Colors of a second earth: from exoplanets to astrobiology

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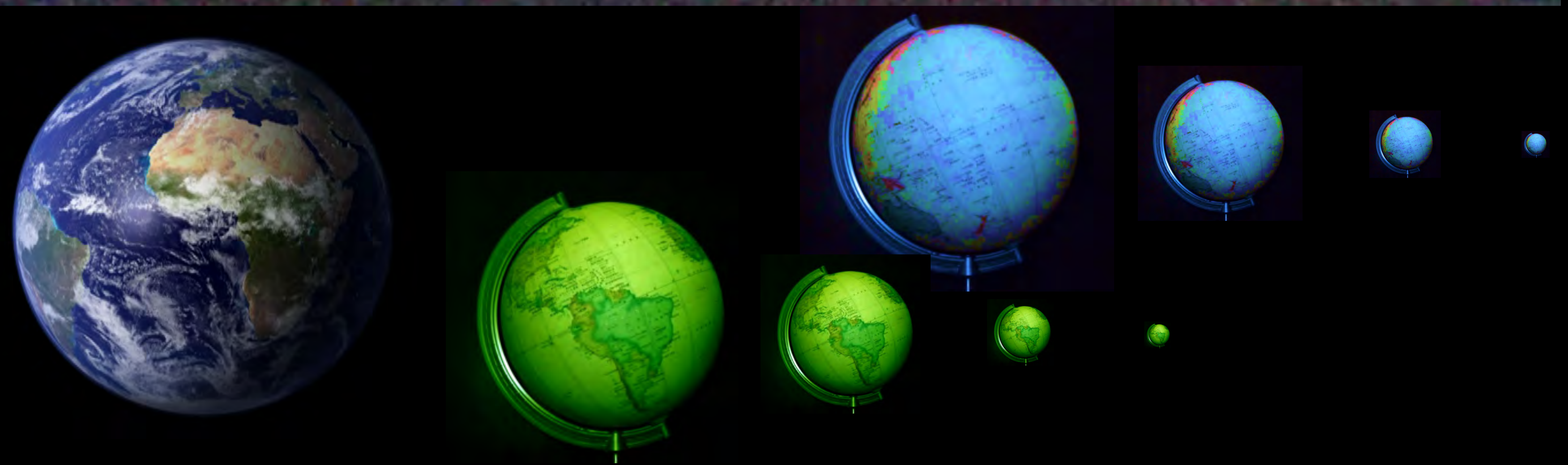
Department of Physics and Research Center for the Early Universe, the University of Tokyo

Introductory astronomy class @ Sejong University, Seoul
10:30-12:00 on Monday, September 5, 2016



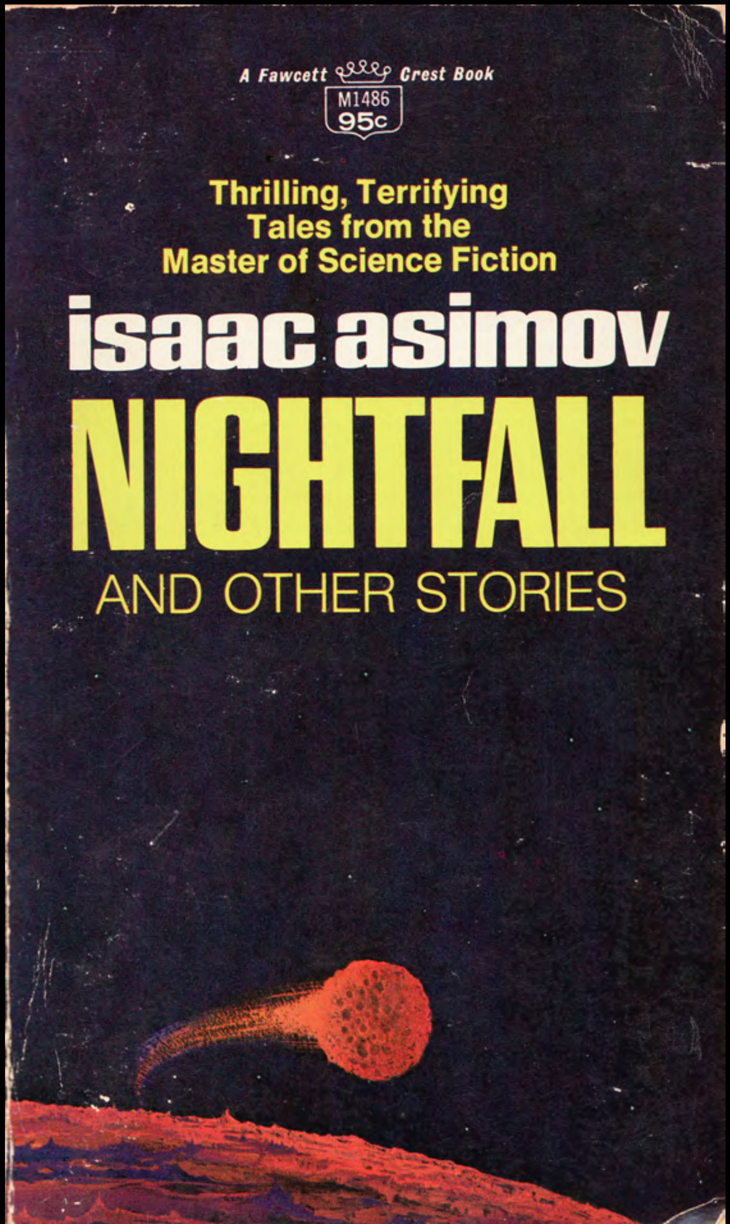
Nightfall: We didn't know anything

A short novel by Issac Asimov

(illustration: Alisa Haba)

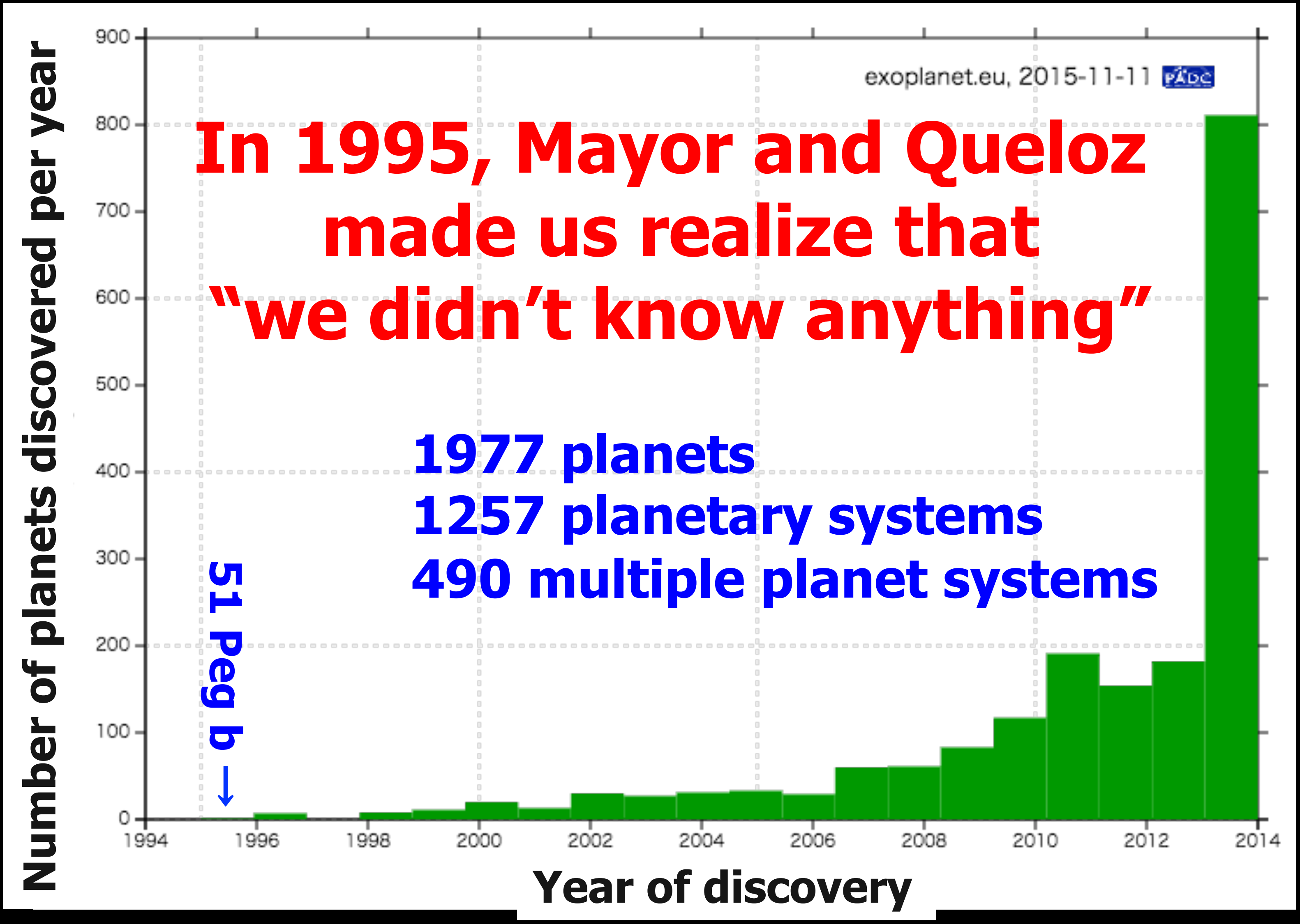
- No "night" except the total eclipse due to an inner planet every 2049 years on the planet "Lagash"
- People realized the true world for the first time

Issac Asimov: Nightfall



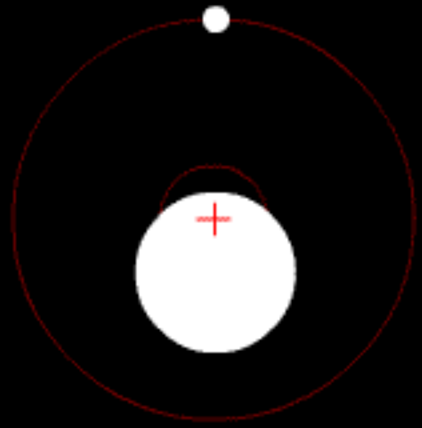
- "Light !" he screamed. Aton, somewhere, was crying, whimpering horribly like a terribly frightened child. *"Stars -- all the Stars -- we didn't know at all. We didn't know anything."*

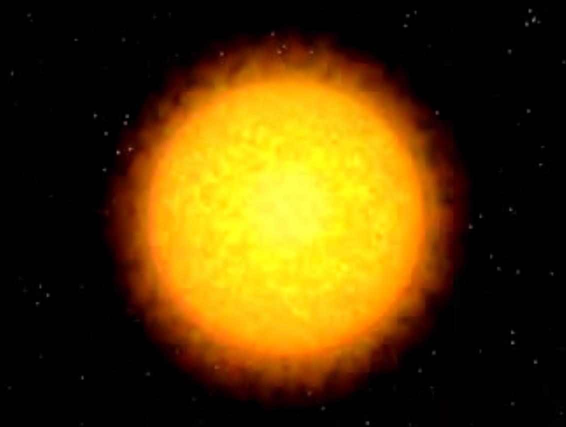
History of exoplanet discovery

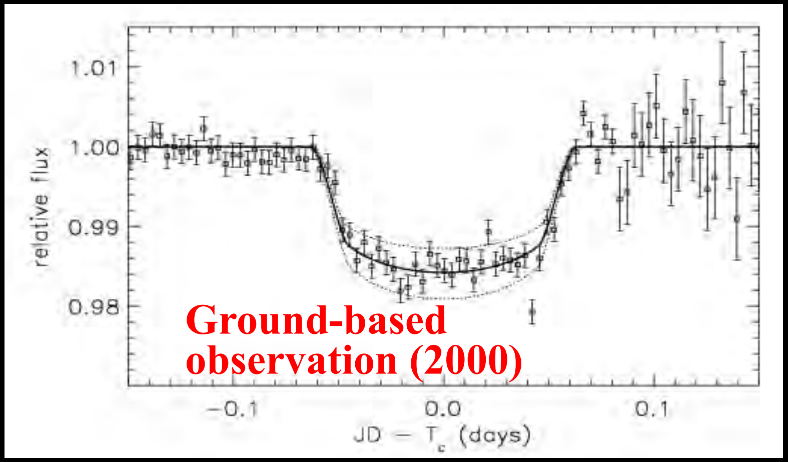


As of November 11, 2015 http://exoplanet.eu/

How to find planets ?





