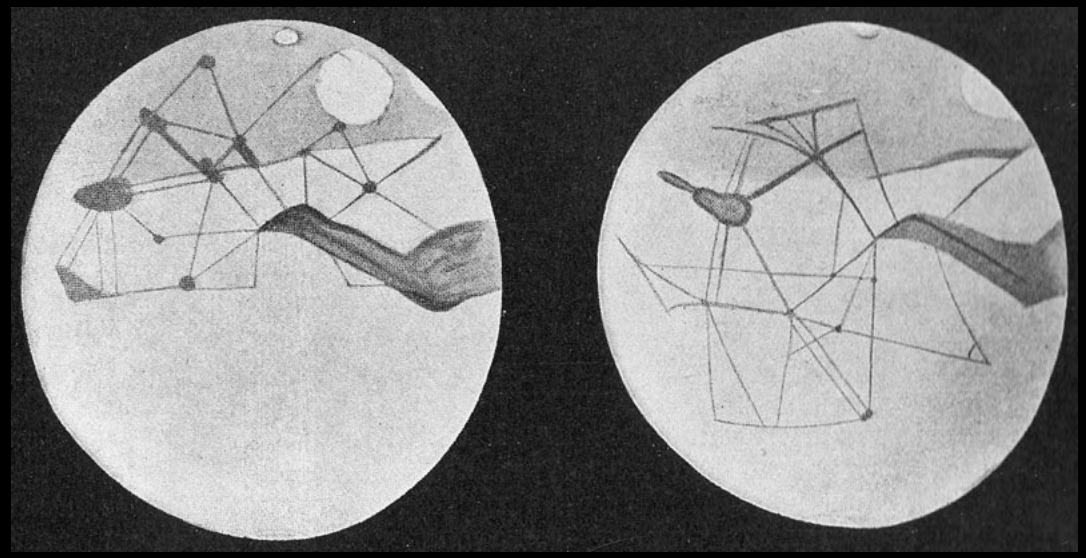
2 Mars and Astrobotany

the origin of life now seemed to be so easy –
and there were so many planetary systems, so
many worlds and so many billions of years
available for biological evolution –
that it was hard to believe the Galaxy was not
teeming with life and intelligence

— Carl Sagan " Contact"

Life on Mars ?

- 1895– Percival L. Lowell
  - Came from a very rich family, and founded the Lowell observatory
  - *Mars (1895), Mars and Its Canals (1906), and Mars As the Abode of Life (1908)*
  - Mars sustained intelligent life forms

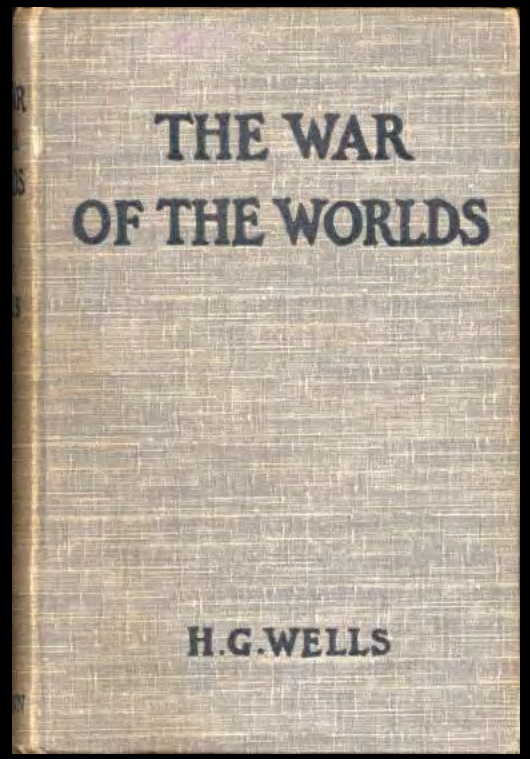


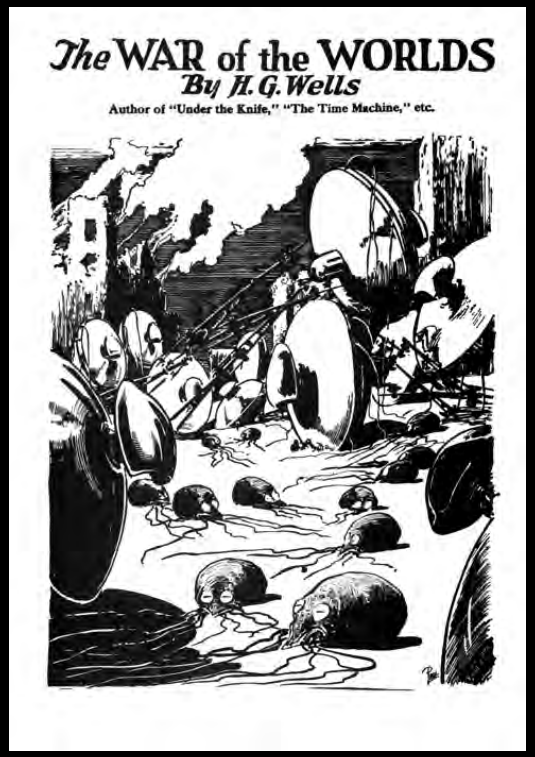
Martian canals depicted by Percival Lowell

Percival Lowell observing Venus from the Lowell Observatory in 1914

The War of the Worlds

- 1897 H.G.Wells Science Fiction: The War of the Worlds
- 1938 Orson Welles radio drama: The War of the Worlds by H.G.Wells





October 11, 1938: The New York Times

Astrobotany on Mars

- Gavriil Adrianovich Tikhov (1875–1960)
  - Studied earthshine in 1914, and concluded that Earth should be seen as a pale blue dot due to the Rayleigh scattering
  - Studied optical properties of terrestrial plants and particularly spectra of plants growing in conditions similar to those of Mars, looking for plants without chlorophyll, or with unusual chlorophyll spectra
  - Created the word ***astrobotany*** in 1945

  (D. Briot, J. Schneider, and L. Arnold in *Extrasolar planets : Today and Tomorrow* ASP Conference Series, Vol. 321, 2004)
- 1924 E.C.Slipher and V.N.Slipher at the Lowell Observatory
  - Photometric and spectroscopic observations of Mars
- 1957 William M.Sinton
  - Evidence of vegetation on Mars

Vesto Melvin Slipher (1875-1969)

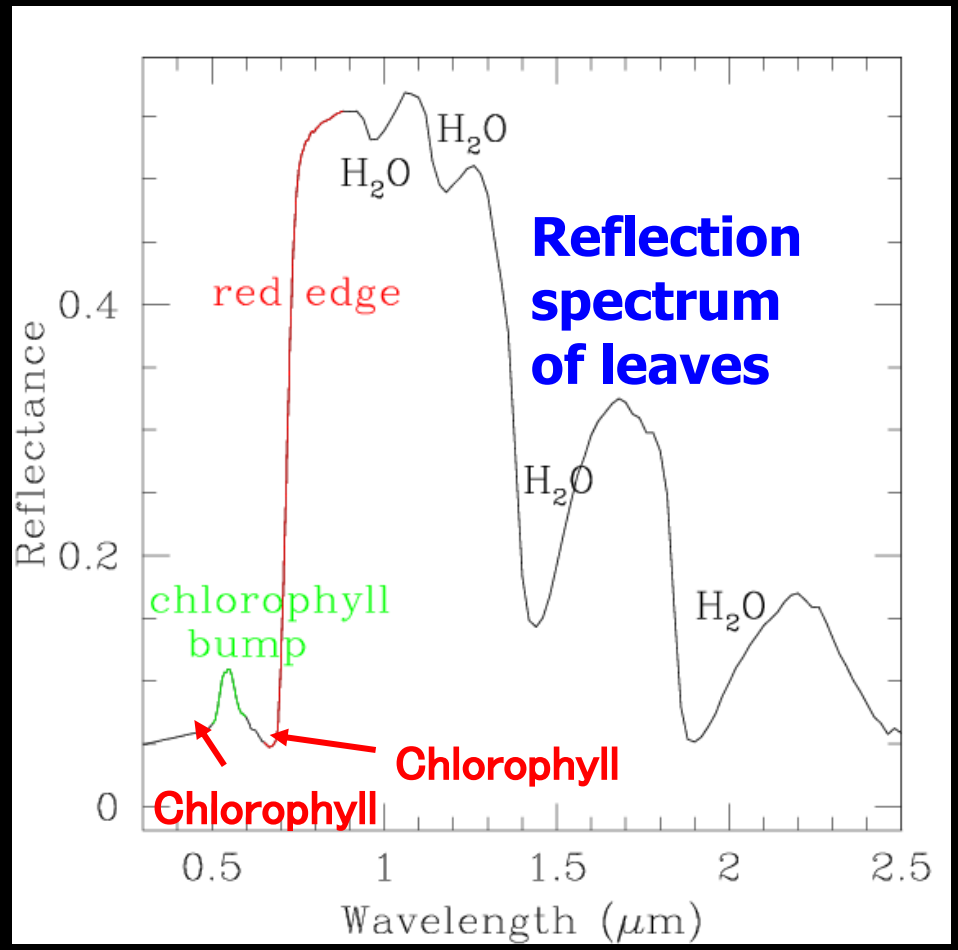
- Discovered that distant "spiral nebulae" are preferentially redshifted, due to the recession velocity
- Both Lemaitre and Hubble discovered the cosmic expansion from his velocity data

"Observations of Mars in 1924 made at the Lowell Observatory: II spectrum observations of Mars"
PASP 36(1924)261

In the case of *Mars*, of course, we are dealing with the reflection spectrum. The Martian spectra of the dark regions so far do not give any certain evidence of the typical reflection spectrum of chlorophyl. The amount and types of vegetation required to make the effect noticeable is being investigated by suitable terrestrial exposures.

Red edge of *(exo)plants:* a possible bio-signature in *exoplanets*

- Red-edge
  - Significant increase of reflectivity of leaves on Earth (terrestrial planets) for λ>7000Å
- Widely used in the remote-sensing of our Earth



Seager, Ford & Turner astro-ph/0210277

Earl C. Slipher (1983-1964)

OBSERVATIONS OF MARS IN 1924 MADE AT THE LOWELL OBSERVATORY

I. Visual and Photographic Observations of the Surface

By E. C. Slipher **PASP 36(1924)255**

From the long series of observations made here, both visual and photographic, it is strongly evidenced that the dark markings of the planet, except the dark border that accompanies the melting cap, are due to the same cause and obey the same law of change. The seasonal date that these dark markings make their appearance, the rate and behavior in their development, the seasonal date at which they mount to the highest intensity which is the summer solstice and thereafter, their color and appearance, and in turn the time of their fadiug out again, all obey the law of change that we should expect of vegetation.

William M.Sinton ApJ 126(1957)231

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 126 SEPTEMBER 1957 NUMBER 2

SPECTROSCOPIC EVIDENCE FOR VEGETATION ON MARS

WILLIAM M. SINTON
Smithsonian Astrophysical Observatory
Received May 6, 1957

ABSTRACT

A new test for the presence of vegetation on Mars depends on the fact that all organic molecules have absorption bands in the vicinity of 3.4 μ. These bands have been studied in the reflection spectrum of terrestrial plants, and it is found that for most plants a doublet band appears which has a separation of about 0.1 μ and is centered about 3.46 μ. Spectra of Mars taken during the 1956 opposition indicate the probable presence of this band. This evidence and the well-known seasonal changes of the dark areas make it extremely probable that vegetation in some form is present.