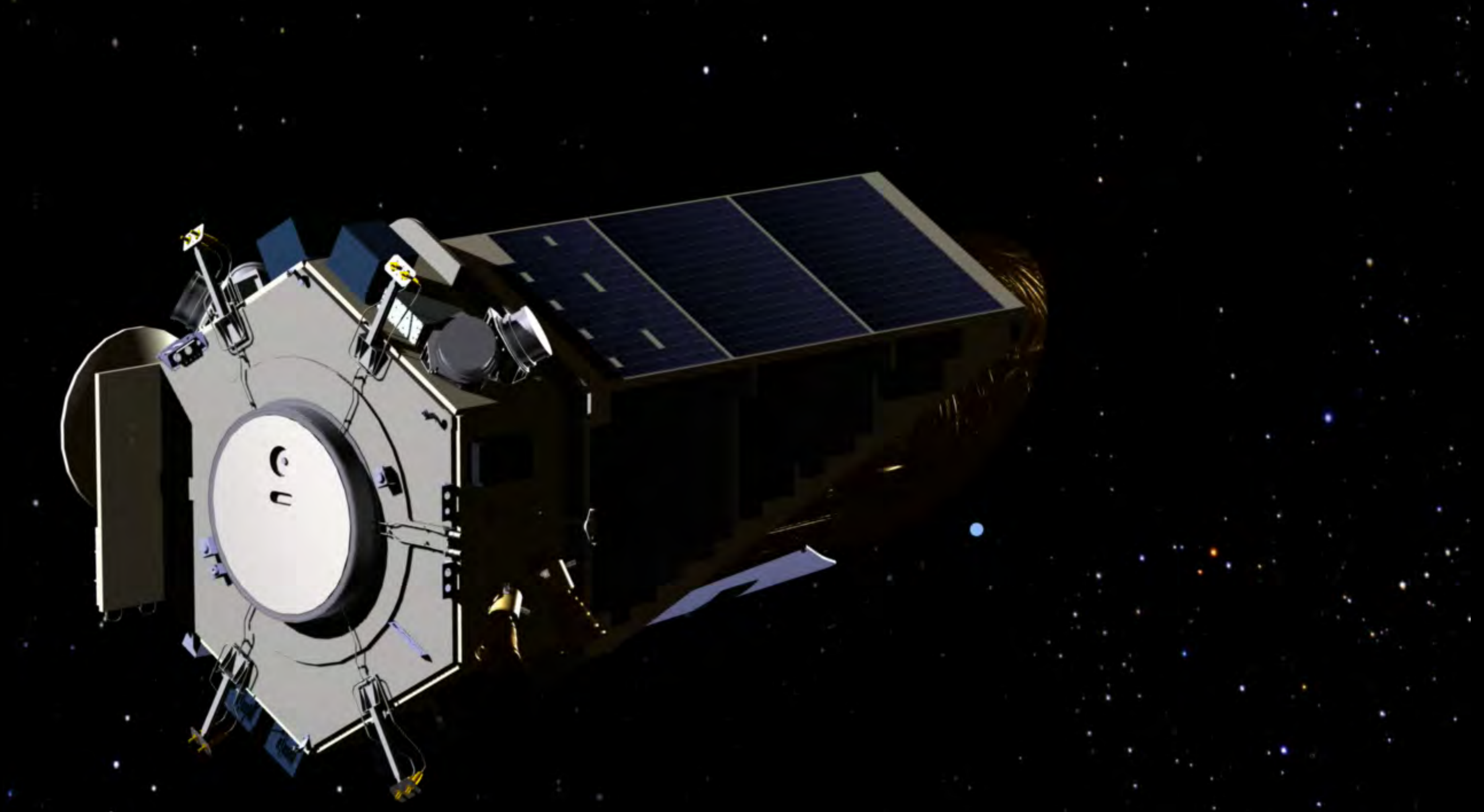


- Radial velocity
  - Periodic modulation of the velocity of star due to the presence of planets
- Transit
  - Periodic dimming of the stellar light due to the occultation of planets in front of the star
- Direct imaging
  - Separate the light from the star and planets

Kepler mission (March 6, 2009 launch)

Photometric survey of transiting planets

Searching for terrestrial/habitable planets



http://kepler.nasa.gov/

Are we alone ?

a Pale Blue Dot ?
or pale blue dots ?

Sciences with exoplanets

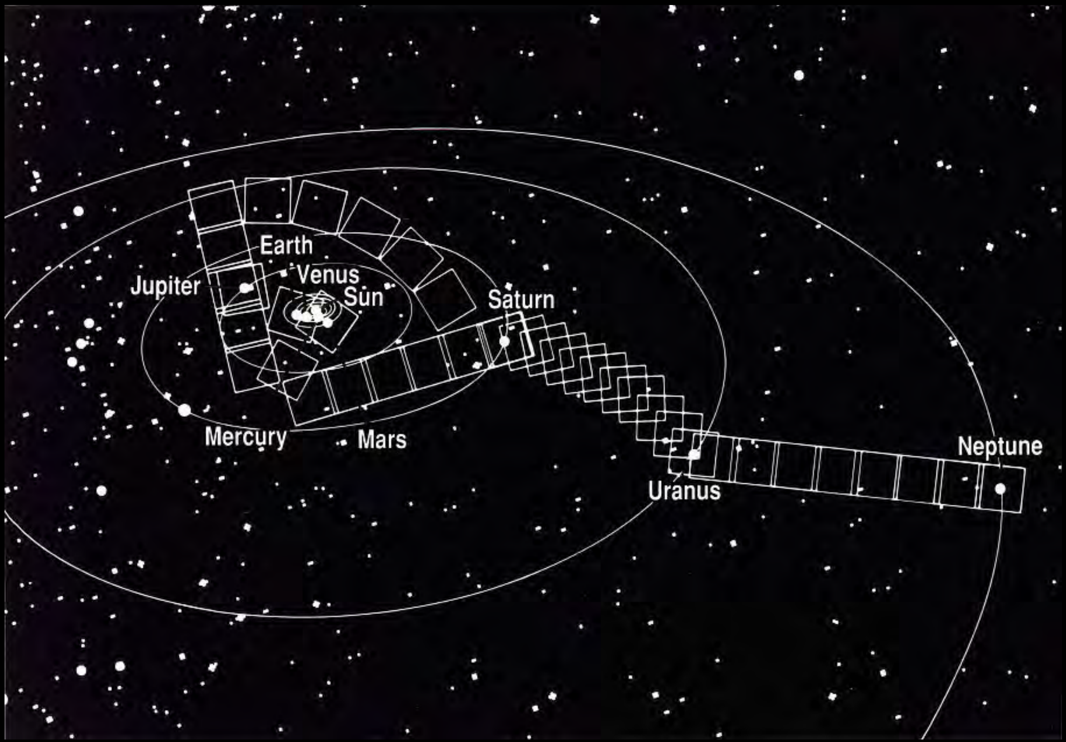
- the ***final*** question: ***Are we alone ?***
  - origin of the earth
  - origin of the Solar System
  - ***habitable*** planets ⇒ origin of life
  - signature of extra-terrestrial life ?

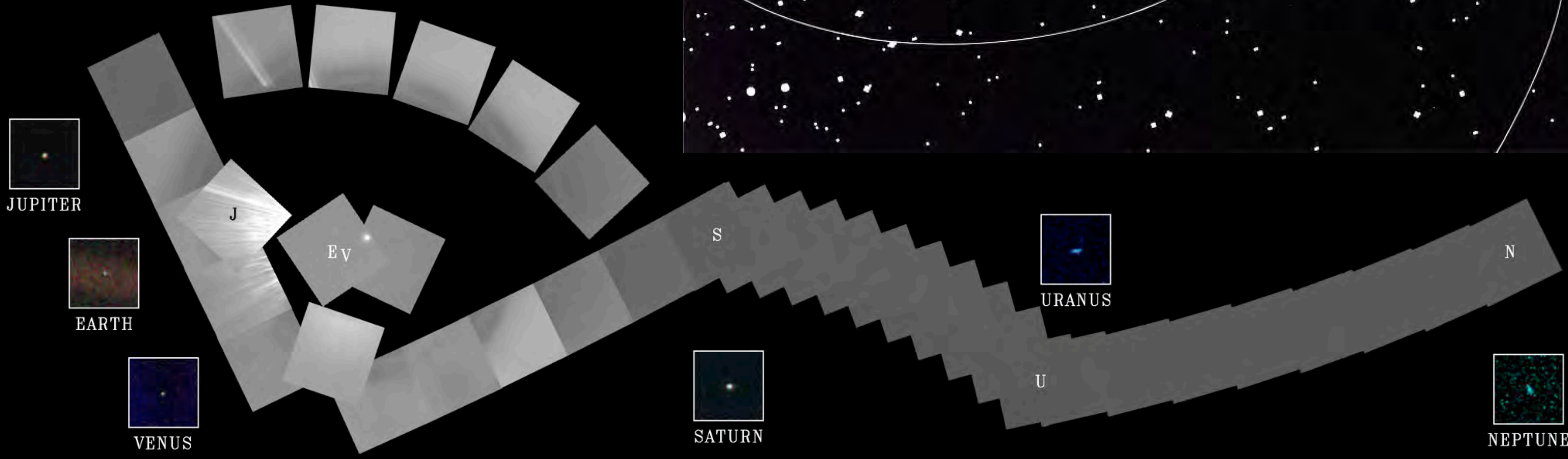
    ⇒ extra-terrestrial intelligence ?

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

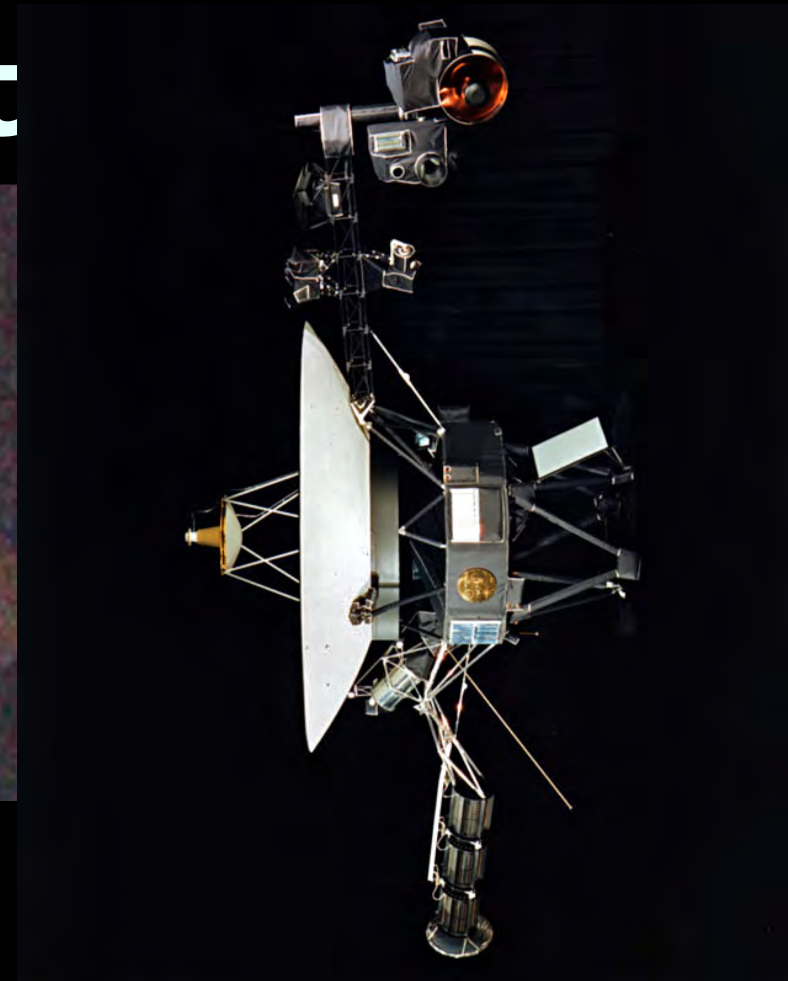
Solar planets imaged by Voyager 1 (February 4, 1990)

- Earth imaged at distance of 40 AU away
- A Pale Blue Dot coined by Carl Segan

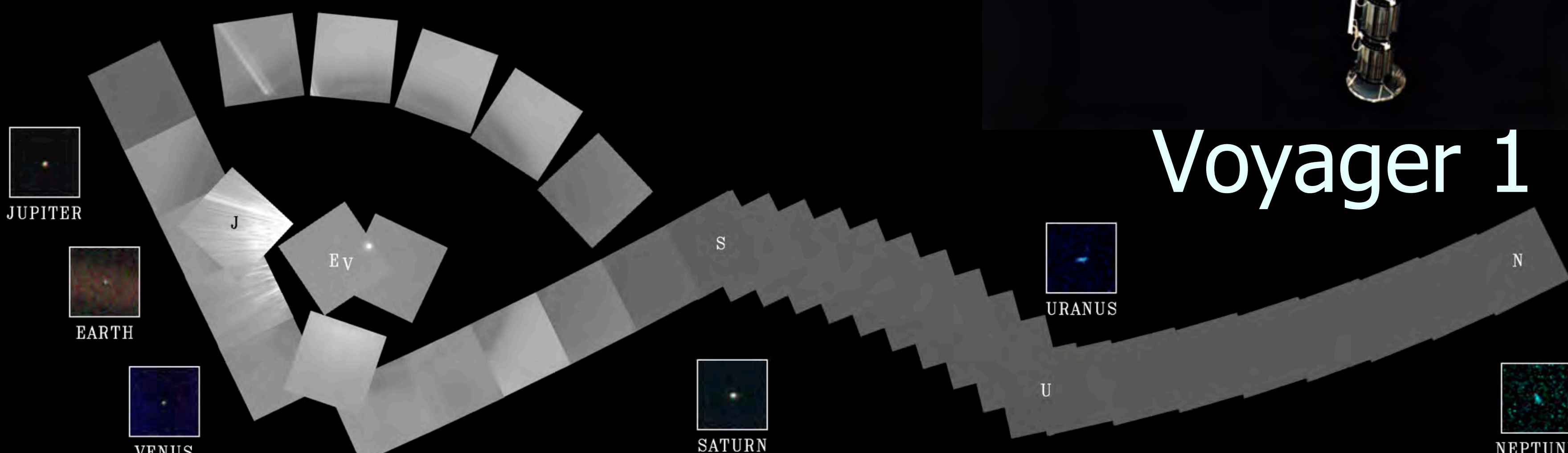




A Pale Blue Dot



Voyager 1



Earth and Moon from Saturn (2013)

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

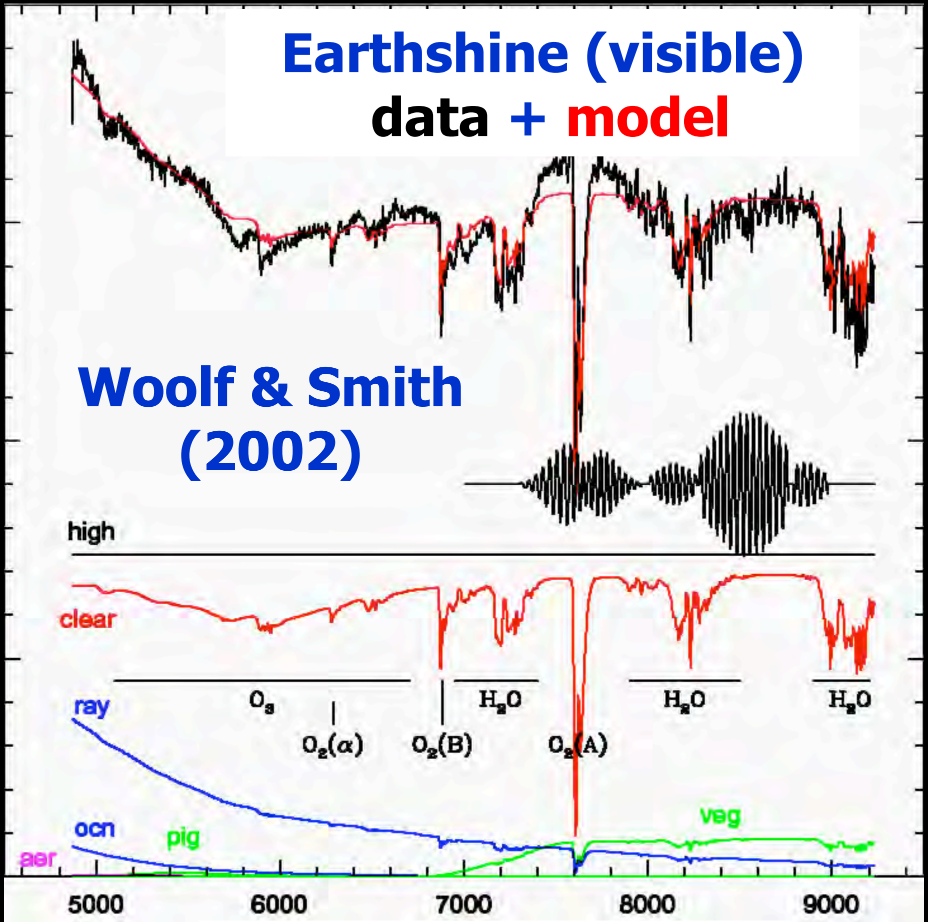
Can we detect signatures of life on our Earth ?

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

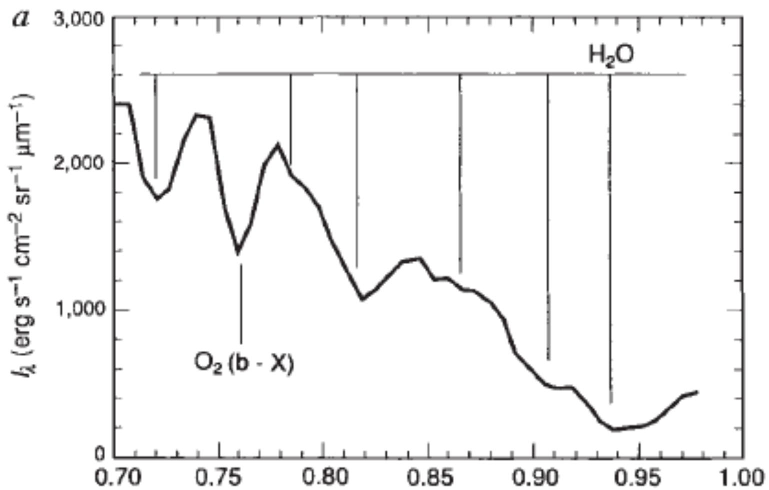


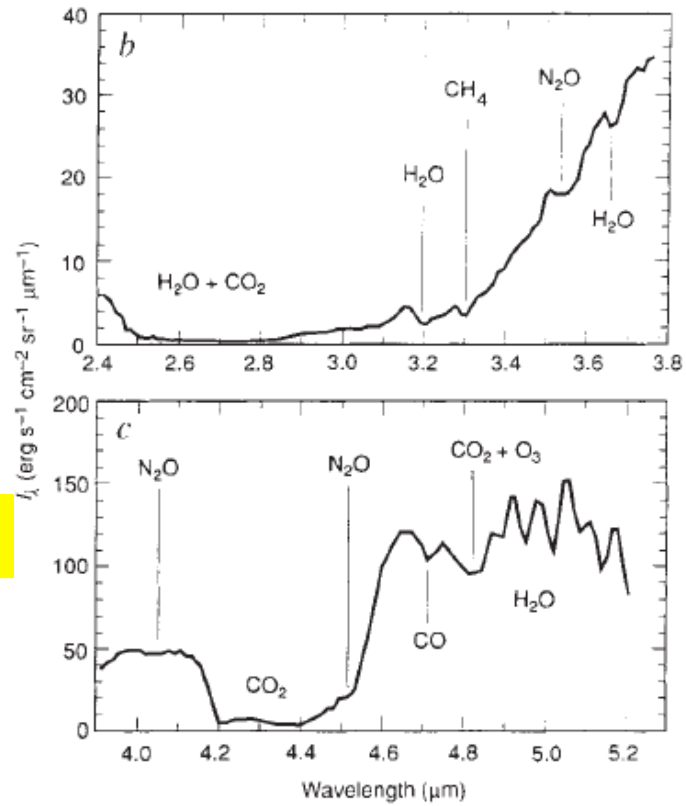
wavelength [Å]

- 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



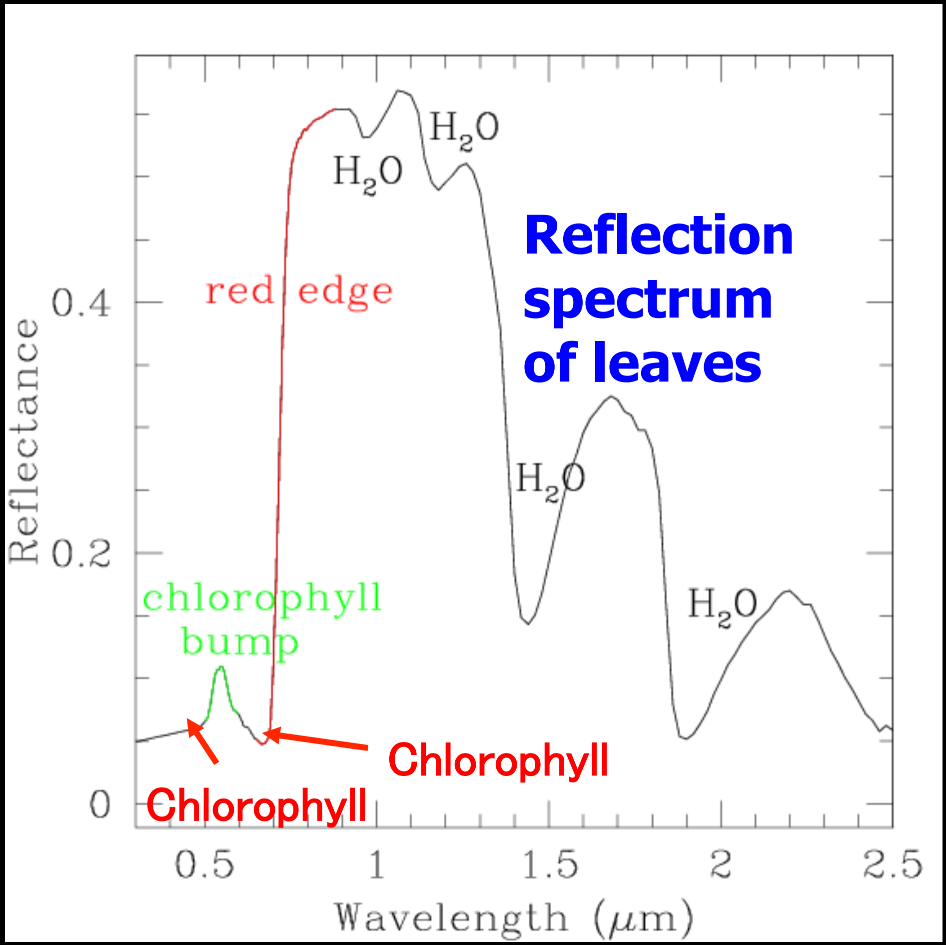


Strong O_2 absorption @A-band(0.76μm)

FIG. 1 a, Galileo long-wavelength-visible and near-infrared spectra of 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).