William M.Sinton ApJ 126(1957)231

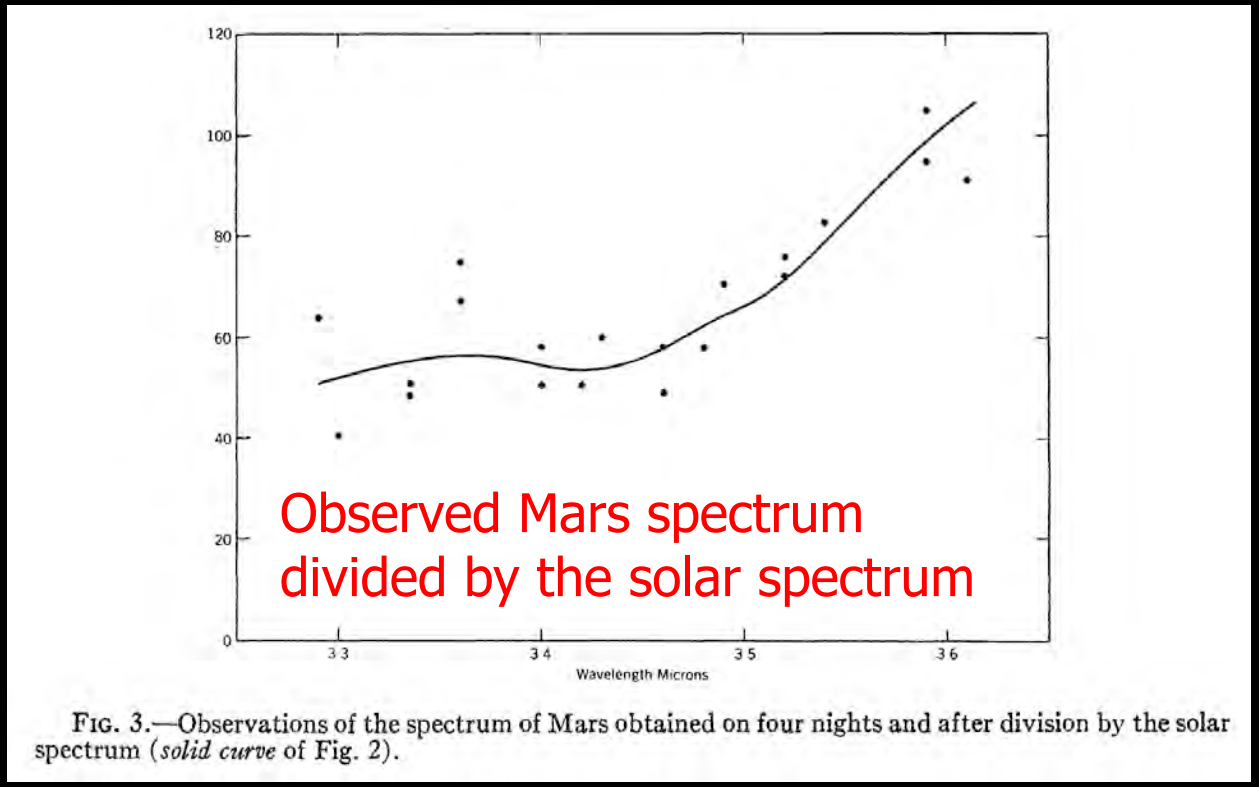


FIG. 3.—Observations of the spectrum of Mars obtained on four nights and after division by the solar spectrum (*solid curve* of Fig. 2).

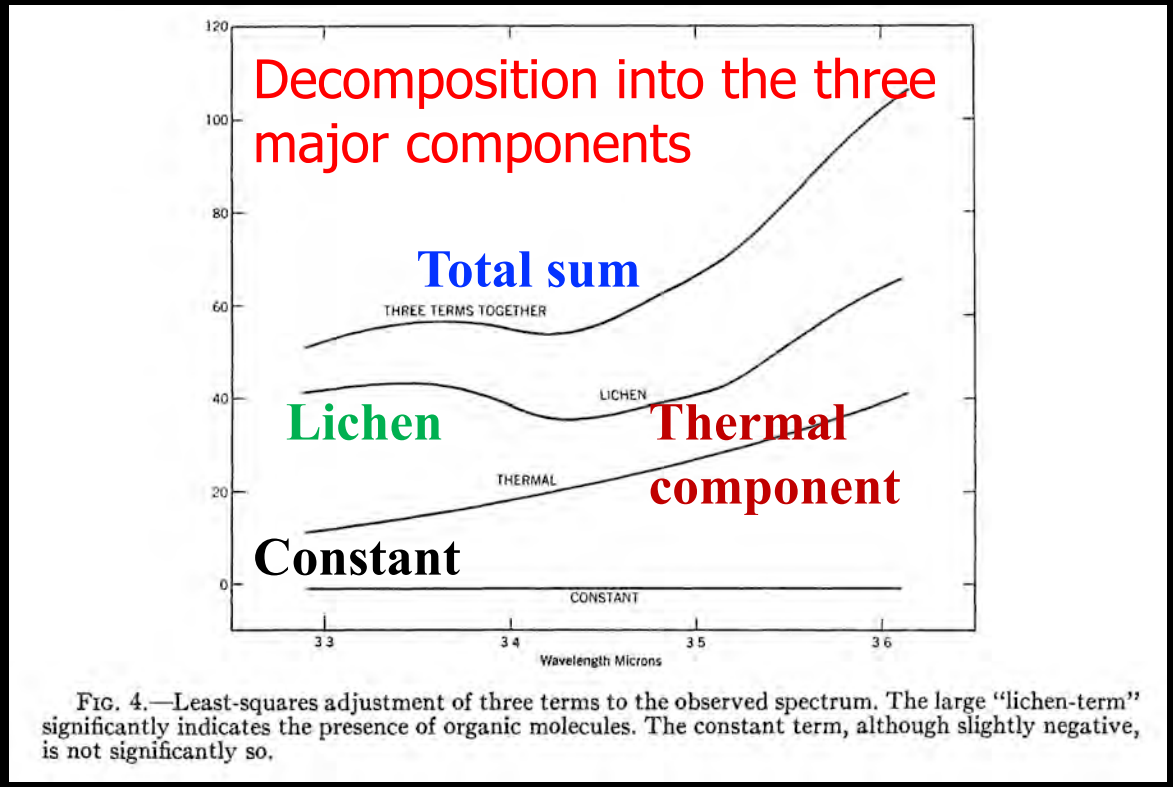


FIG. 4.—Least-squares adjustment of three terms to the observed spectrum. The large "lichen-term" significantly indicates the presence of organic molecules. The constant term, although slightly negative, is not significantly so.

- **Lichen (地衣類)**
  - 陸上性でごく背の低い光合成生物。その点でコケ植物に共通点があり、多くの言語において同一視され、実際に地衣類の和名の多くに「○○ゴケ」といったものがあたえられている。しかし地衣類の構造を作っているのは菌類

LOWELL OBSERVATORY

BULLETIN No. 103

Vol. IV No. 15

Bulletin of Lowell Observatory 4(1959)252

FURTHER EVIDENCE OF VEGETATION ON MARS

William M. Sinton

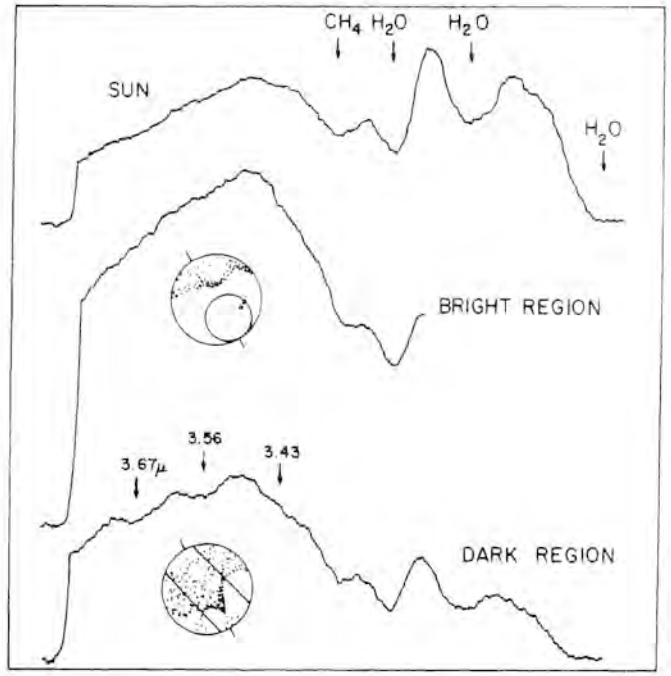
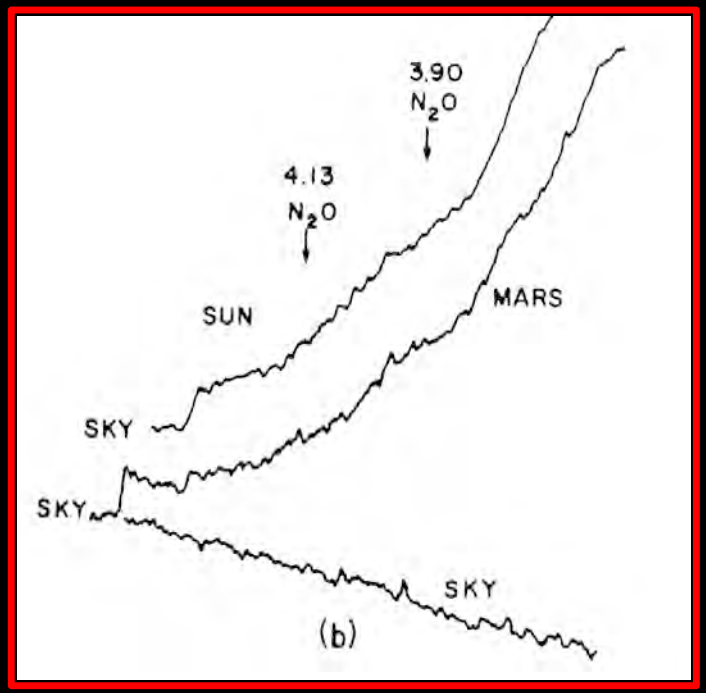


Figure 1. Infrared spectra of Mars and the sun. The upper curve shows the spectrum of the sun with absorptions produced by water and methane in the earth's atmosphere. The middle curve is the spectrum of Amazonis, the desert region within the circle in the sketch. The bottom curve shows the spectrum of a strip across Mars as shown in the sketch and includes Syrtis Major. The last spectrum shows the absorptions supposedly due to organic molecules.



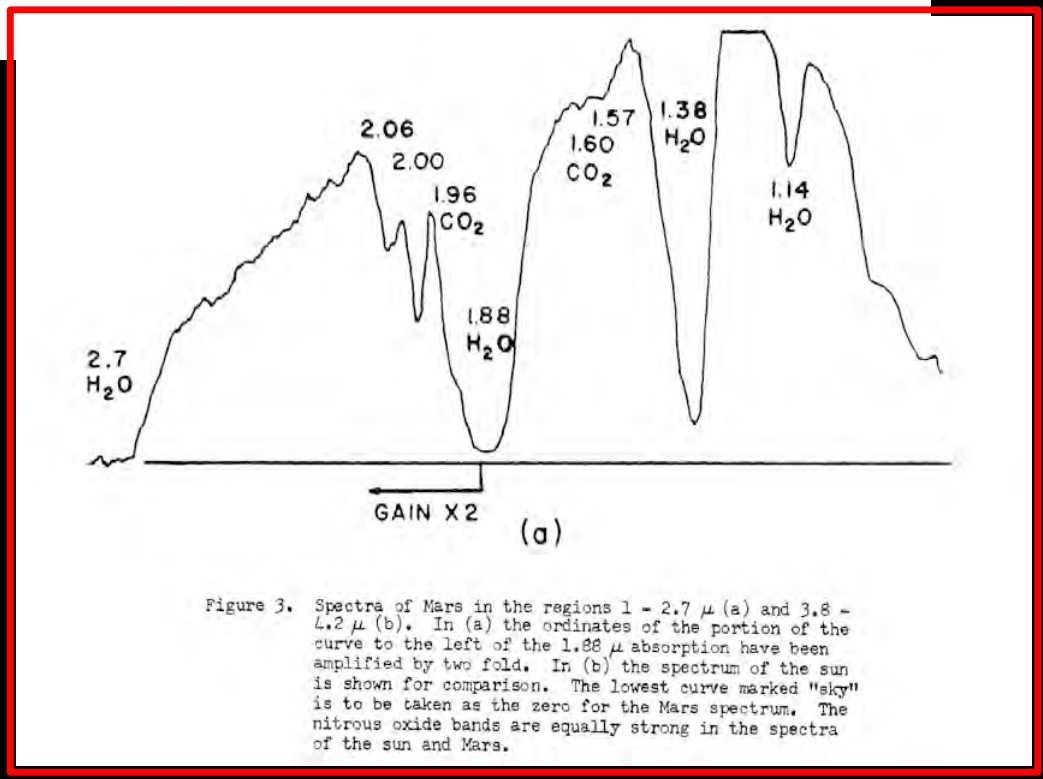
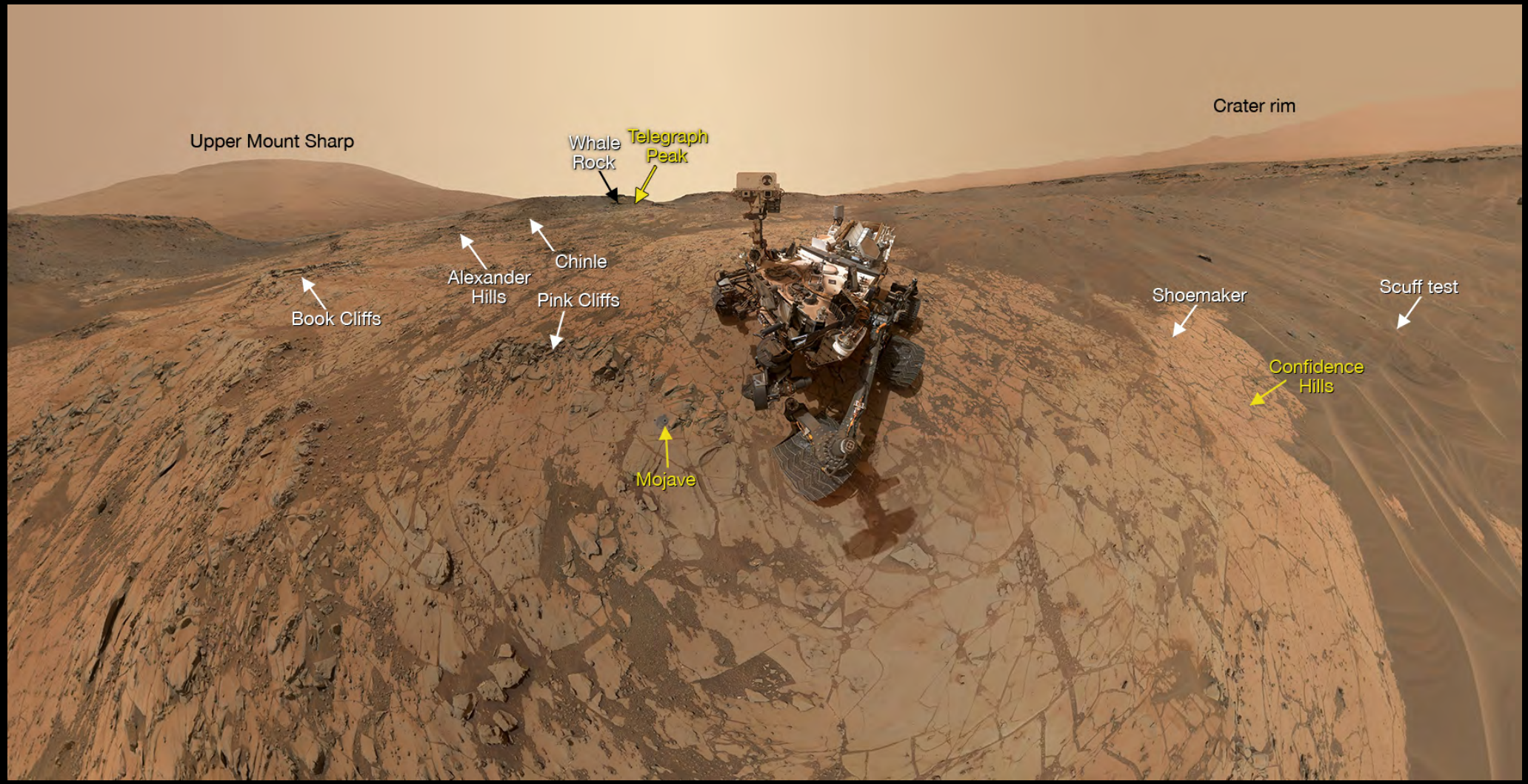


Figure 3. Spectra of Mars in the regions 1 - 2.7 μ (a) and 3.8 - 4.2 μ (b). In (a) the ordinates of the portion of the curve to the left of the 1.88 μ absorption have been amplified by two fold. In (b) the spectrum of the sun is shown for comparison. The lowest curve marked "sky" is to be taken as the zero for the Mars spectrum. The nitrous oxide bands are equally strong in the spectra of the sun and Mars.

Now, we can take direct pictures of Mars



Curiosity (Mars Science Laboratory) launched on November 26, 2011
landed on Mars on August 6, 2012 https://mars.jpl.nasa.gov/msl/

Surface on Mars https://eyes.nasa.gov/curiosity/

Mars or Earth ?

アイオリス山(標高5500m) 2015年9月

チコ山（標高5150m）とオナール山
（標高5400m） 2003年

アイオリス山麓の盆地　2015年10月

アスペロ山（標高5262m）2002年2月

https://photojournal.jpl.nasa.gov/catalog/PIA19912

Courtesy of M.Doi and K.Kohno

https://mars.nasa.gov/resources/7505/strata-at-base-of-mount-sharp/

3 Detection of bio-signatures on our own Earth

Everything not forbidden by the laws of nature is mandatory

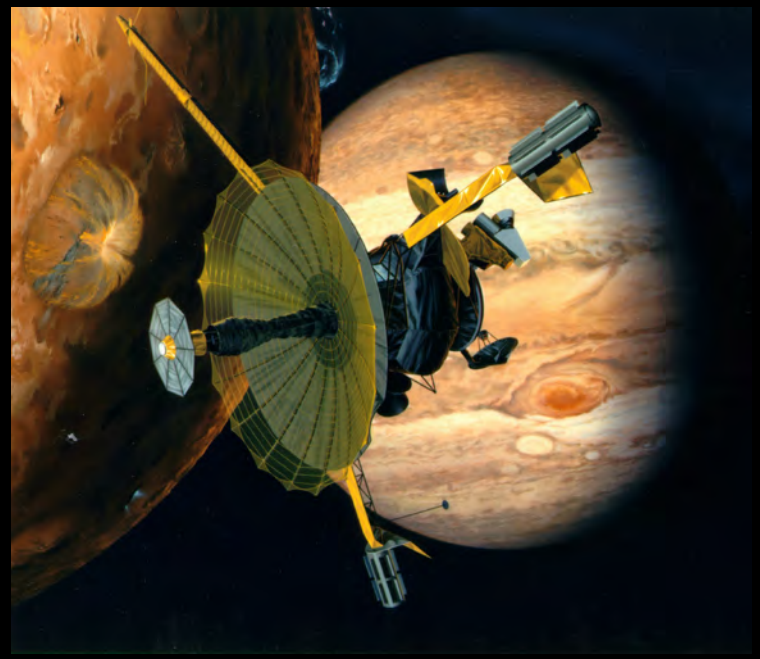
— Carl Sagan "Contact"

Searching for bio-signatures on exoplanets

- (Working) definition of Life in biology
  - Isolation, metabolism, self-reproduction
- Observable bio-signatures in astronomy
  - Significant changes in planetary surfaces
  - Remote-sensing of (habitable) planets
- What we should/can detect
  - Oxygen and red-edge of vegetation
  - Electromagnetic signals from advanced civilizations

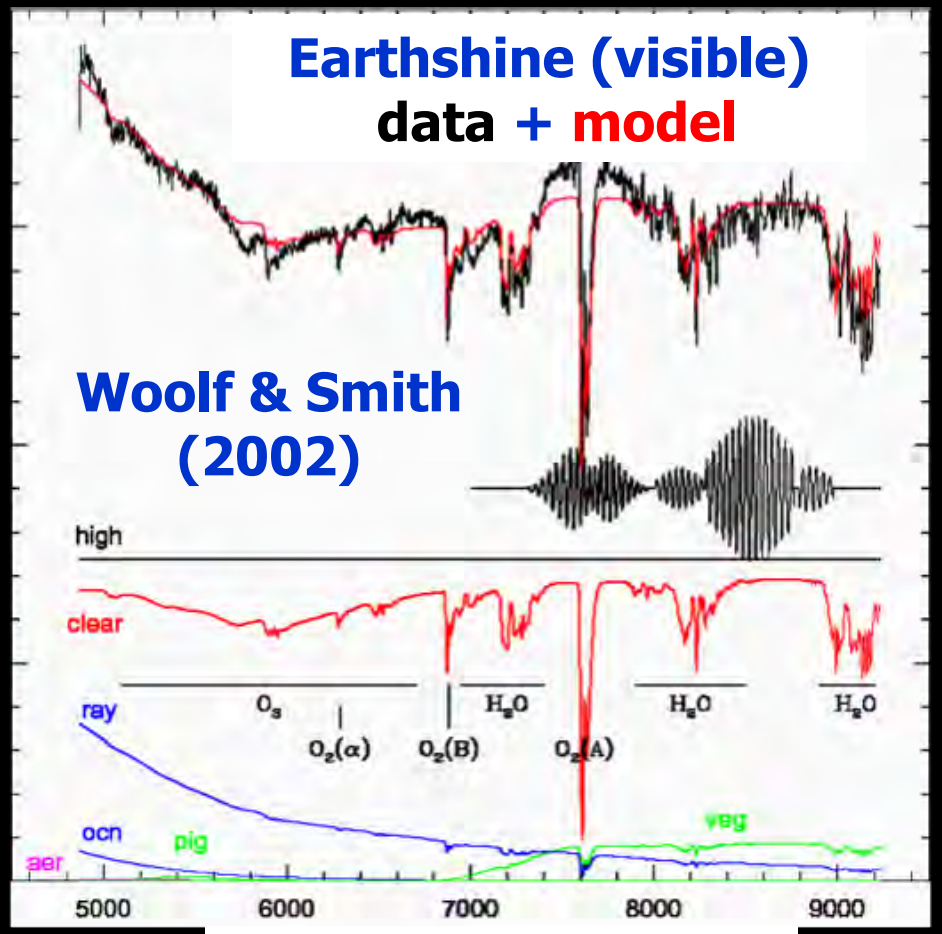
Search for signatures of life on "Earth" with Galileo mission (1990)

- Launched in May, 1986
- Earth observed on December 8, 1990
- ***Conclusion: it is likely that life exists on Earth !***
  - Abundant O_2
  - Red-edge of vegetation
  - CH_4 abundance out of thermal equilibrium
  - Artificial pulsed radio signal



Sagan, Thompson, Carlson, Gurnett & Hord: Nature 365(1993)715

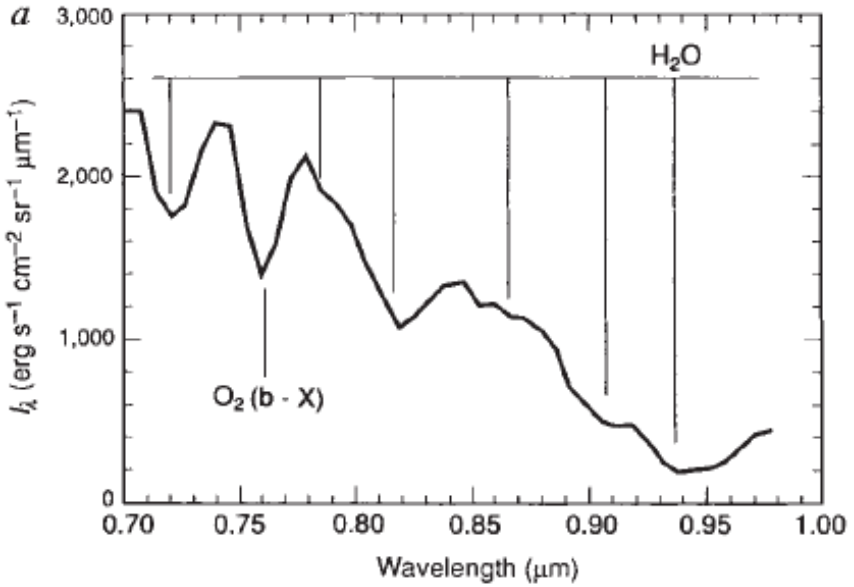
Conventional bio-signatures



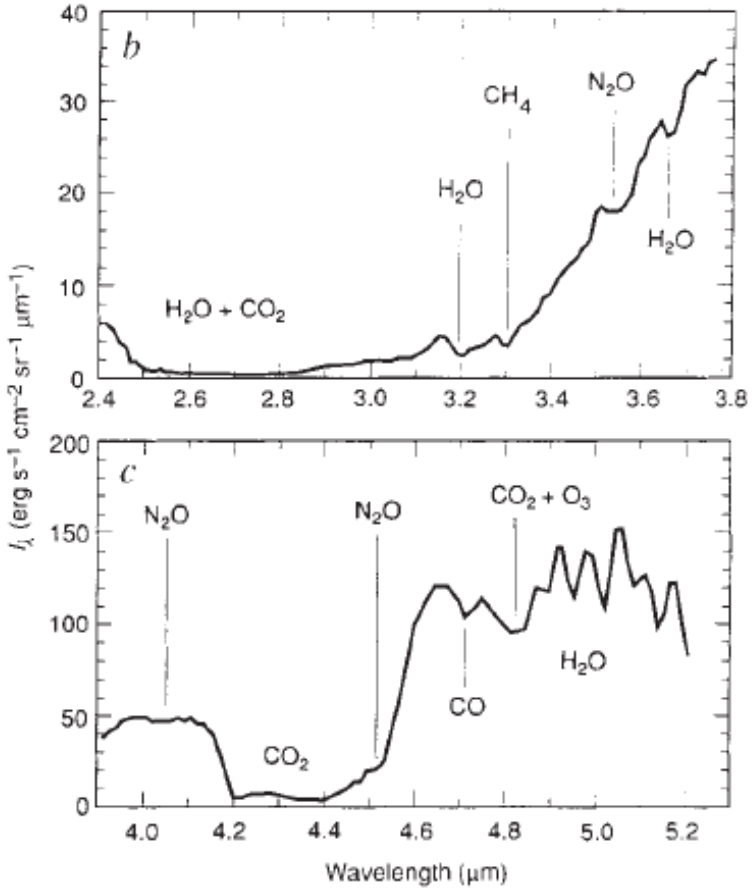
- O_2
  - A-band@0.76μm
  - B-band@0.69μm
- H_2O
  - 0.72, 0.82, 0.94μm
- O_3
  - Chappuis band@(0.5-0.7)μm
  - Hartley band@(0.2-0.3)μm

Kasting et al. arXiv:0911.2936
"Exoplanet characterization and the search for life"