Red edge of *(exo)plants:* a possible biosignature 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

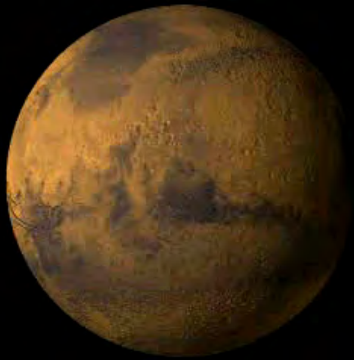


Seager, Ford & Turner astro-ph/0210277

Vesto Melvin Slipher (1875-1969)

- Discovered redshifts of galaxies and thus cosmic expansion via the Doppler method

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

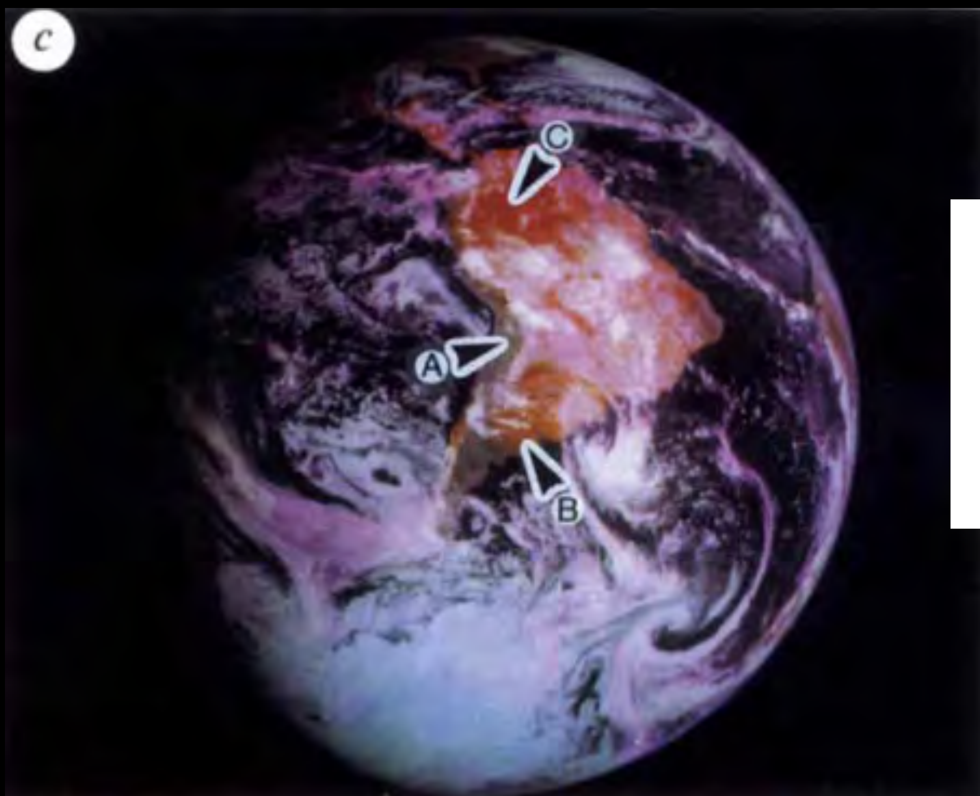


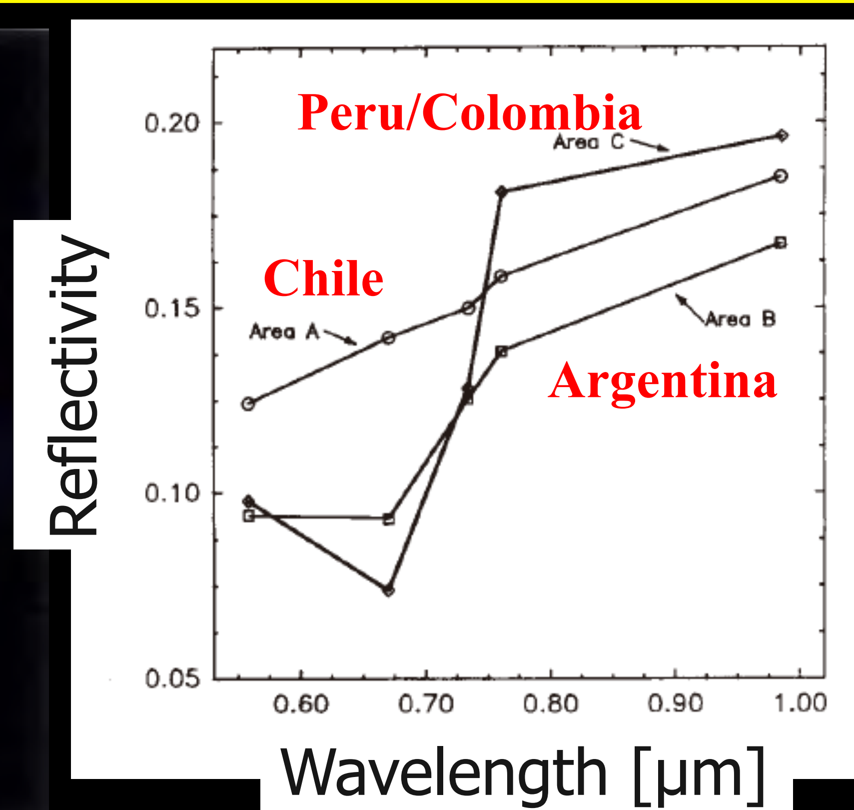
reflection spectrum. The Martian spectra of the dark regions so far do not give any certain evidence of the typical reflection spectrum of chlorophyl. The amount and types of vegetation required to make the effect noticeable is being investigated by suitable terrestrial exposures.

Astrobiology indeed in 1924 !

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

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





Sagan et al. (1993): radio observation

Detection of pulsed radio signals unlikely of natural/astronomical origin

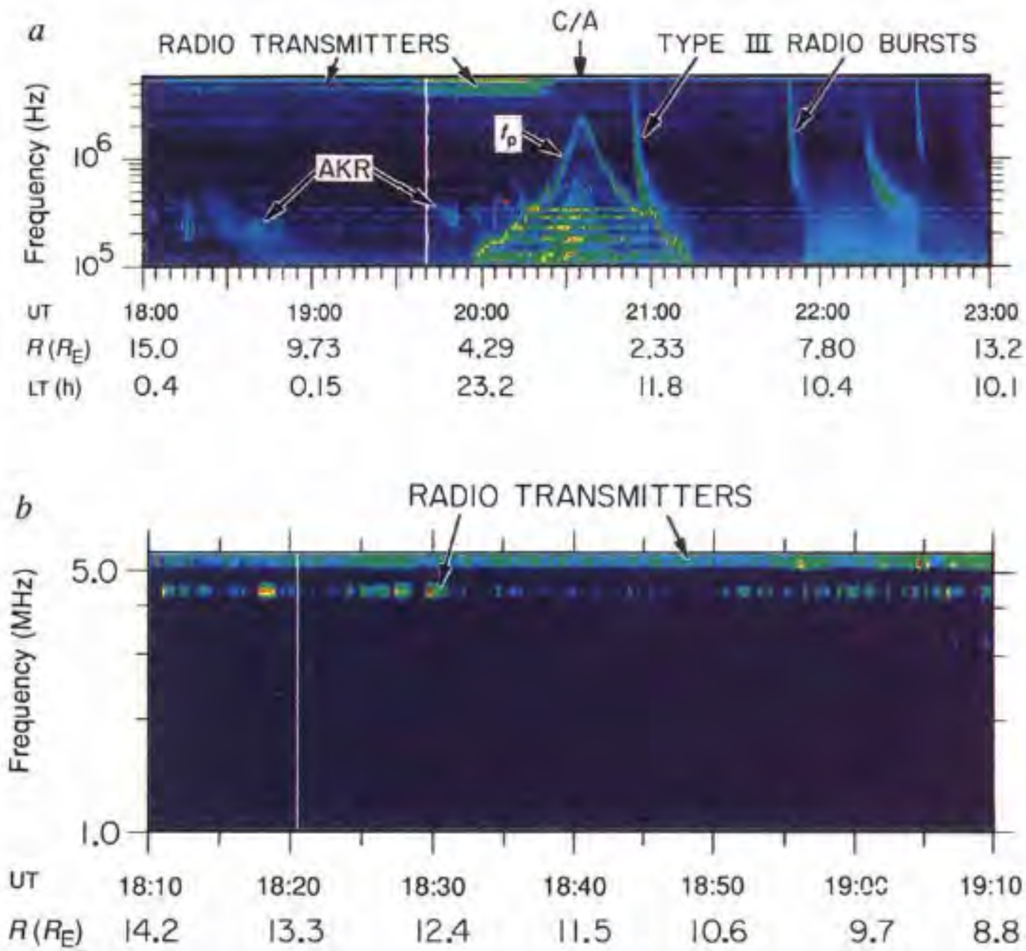
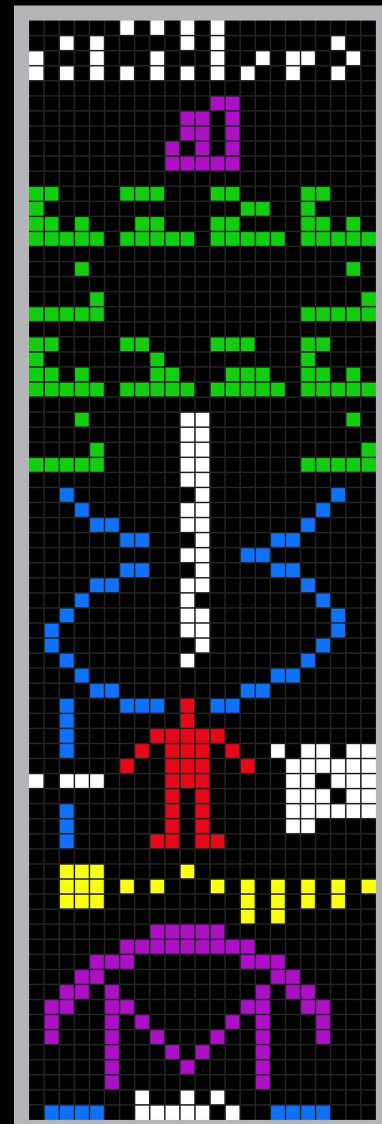


FIG. 4 A frequency–time spectrogram of the radio signals detected by the Galileo plasma wave instrument. The intensities are coded in the sequence blue–green–yellow–red, with blue lowest and red highest. Several natural sources of radio emission are shown in *a*, including auroral kilometric radiation (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.)