Sagan et al. (1993): spectrum of atmosphere



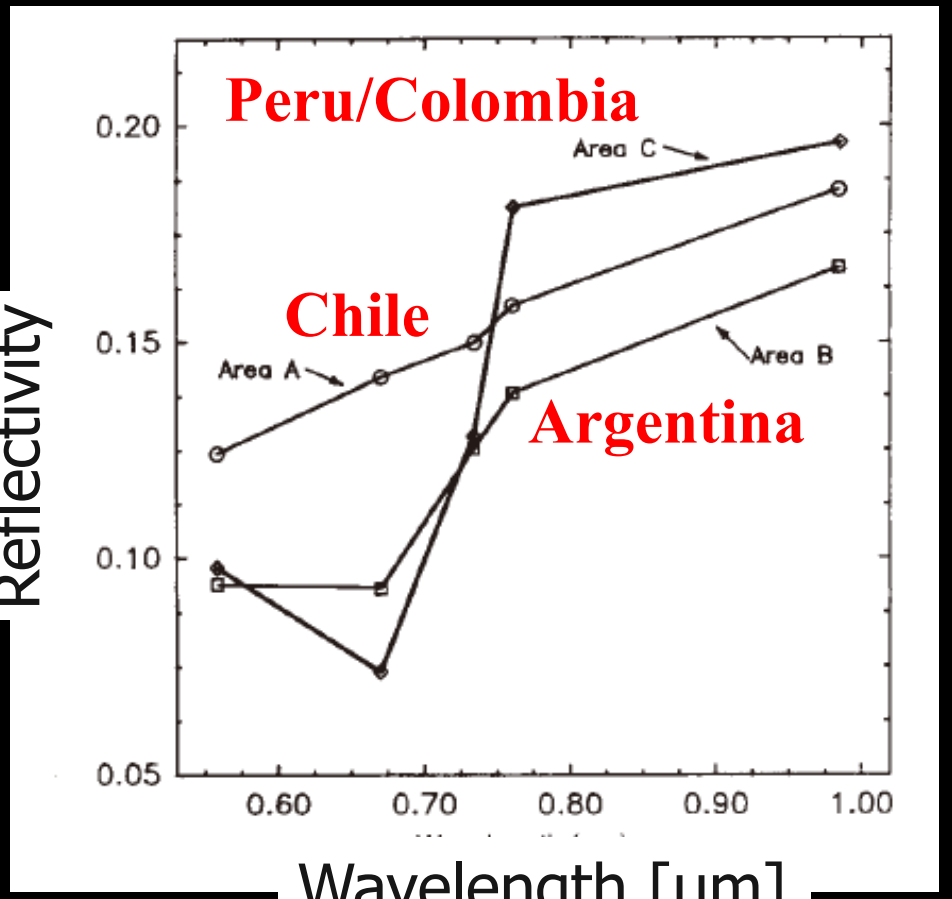
Strong O_2 absorption @A-band(0.76μm)



the Earth over a relatively cloud-free region of the Pacific Ocean, north of Borneo. The incidence and emission angles are 77° and 57° respectively. The ($b'\Sigma_g^+$—$X^3\Sigma_g^-$) 0–0 band of O_2 at 0.76 μm is evident, along with a number of H_2O features. Using several cloud-free regions of varying airmass, we estimate an O_2 vertical column density of 1.5 km-amagat ± 25%. *b* and *c*, Infrared spectra of the Earth in the 2.4–5.2 μm region. The strong υ_3 CO_2 band is seen at the 4.3 μm, and water vapour bands are found, but not indicated, in the 3.0 μm region. The υ_3 band of nitrous oxide, N_2O, is apparent at the edge of the CO_2 band near 4.5 μm, and N_2O combination bands are also seen near 4.0 μm. The methane (0010) vibrational transition is evident at 3.31 μm. A crude estimate[10] of the CH_4 and N_2O column abundances is, for both species, of the order of 1 cm-amagate (≡1 cm path at STP).

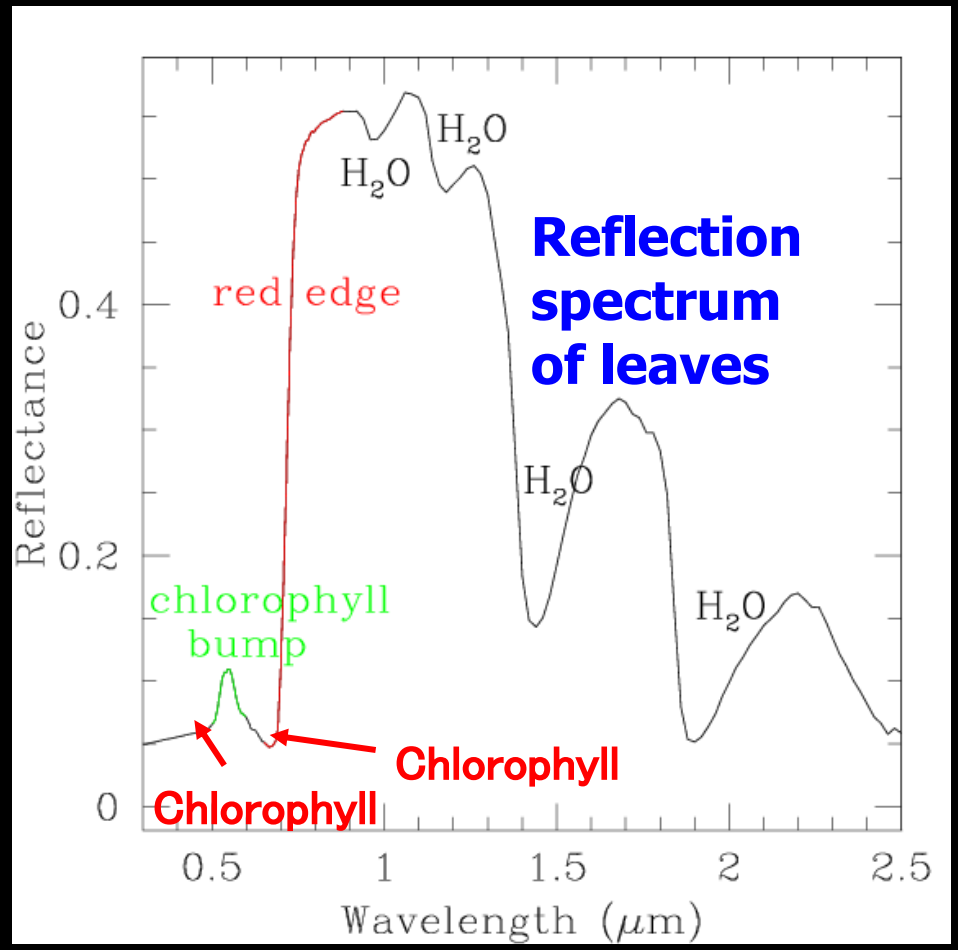
Sagan et al. (1993): colors of the earth

Red-edge of the vegetation on the earth detected by the Galileo mission



Red edge of *(exo)plants:* a possible bio-signature in *exoplanets*

- Red-edge
  - Significant increase of reflectivity of leaves on Earth (terrestrial planets) for λ>7000Å
- Widely used in remote-sensing of our Earth



Seager, Ford & Turner astro-ph/0210277

Sagan et al. (1993): radio observation

Detection of pulsed radio signals unlikely of natural/astronomical origin

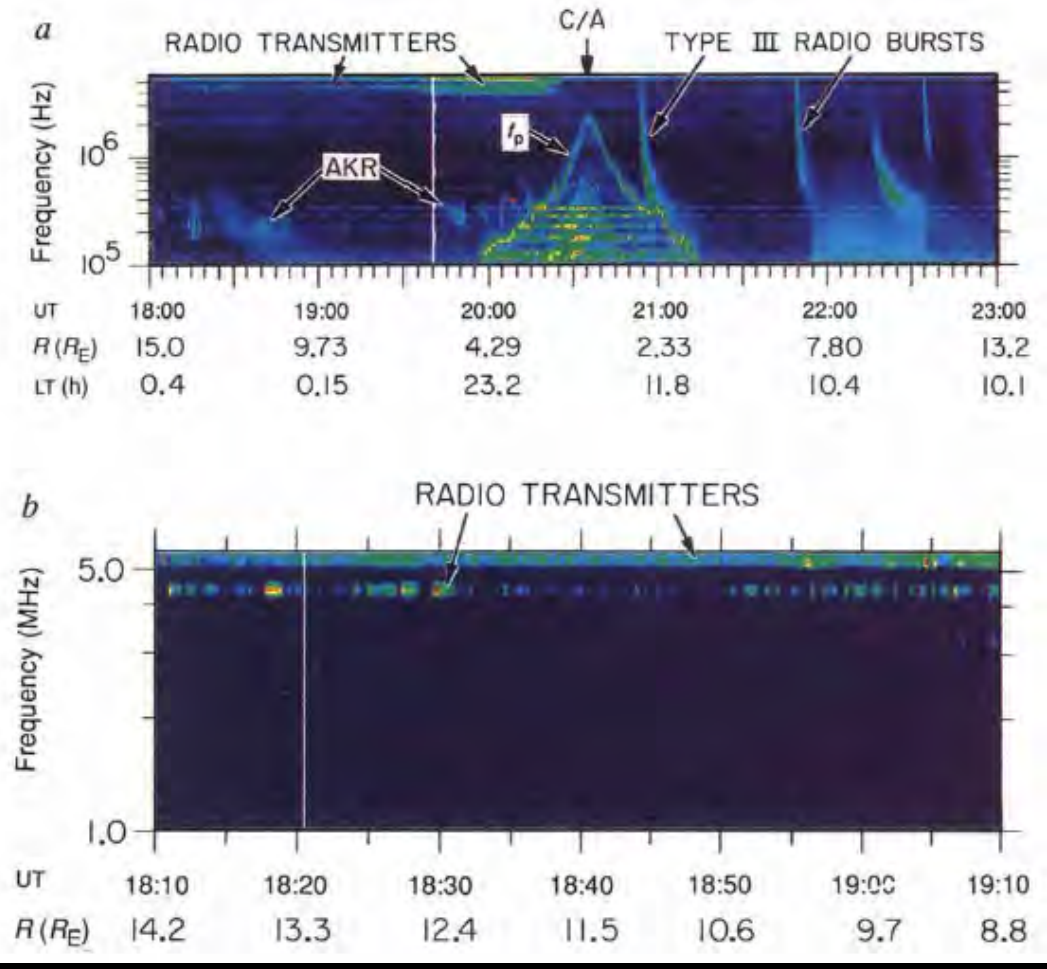


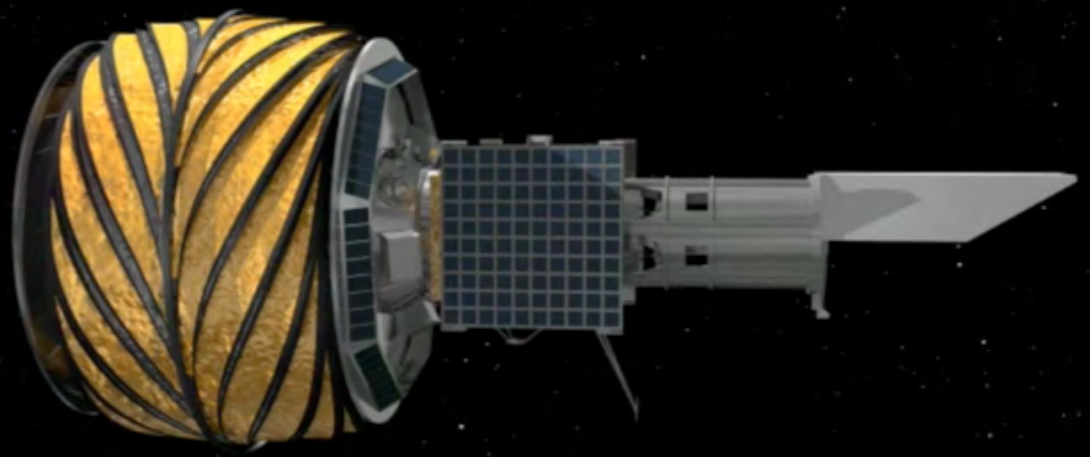
FIG. 4 A frequency–time spectrogram of the radio signals detected by the Galileo plasma wave instrument. The intensities are coded in the sequence blue–green–yellow–red, with blue lowest and red highest. Several natural sources of radio emission are shown in *a*, including auroral kilometric radiation (AKR). Modulated emission at $f > 4$ MHz is shown with an expanded time scale in *b*. Modulated patterns of this type are characteristic of the transmission of information, and would be highly unusual for a naturally occurring radio source. (UT, universal time; *R* is distance of Galileo from Earth in units of Earth's radius, R_E; LT, local time.)

4 Remote-sensing of a second Earth

There's hundreds of billions of stars in the Galaxy.
You've looked at only a handful. Wouldn't you
say it's a little premature to give up?
You've done one-billionth of the problem.
Probably much less than that,
if you consider other frequencies

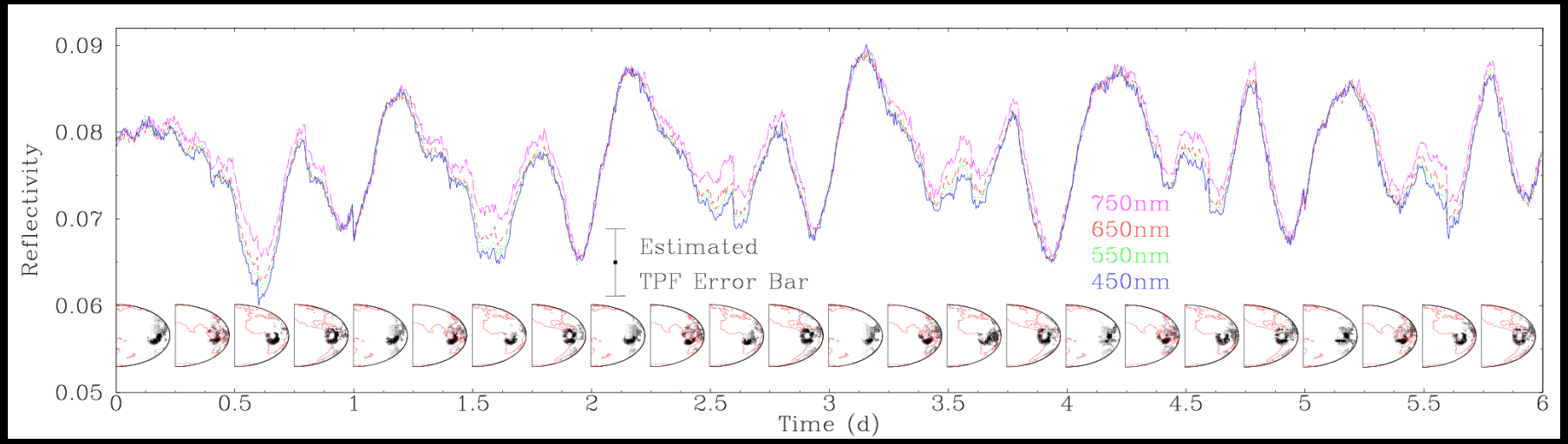
— Carl Sagan "Contact"

Starshade project:
direct imaging of a second earth



Space telescope + occulting satellite at 50,000km away!
(Princeton Univ. + JPL/Caltech)

Expected daily change of the reflected light of the earth



Ford, Seager & Turner: Nature 412 (2001) 885

- *Assume* that the earth's reflected light is completely separated from the Sun's flux !
- *Periodic change of 10% level* due to different reflectivity of land, ocean, forest
- Cloud is the most uncertain factor: *weather forecast !*

Colors of a Second Earth: estimating the fractional areas of ocean, land and vegetation of Earth-like exoplanets

ApJ. 715(2010)866, arXiv:0911.5621

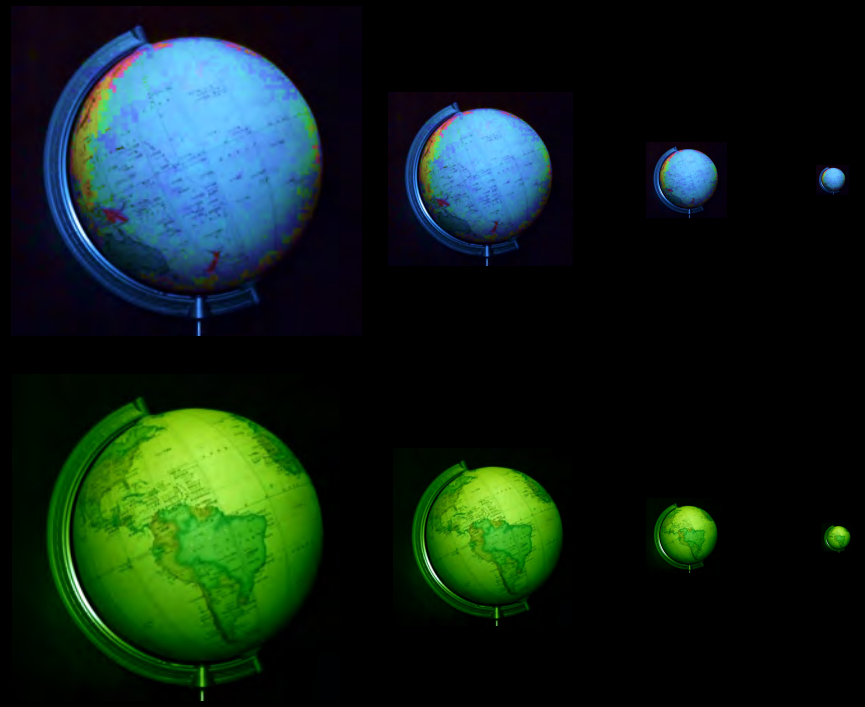
Colors of a Second Earth. II: Effects of Clouds on Photometric Characterization of Earth-like Exoplanets

ApJ. 738(2011)184, arXiv:1102.3625

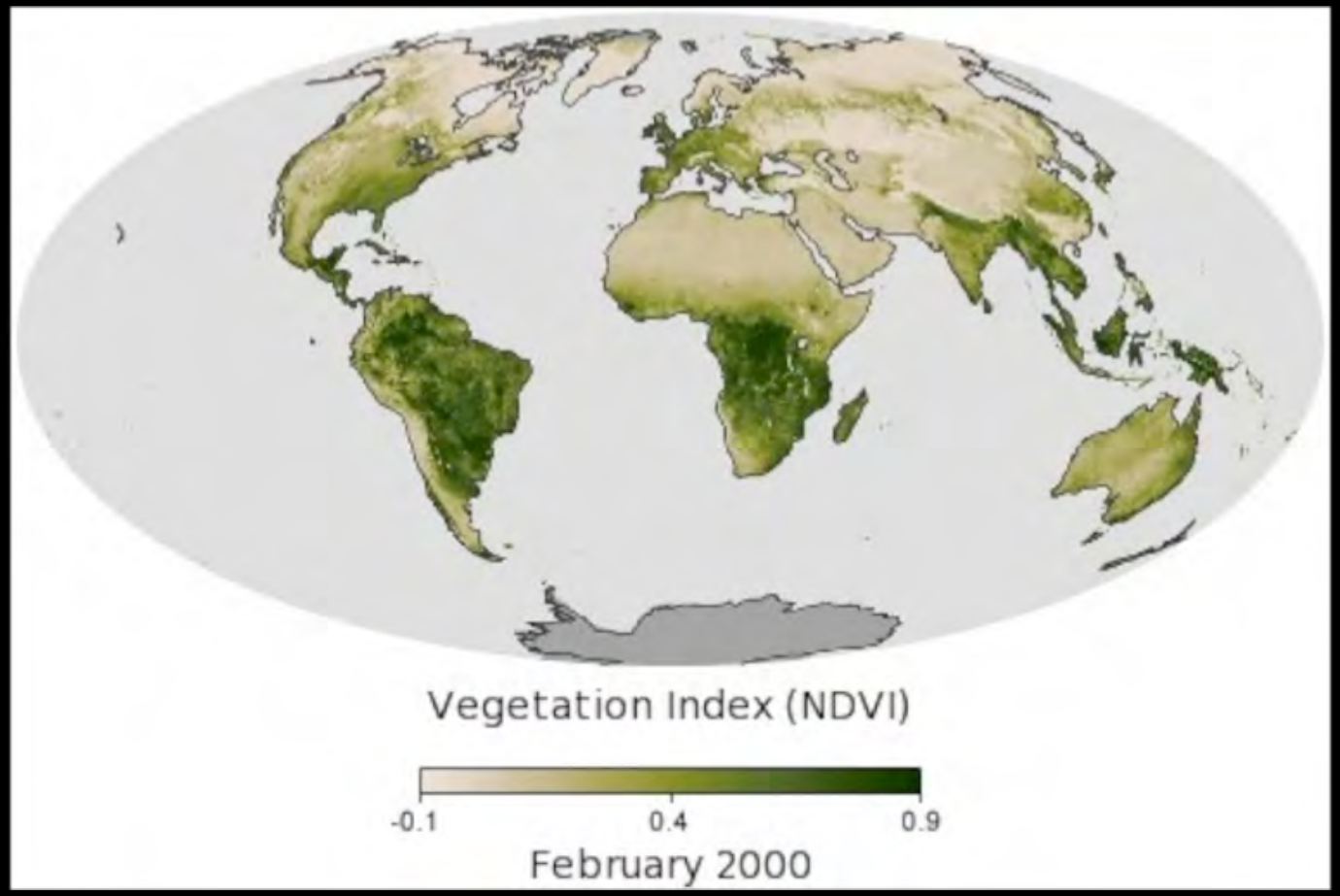
- Yuka Fujii, H.Kawahara, A.Taruya, Y.Suto (Dept. of Phys., Univ. of Tokyo), S.Fukuda, T.Nakajima (Center of climate system research, Univ. of Tokyo), Edwin Turner (Princeton Univ.)

Colors of a second earth

- Beyond a pale blue dot
  - Impossible to spatially resolve the surface of a second earth
  - Color should change due to the rotation
  - A second earth = a color-changing dot