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, if decoded properly, should look like this.

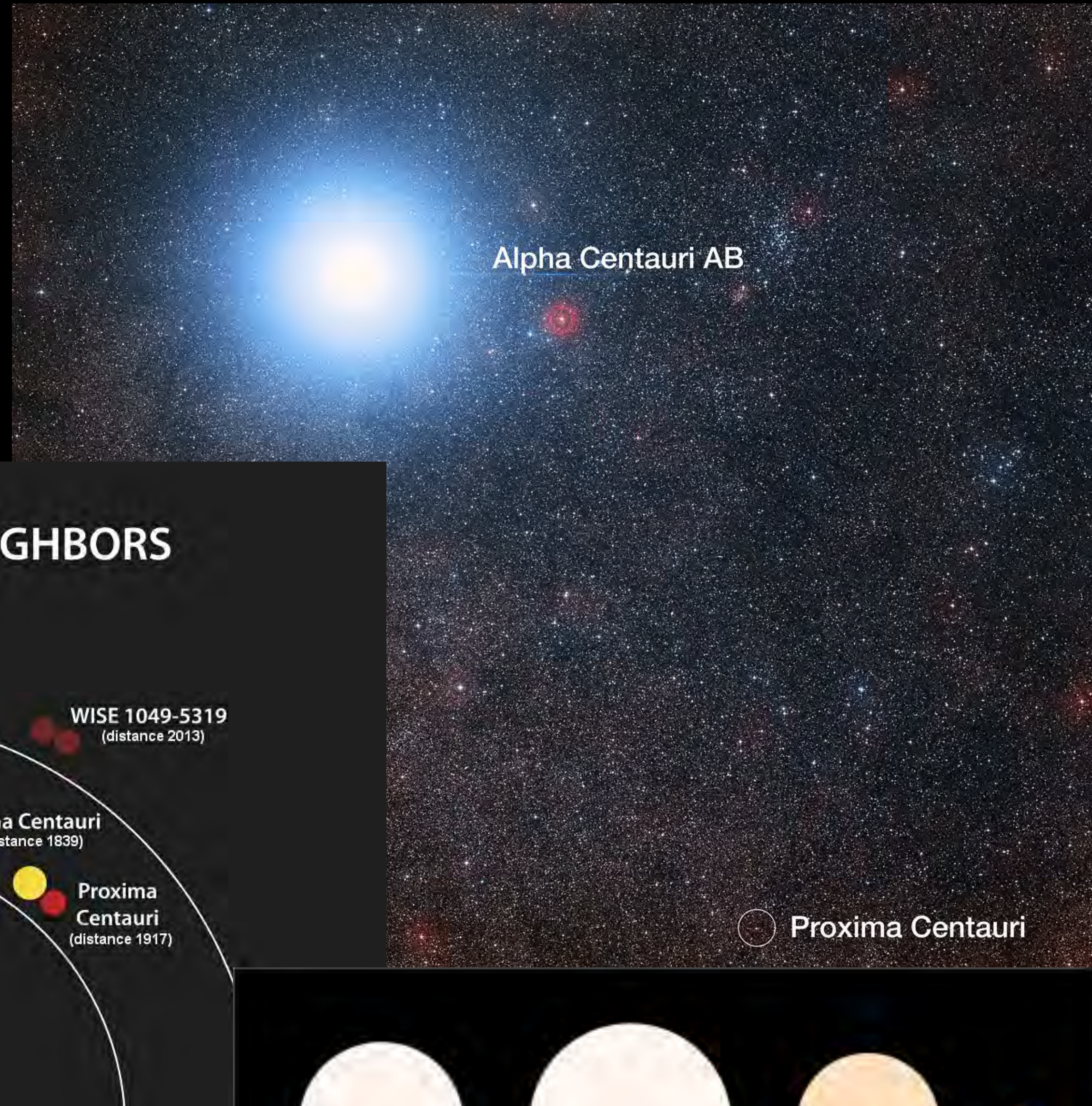


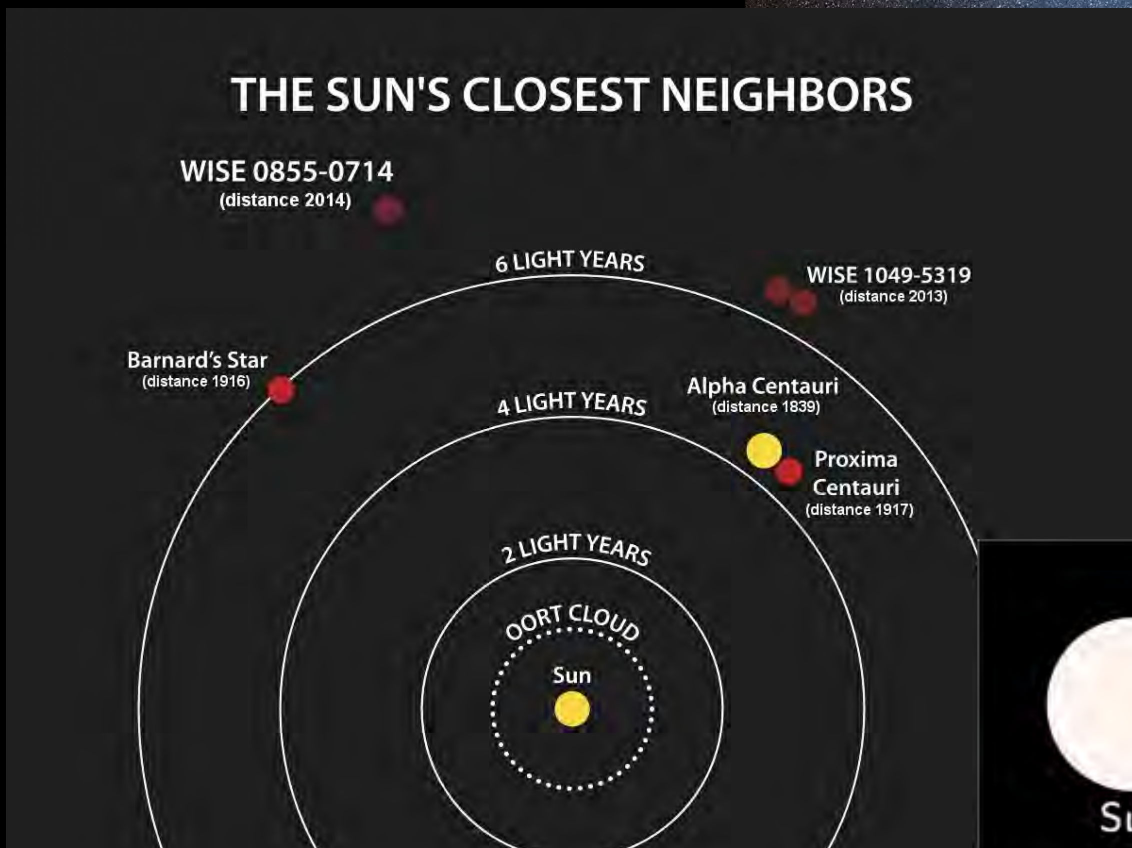
Proxima Centauri b

Proxima Centauri

- Alpha Centauri
  - The closest triple star system to our Sun
  - α Cen A, α Cen B, α Cen C (=Proxima Centauri)
- Proxima Centauri
  - Distance =1.295 pc (4.25 light year) from us
  - M5.5 V Red dwarf
  - $T=(3042\pm117)K$, $L=0.0017L_{\odot}$
  - $R=(0.141\pm0.007)R_{\odot}$, $M=(0.123\pm0.006)M_{\odot}$
  - Spin period = 83.5 days
  - Age = 4.85 G years

Proxima Centauri





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

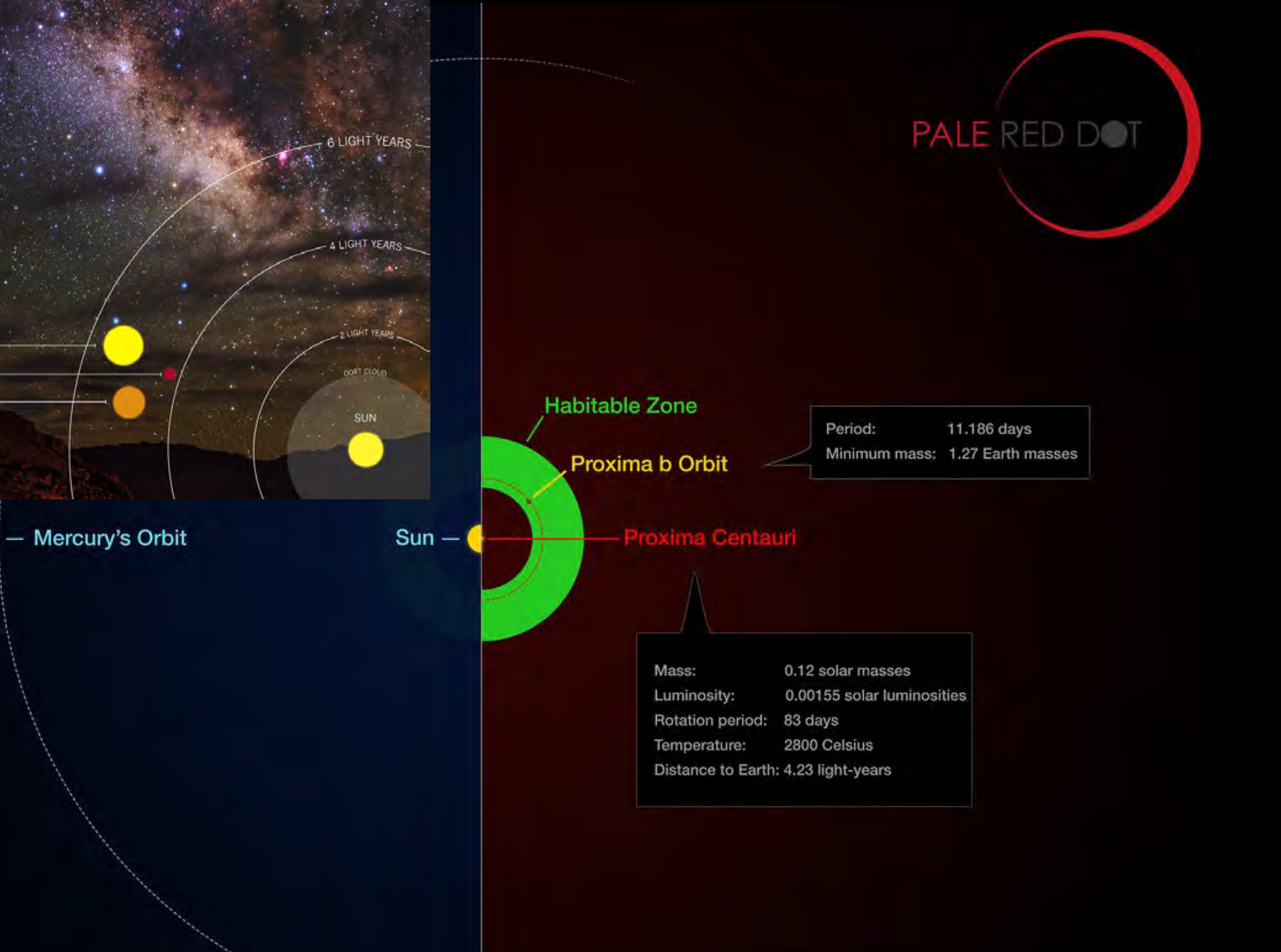
A terrestrial planet candidate in a temperate orbit around Proxima Centauri

- G.Anglada-Escude et al.