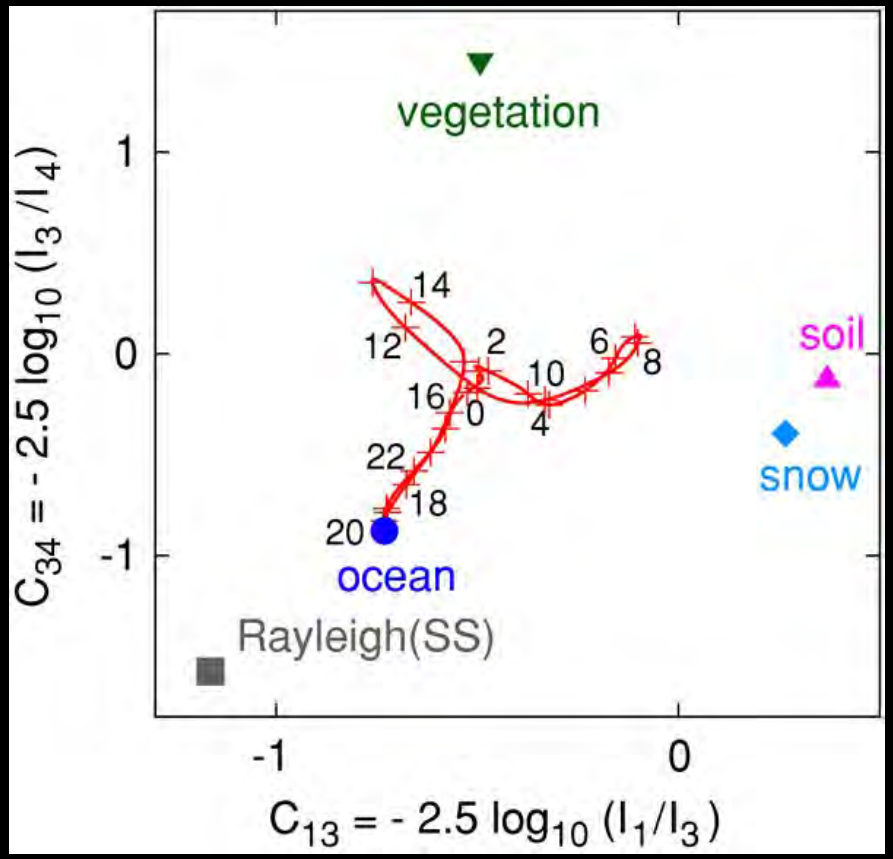


annual vegetation global map by the earth-observing satellite Terra

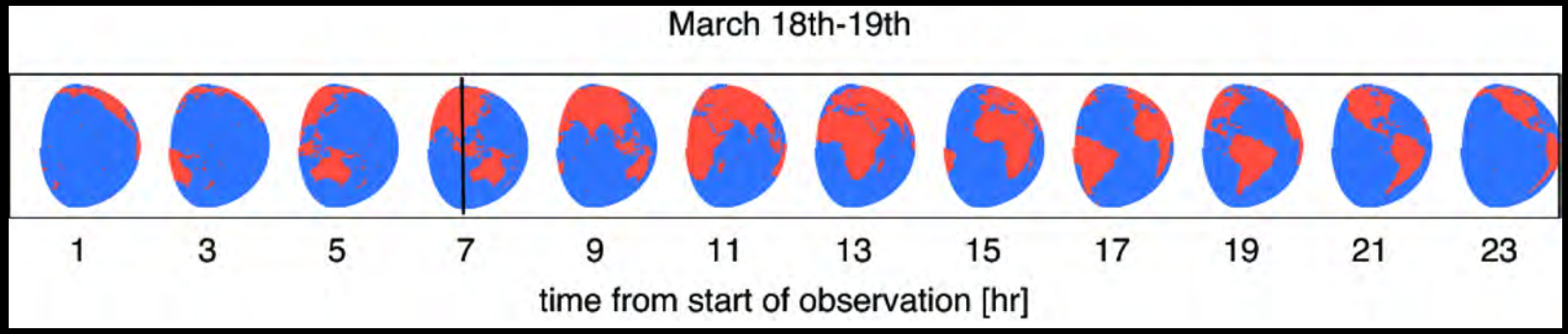


http://earthobservatory.nasa.gov/GlobalMaps/

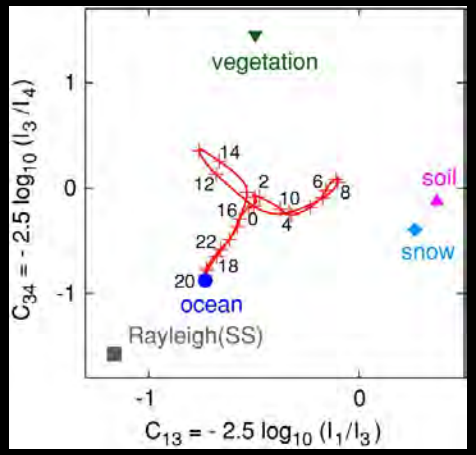
Colors of our earth



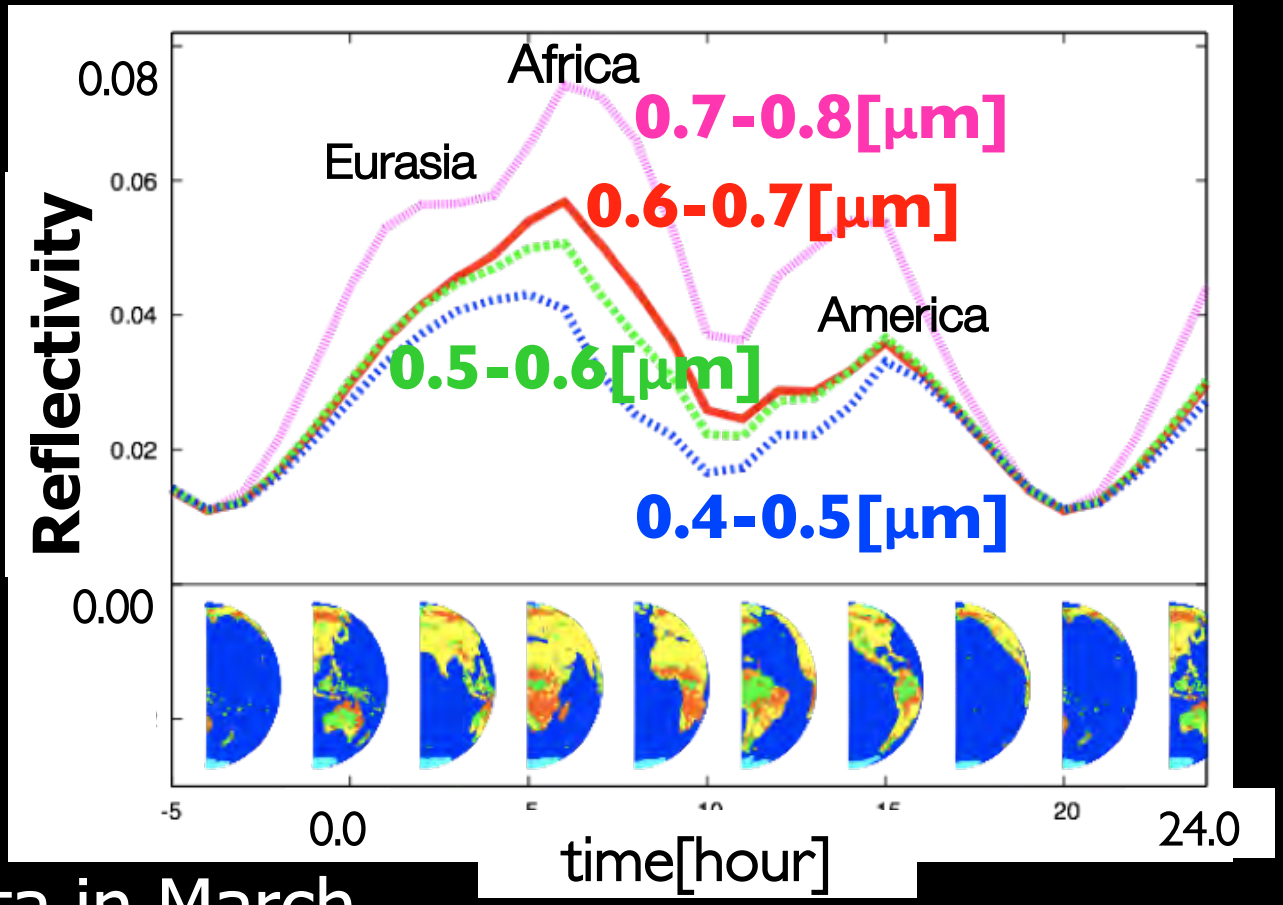
Fujii et al. (2010)



A pale blue dot ? Not really



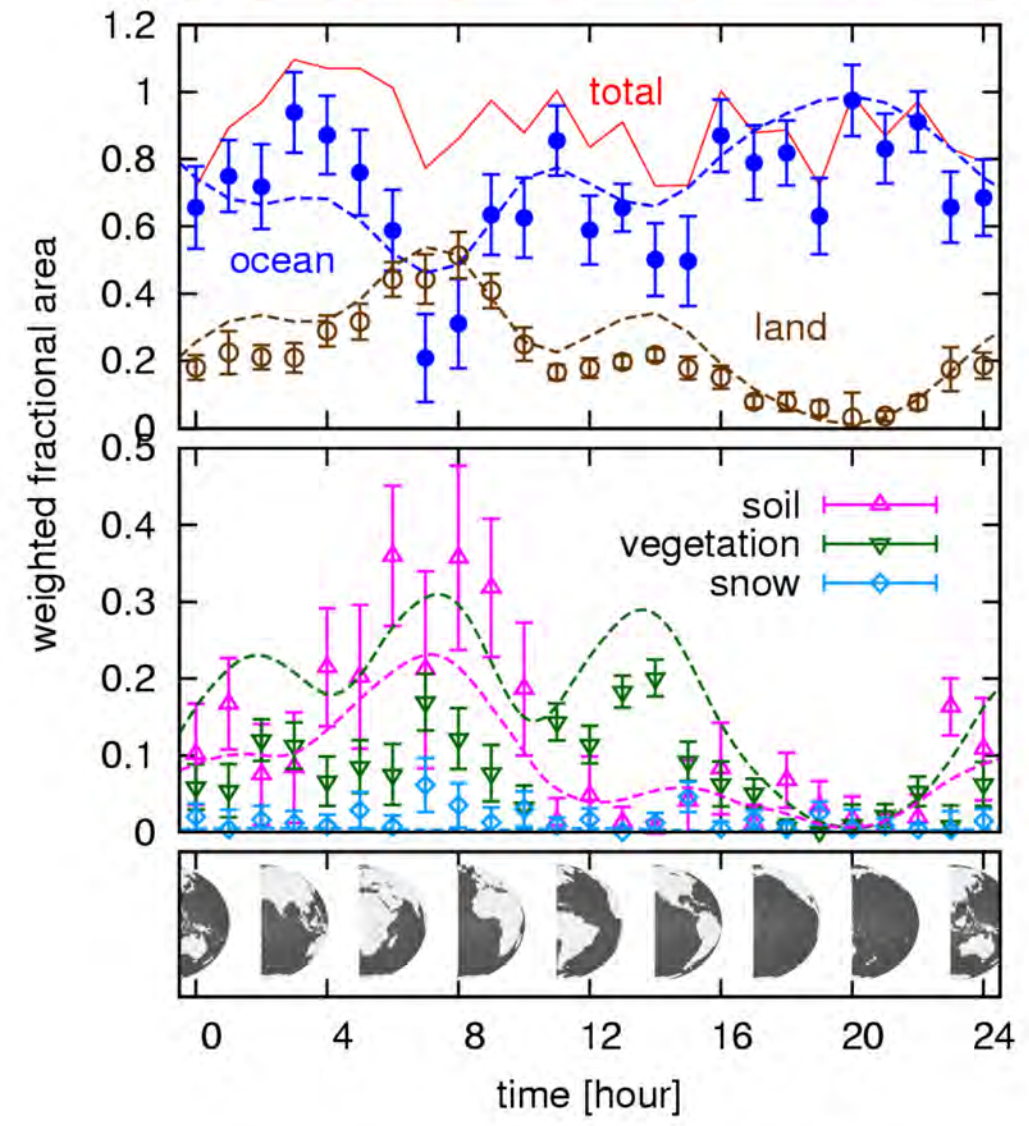
Simulated photometric light-curves of Earth



- Adopted Earth data in March
- Spin inclination = 0 (edge-one view at vernal equinox)
- cloudless

Fujii et al. (2010)

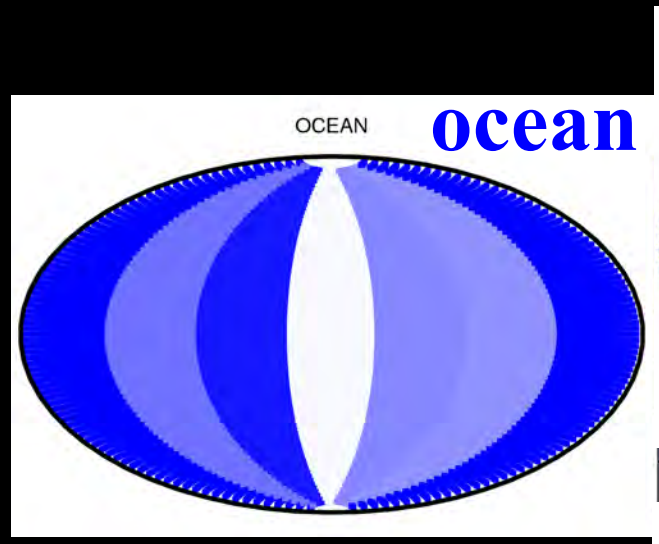
Estimating fractional areas of surface components from colors of a second earth

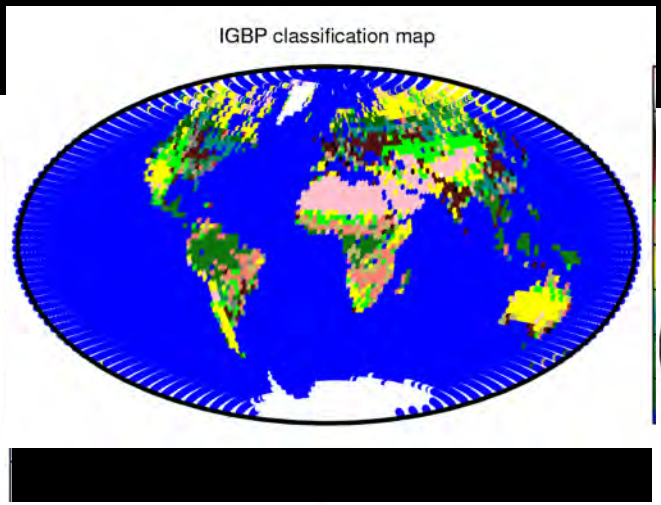


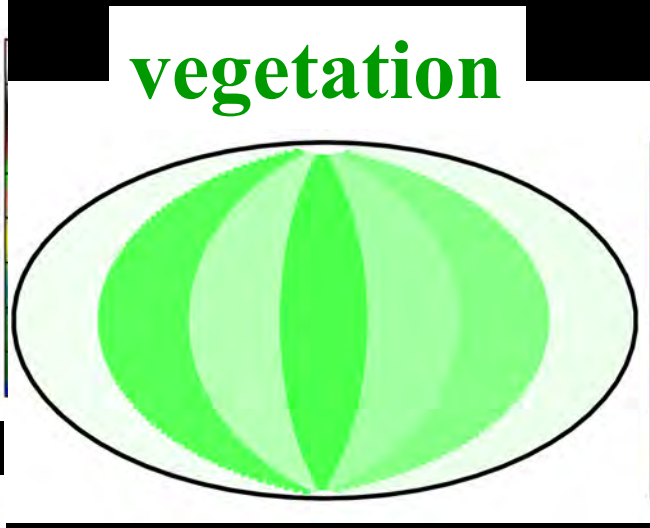
- 2 week mock observation of a *cloudless* Earth at 10 pc away with 6m space telescope
- Reasonably well reproduced
- possible to identify vegetation !