  Nature 25 August 2016 issue, 536(2016)437
- Proxima Centauri b
  - Orbital period 11.186 (11.184-11.187) days
  - $M_p \sin i = 1.27$ (1.10-1.46) M_{earth}
  - Eccentricity < 0.35
  - Semi-major axis = 0.0485 (0.0434-0.0526) AU
  - Equilibrium temperature = 234 (220-240) K

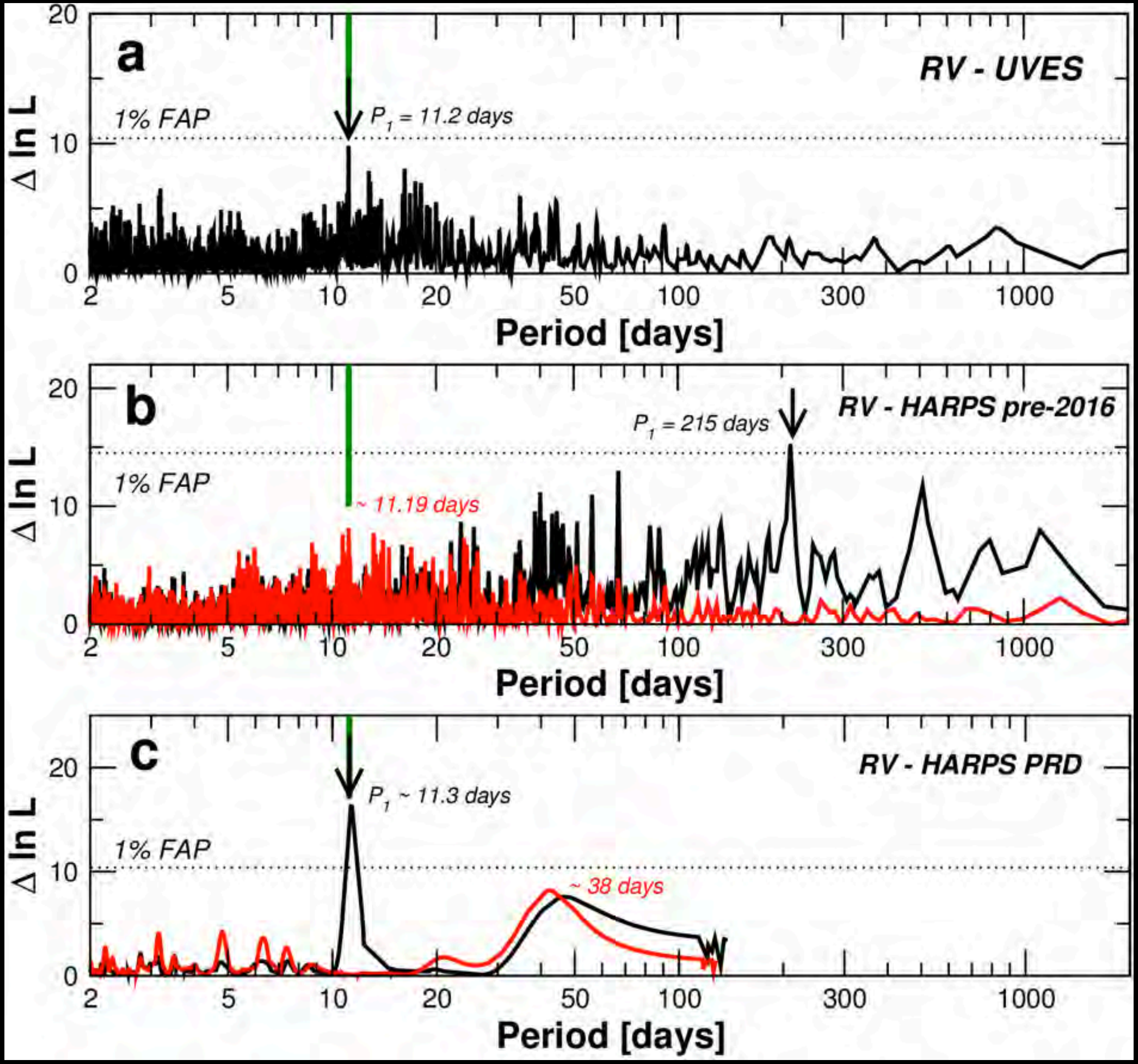
http://www.eso.org/public/usa/news/eso1629/

Pale red dot: a habitable planet ?



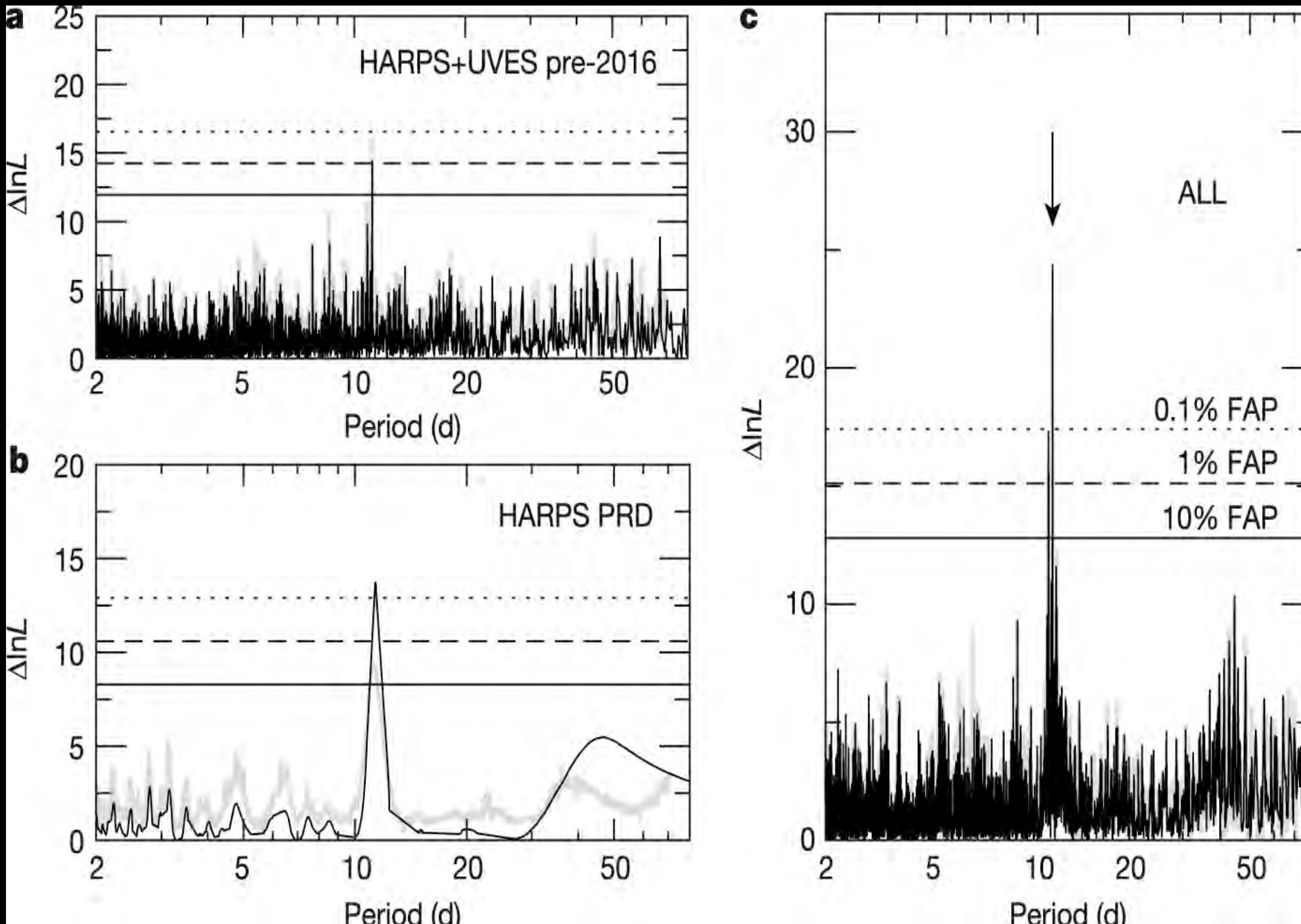
http://www.eso.org/public/usa/news/eso1629/

Periodograms of the independent Doppler signal



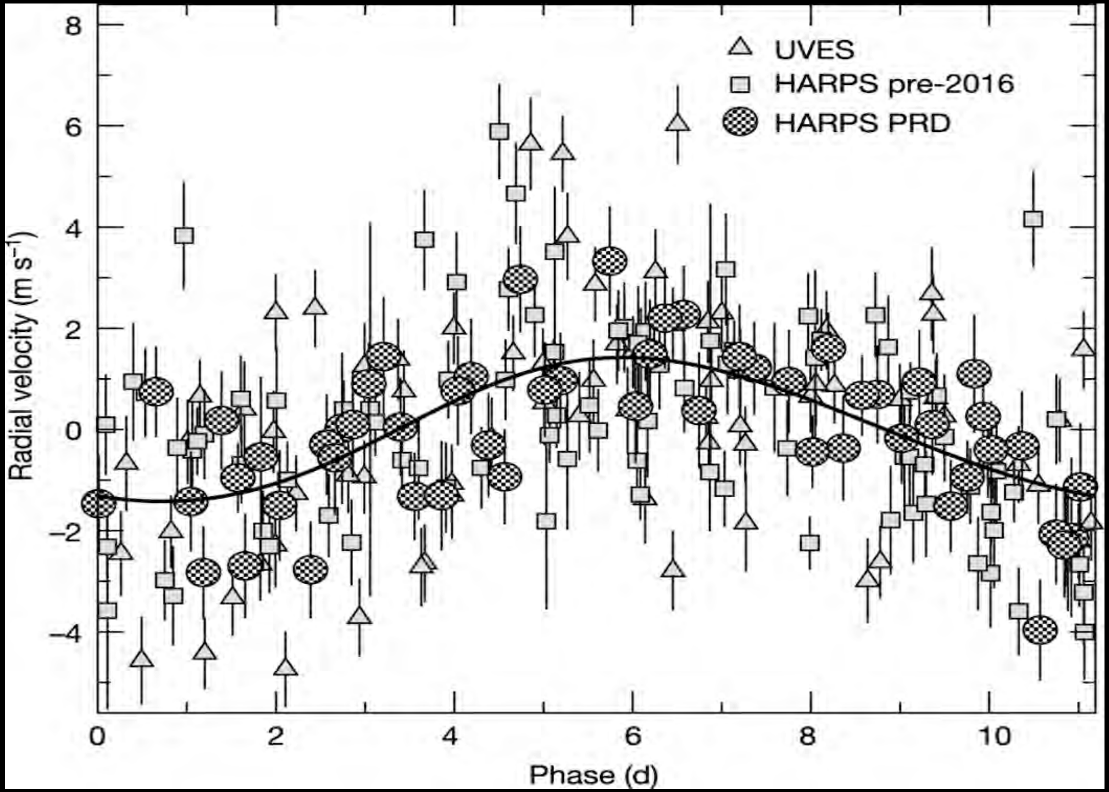
G Anglada-Escudé *et al.* *Nature* 536, 437–440 (2016)