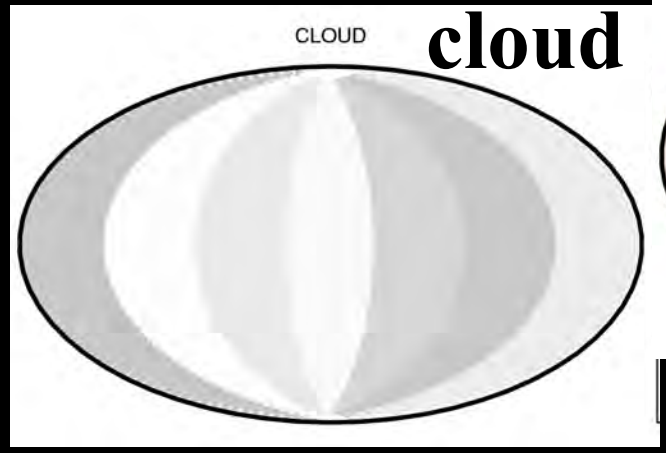
Fujii et al.（2010）

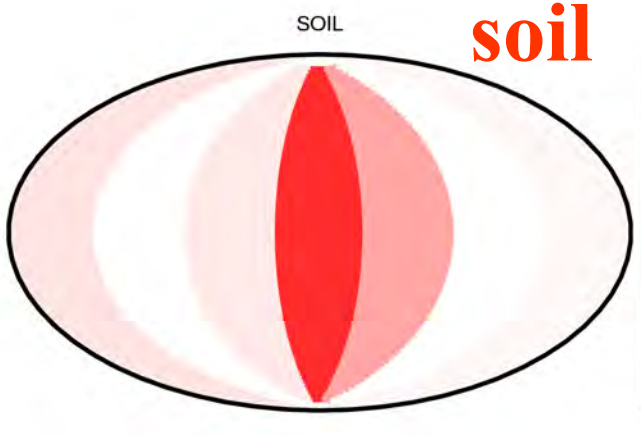
Surface latitude map estimated from real satellite data *with cloud model*

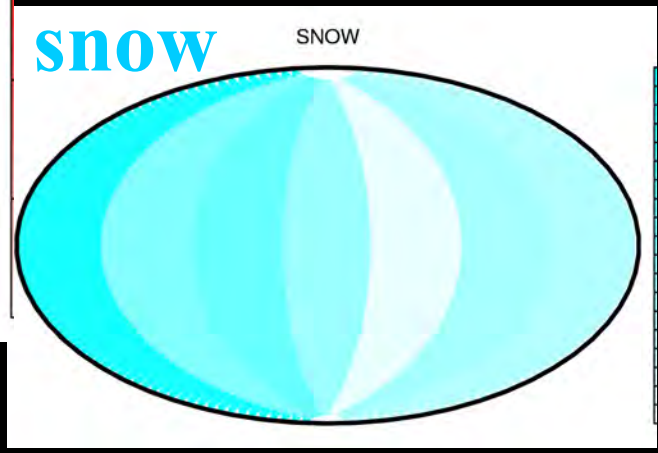












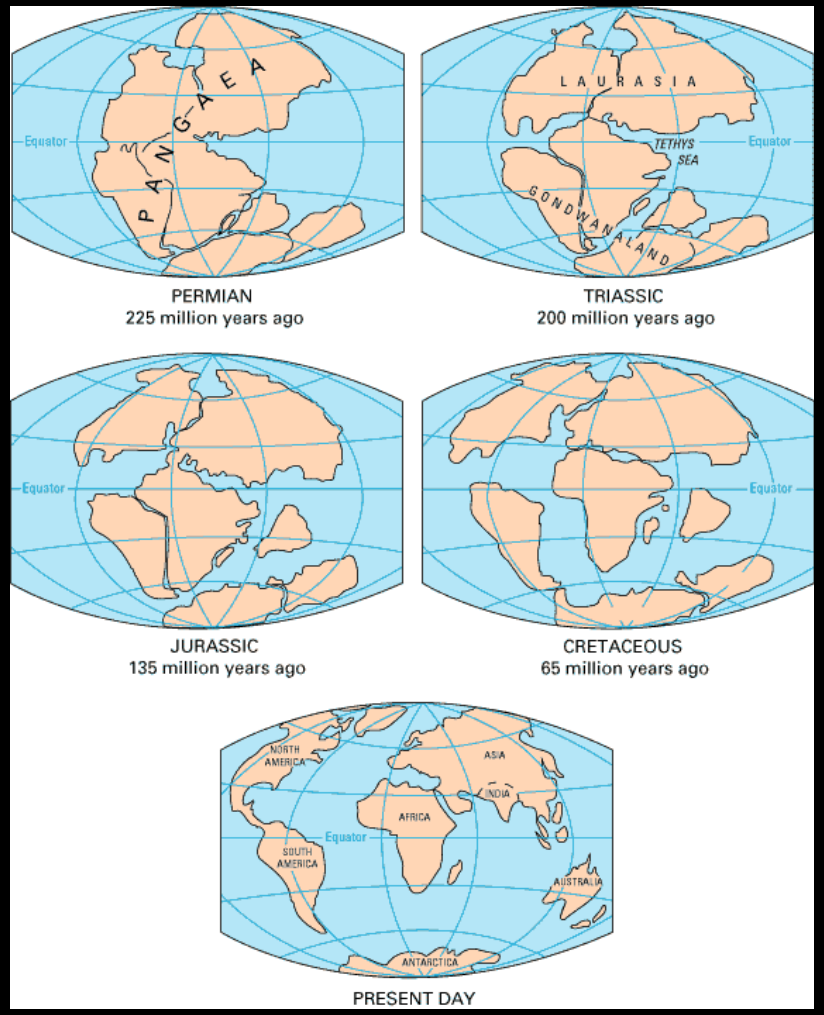
Fujii et al. (2011)

Nakagawa et al. (2020) tomorrow's talk Mock analysis of "Earth" simulated with GCM (general circulation model)

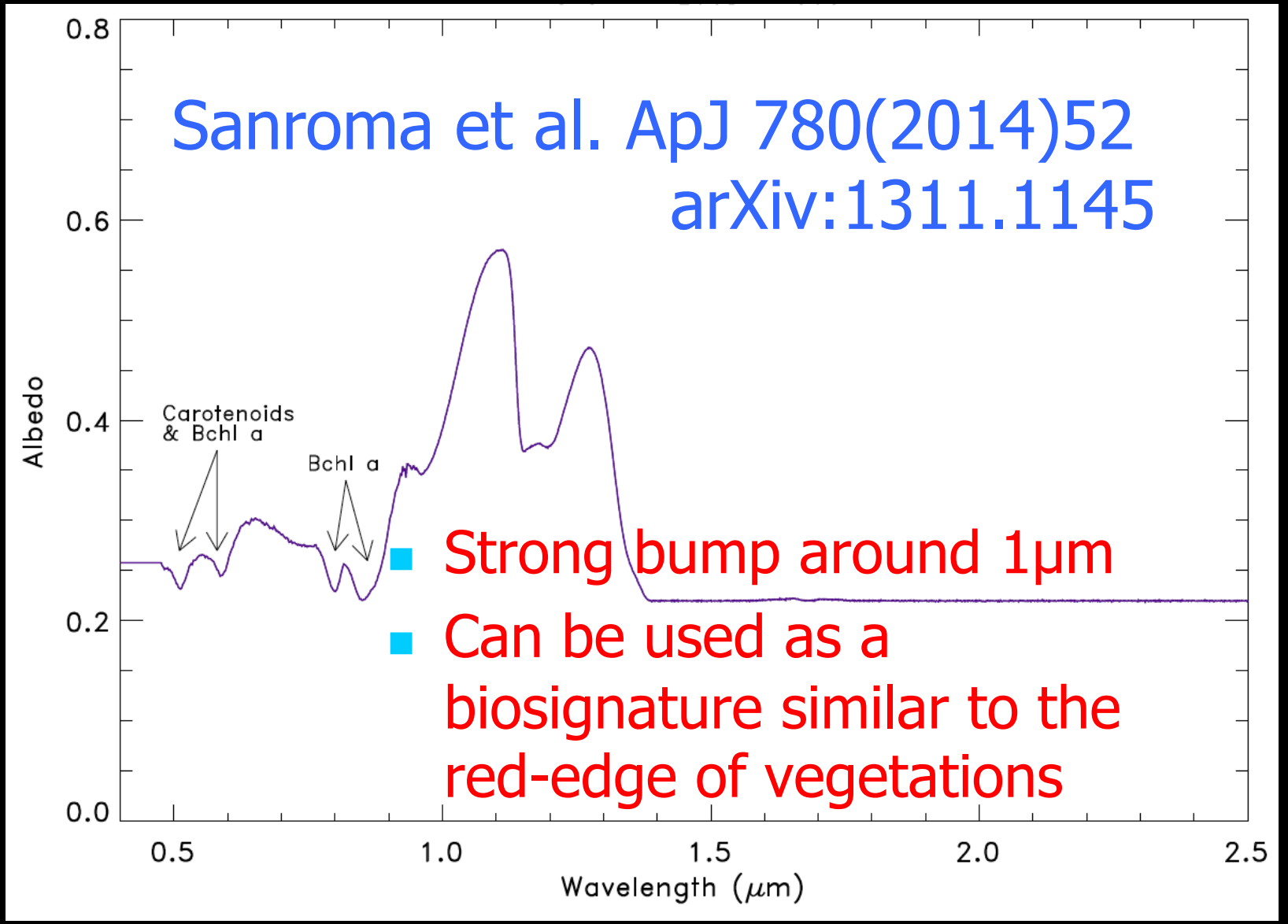
- GCM code for planetary climate simulation
  - DCPAM5 (Dennou-Club Planetary Atmospheric Model) http://www.gfd-dennou.org
  - (longitude, latitude, pressure altitude)=(32,64,26)
  - Surface data from Earth+Obliquity ζ [deg]=0, 30, 60, 90, 150, 180
- Radiation transfer code libRadtran to compute lightcurves
- Frequency modulation analysis to estimate the planetary obliquity based on Kawahara (2016)

Purple bacteria (~3Gyr ago) as a possible bio-signature before the vegetation on land

Sanroma et al. ApJ 780(2014)52



Reflection spectrum of purple bacteria



"The color of plants on other worlds"
N.Kiang, Scientific American (2008)

5 SETI: Search for Extra-Terrestrial Intelligence

Adolf Hitler! It makes me furious.
Forty million people die to defeat that
megalomaniac, and he's the star of the first
broadcast to another civilization?
He's representing us. And them.
It's that madman's dream come true.

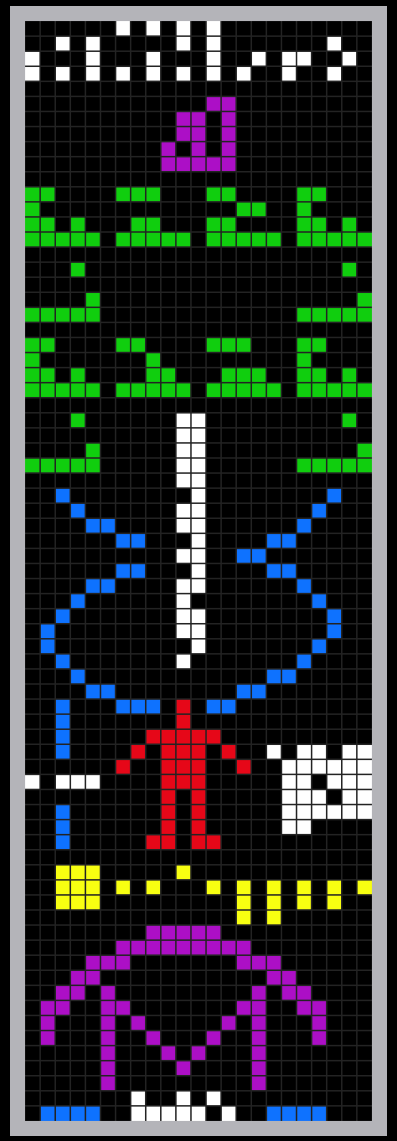
— Carl Sagan "Contact"

SETI: Search for Extra-Terrestrial Intelligence

- **Conventional bio-signatures are suggestive for biological origin, but could be abiotic as well**
- **Artificial electromagnetic signals are the most unambiguous evidence for life/advanced civilizations**
  - Radio band 1GHz<f<20GHz is well suited
  - Lower frequency signals are contaminated by Galactic synchroton,
  - Higher frequency signals are dominated by atmospheric noises
- **Project Ozma (1960)**
  - Frank Drake used a 26m radio telescope to examine the stars Tau Ceti and Epsilon Eridani around 1.4GHz for 150 hours over 4 months
  - A false signal was detected on April 8, 1960, which turned out to have originated from a high-flying aircraft

Arecibo message (1974)

- Frank Drake sent a radio message from Arecibo radio observatory on November 16, 1974 towards globular cluster M13 (25,000 light-year away)
- The message (73x23 bits), if decoded properly, should look like this, apparently assuming that aliens can recognize the pattern "visually".



1 to 10 in binary

Atomic numbers of H, C, N, O, P that form DNA in binary

Formulas for the sugars and bases in the nucleotides of DNA

Double helix of DNA

Human and the human population on earth

The solar system

Arecibo radio telescope

6 Proxima Centauri b

Alpha Centauri was a triple system, two suns tightly orbiting one another, and a third, more remote, circling them both.

What would it be like to live on a world with three suns in the sky?

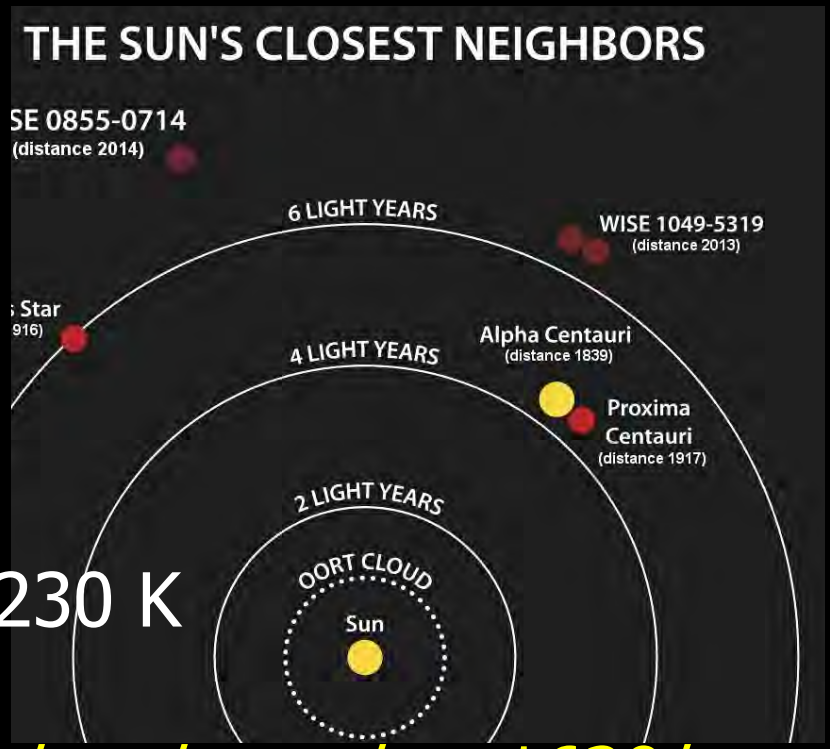
— Carl Sagan "Contact"

A terrestrial planet candidate in a temperate orbit around Proxima Centauri

- G.Anglada-Escude et al.

  Nature 25 August 2016 issue, 536(2016)437

- Proxima Centauri b
  - Orbital period 11days
  - M_p sin i =1.3 M_{earth}
  - Eccentricity < 0.35
  - Semi-major axis = 0.05 AU
  - Equilibrium temperature = 230 K



http://www.eso.org/public/usa/news/eso1629/

Breakthrough Initiatives

http://breakthroughinitiatives.org/Initiative

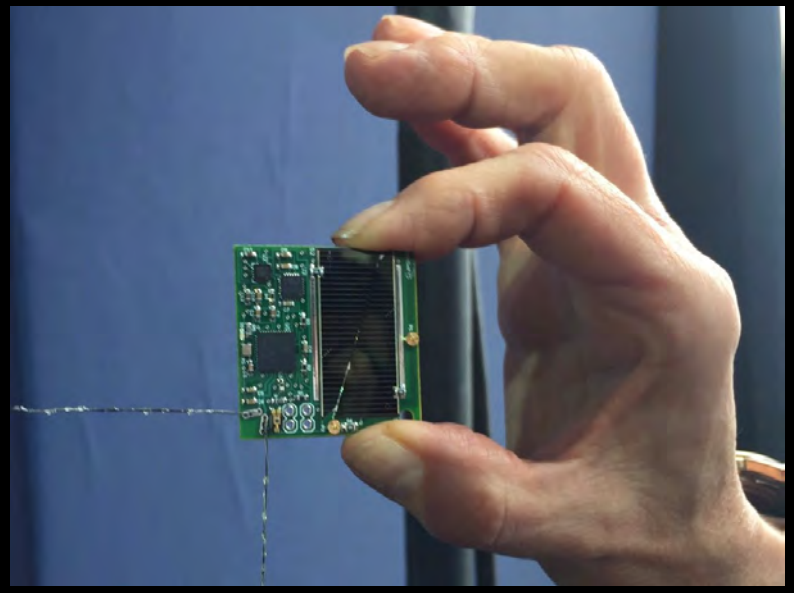
- A program founded on July 20, 2015 by a Russian internet investor Yuri Milner to search for extraterrestrial intelligence
  - Breakthrough Listen to discover signs of extraterrestrial civilizations through radio and laser transmissions
  - Breakthrough Message to study the ethics of sending messages into deep space
  - Breakthrough Starshot to develop a proof-of-concept light sail spacecraft fleet capable of making the journey to Alpha Centauri

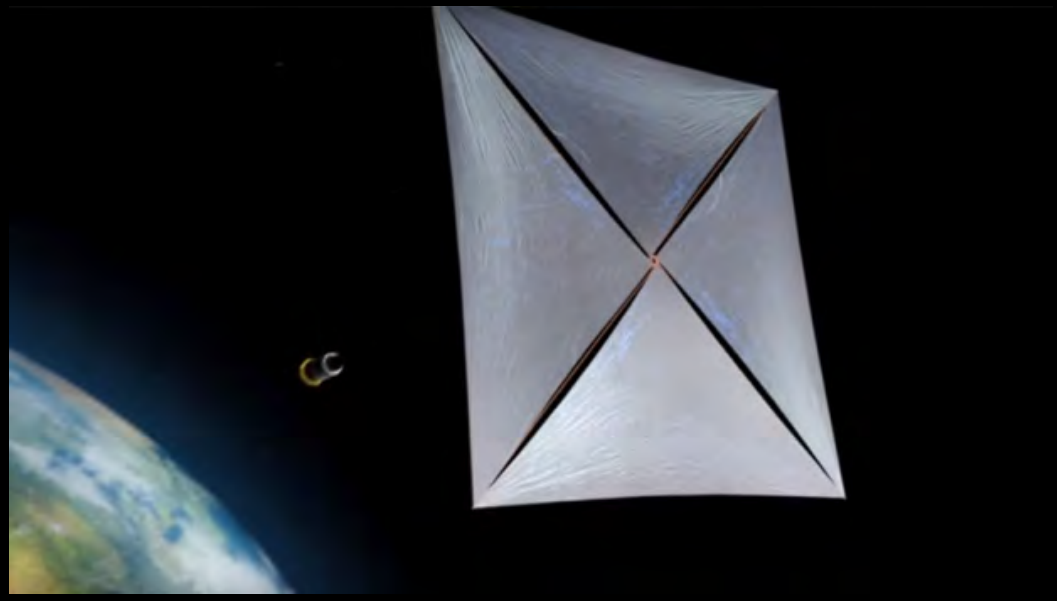
Breakthrough Starshot

http://breakthroughinitiatives.org/Initiative/3

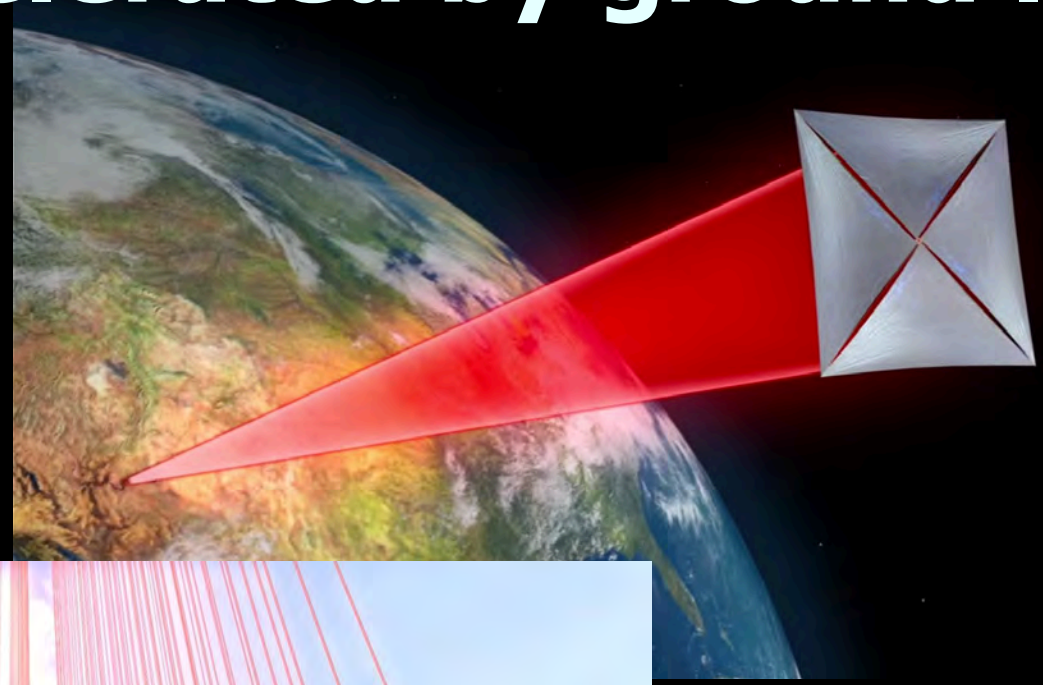
- StarChip
  - A cm-sized nano-spacecraft of several grams
  - With camera, computer, communication laser, plutonium power source, and light sail
  - A 4m × 4m light sail for each spacecraft is accelerated by the focused ground-based lasers
  - 0.2c in 10 minutes
- A fleet of 1000 StarChips to Proxima Centauri in 20 years
- Technology not available yet, but in 20 years

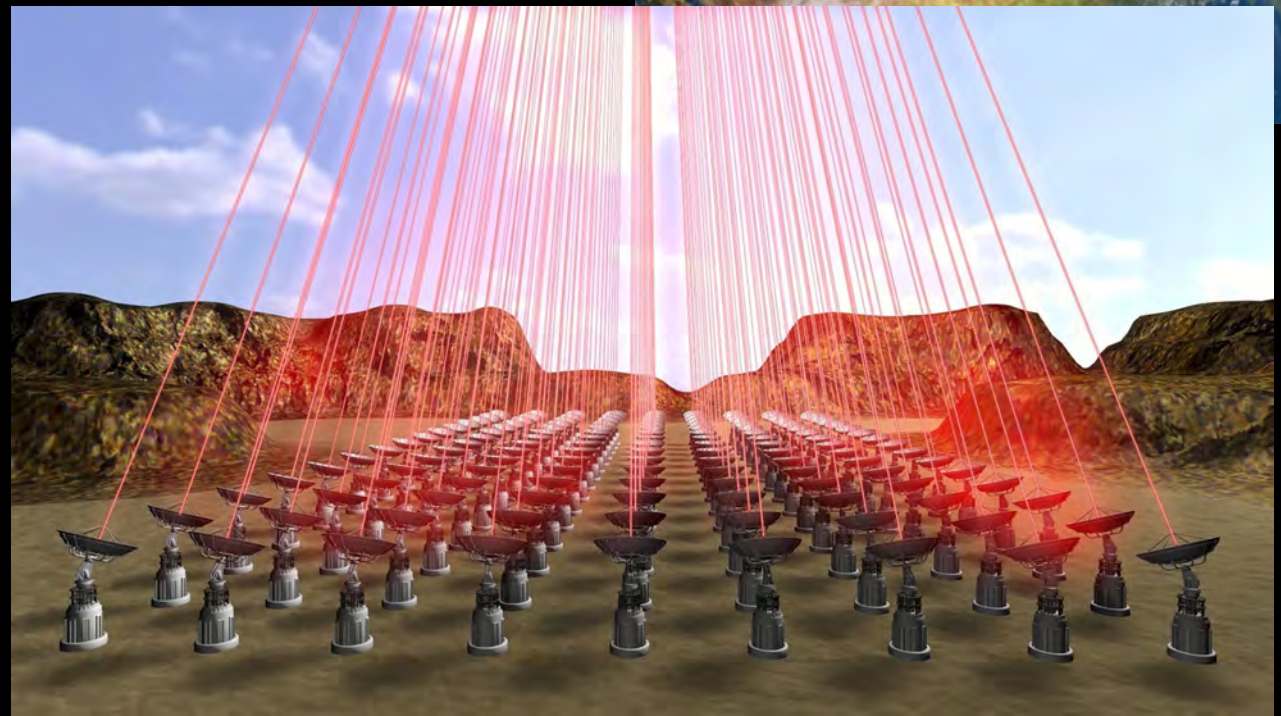
StarChip





Light sail accelerated by ground lasers





7 Summary and conclusion

We're just beginning SETI. You know how many possibilities there are. This is the time to leave every option open. This is the time to be optimistic

— Carl Sagan "Contact"

Summary: unveiling a pale blue dot

- Diurnal change of colors of another earth is challenging, but reveals the presence of ocean, land, cloud, and/or even vegetation on their surface
- Detection of oxygen, water vapor, and even the red-edge of vegetation may be a promising path towards astrobiology
- Needs more detailed GCM simulation and mock analysis

Sagan’s conclusion

Nobody's guaranteeing success.
But can you think of a more important question?
Imagine them out there sending us signals,
and nobody on Earth is listening.
That would be a joke, a travesty.
Wouldn't you be ashamed of your civilization
if we were able to listen
and didn't have the gumption to do it?

— Carl Sagan "Contact”