Combined periodograms of the Doppler signal

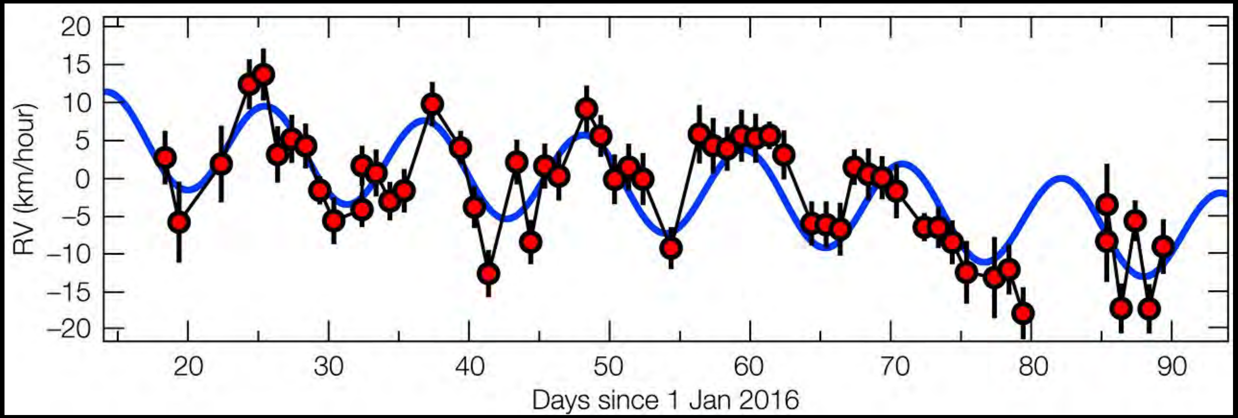


G Anglada-Escudé *et al.* *Nature* 536, 437–440 (2016)

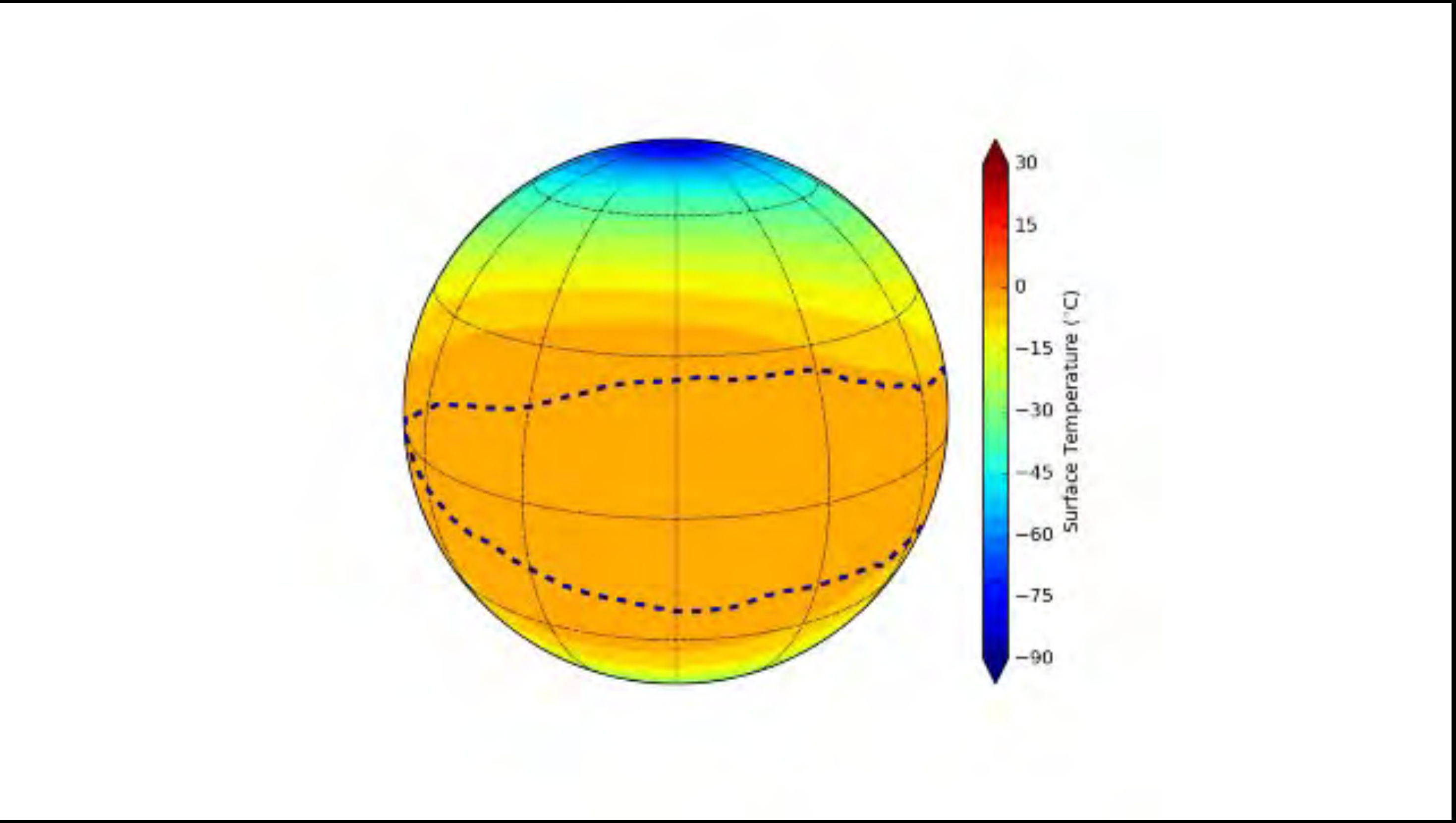
Radial velocity data



G Anglada-Escudé *et al.*
Nature 536 (2016) 437

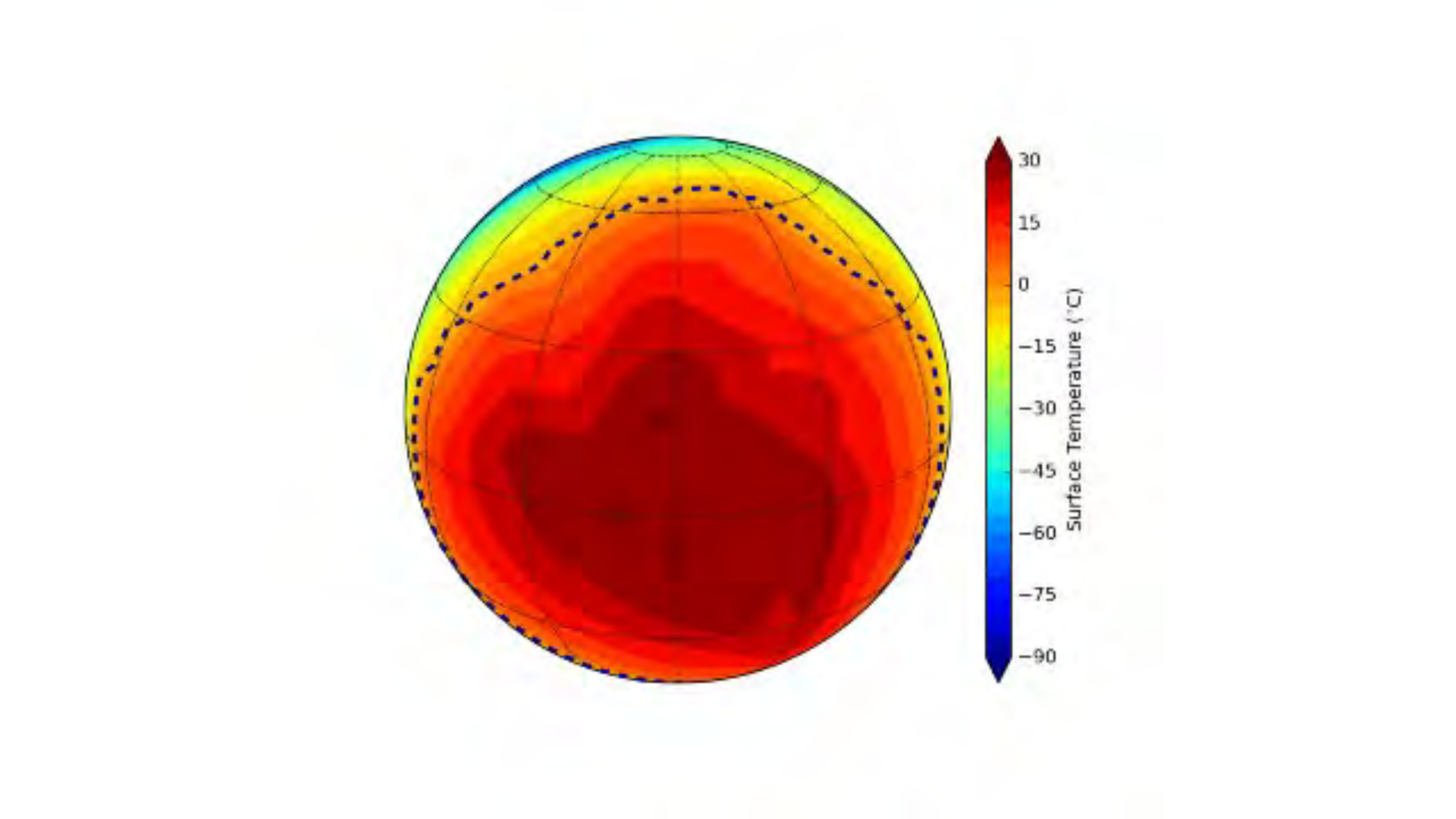


Simulated surface temperature (3:2 resonance case)



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

Simulated surface temperature (synchronous case)



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

Breakthrough Initiatives

http://breakthroughinitiatives.org/Initiative

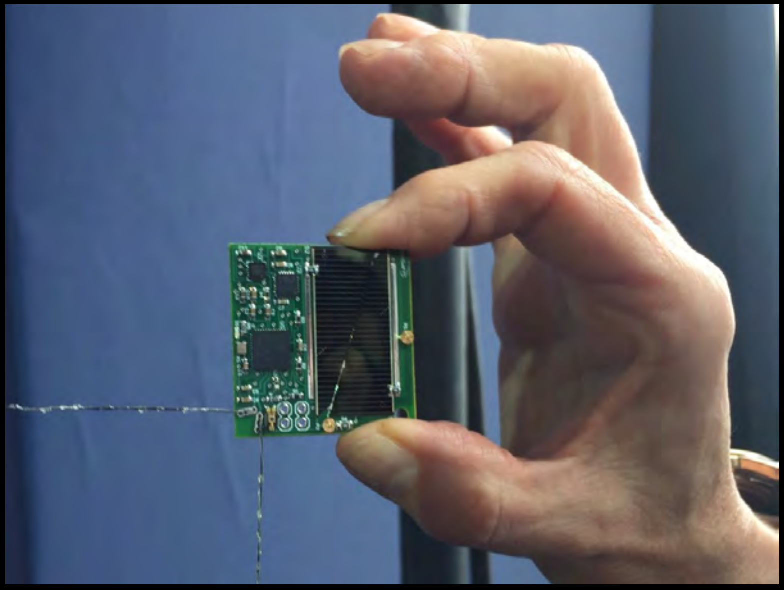
- A program founded on July 20, 2015 by a Russian internet investor Yuri Milne to search for extraterrestrial intelligence
  - Breakthrough Listen to discover signs of extraterrestrial civilizations through radio and laser transmissions
  - Breakthrough Message to study the ethics of sending messages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

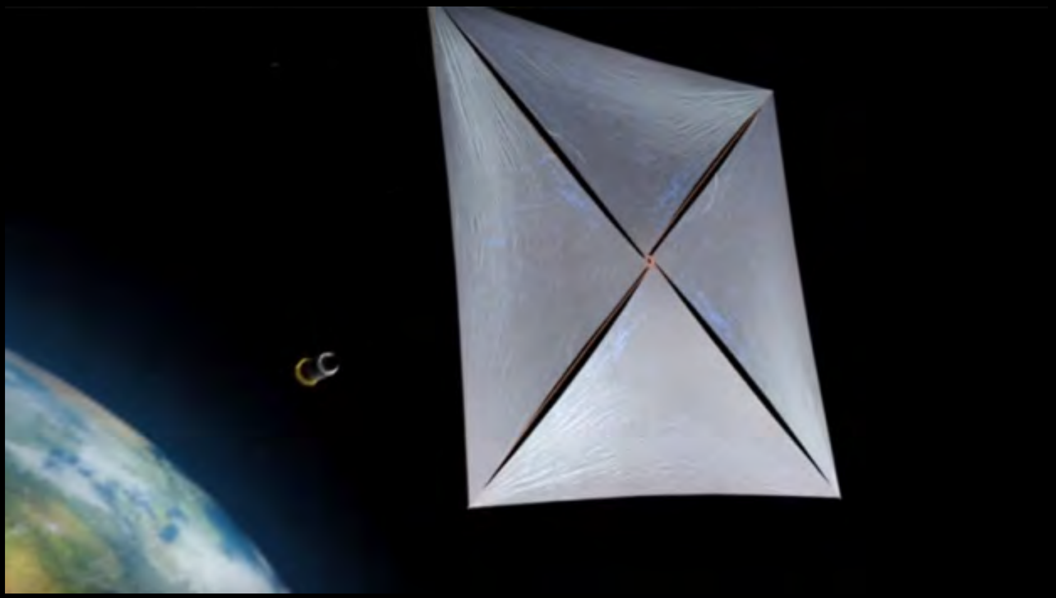
Breakthrough Starshot

http://breakthroughinitiatives.org/Initiative/3

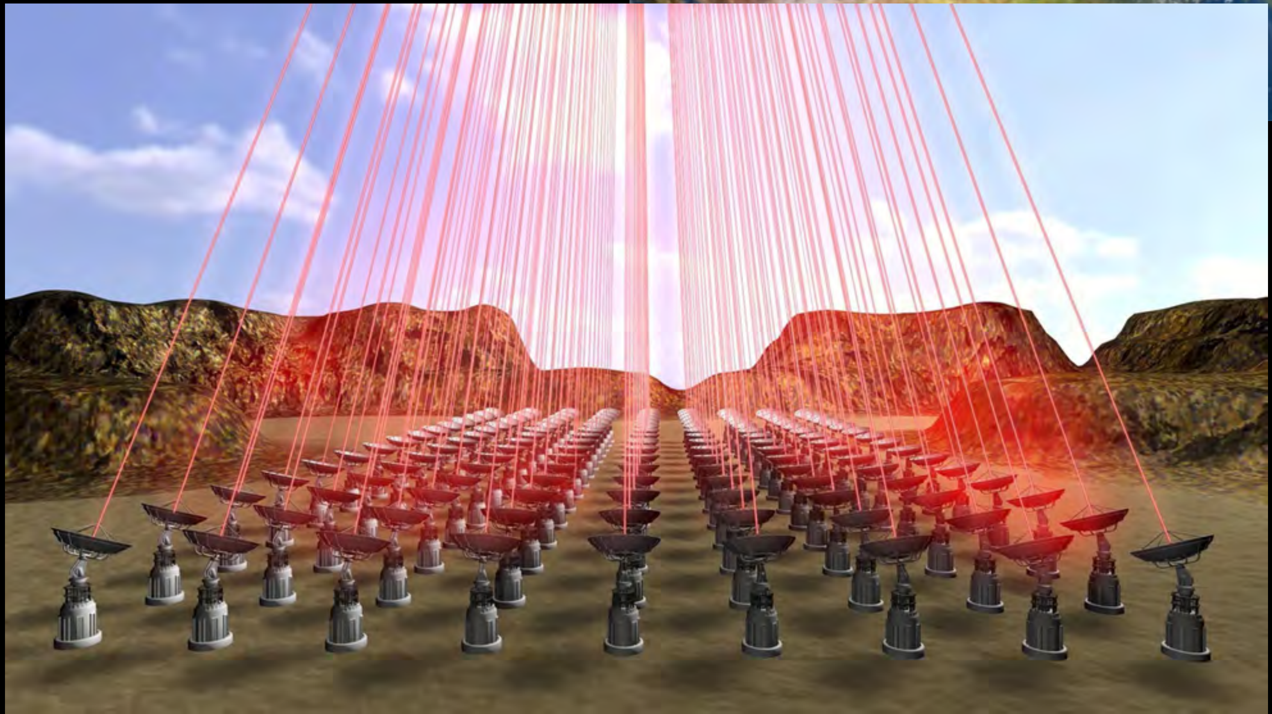
- StarChip
  - A cm-sized nano-spacecraft of several grams
  - With camera, computer, communication laser, plutonium power source, and light sail
  - A 4m×4m light sail for each spacecraft is accelerated by the focused ground-based lasers
  - 0.2c in 10 minutes
- A fleet of 1000 StarChips to Proxima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

StarChip





Light sail accelerated by ground lasers



From Earth to Proxima Centauri b

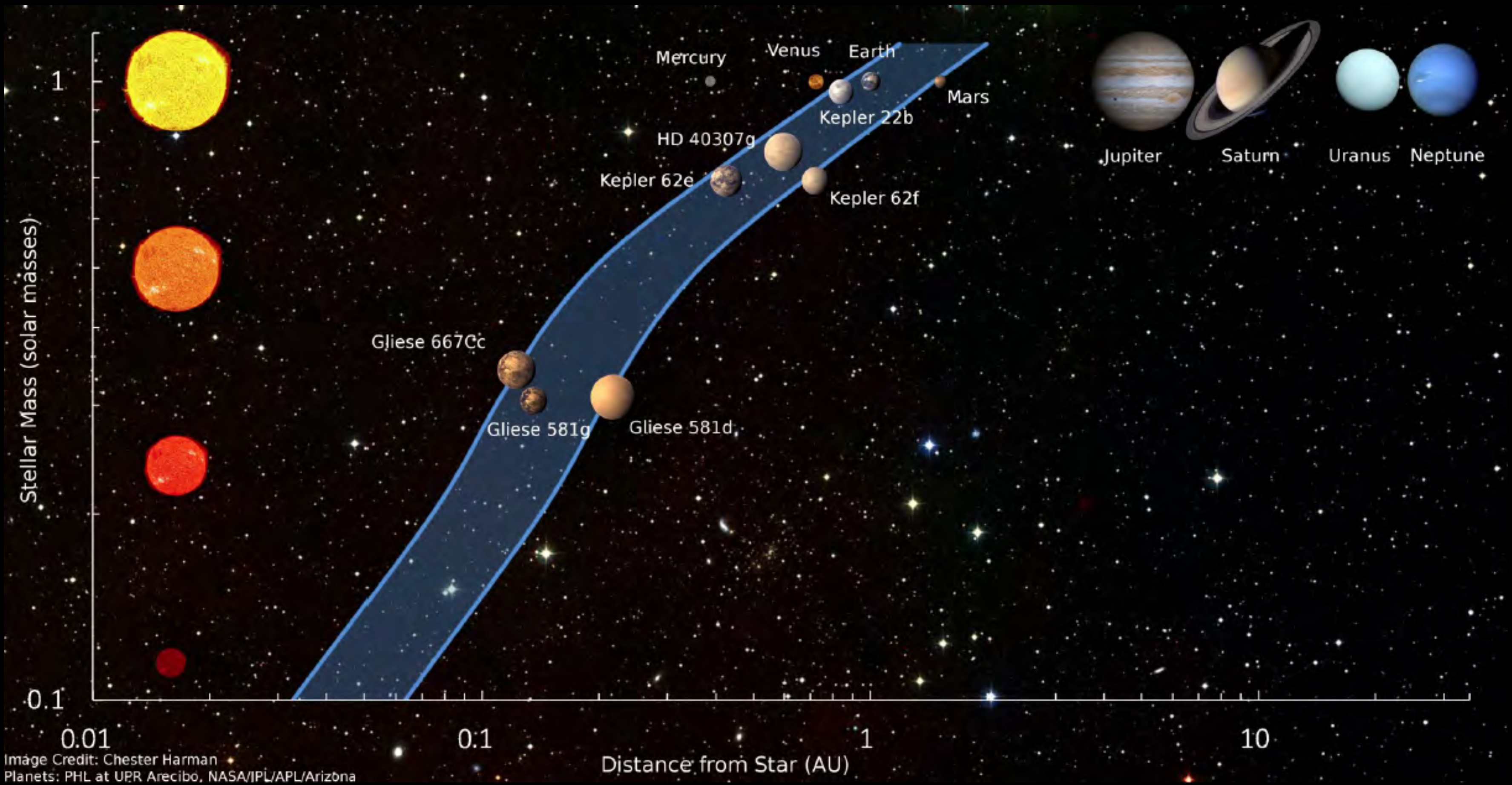
http://www.eso.org/public/usa/news/eso1629/

Proxima Centauri b

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

Simulated Earth observed at 10pc away

Habitable zone around host stars



Kasting, Kopparapu, Raminez & Harman: arXiv:1312.1328

Occurrence of earth-size habitable planets around Sun-like stars

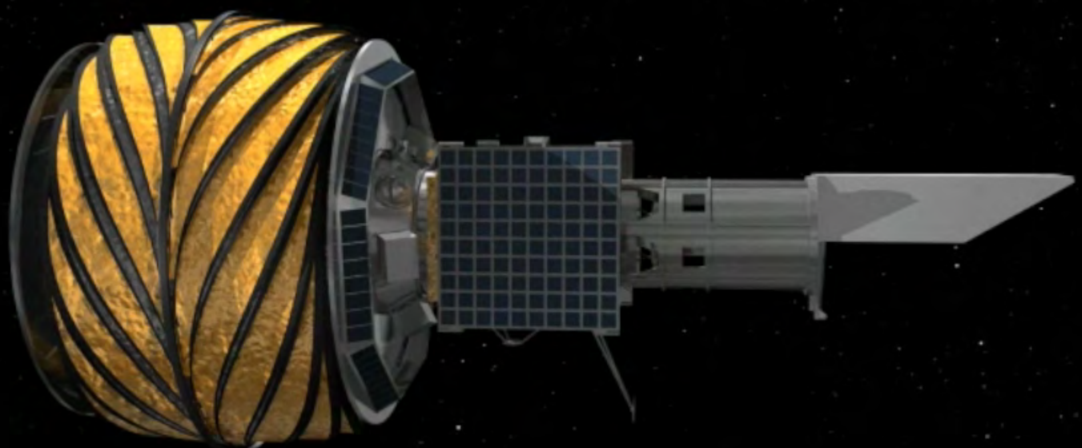
- Planets with (1-2) Earth radius around GKstars
  - Kepler Transit planets corrected for selection effect
  - 11±4 % (1-4 times the Solar flux on the earth)
  - 5.7+2.2-1.7 % (orbital period of 200-400days)

Table 1. Occurrence of small planets in the habitable zone

HZ definition	a_{inner}	a_{outer}	$F_{P,inner}$	$F_{P,outer}$	f_{HZ} (%)
Simple	0.5	2	4	0.25	22
Kasting (1993)	0.95	1.37	1.11	0.53	5.8
Kopparapu et al. (2013)	0.99	1.70	1.02	0.35	8.6
Zsom et al. (2013)	0.38		6.92		26*
Pierrehumbert and Gaidos (2011)		10		0.01	~50[†]

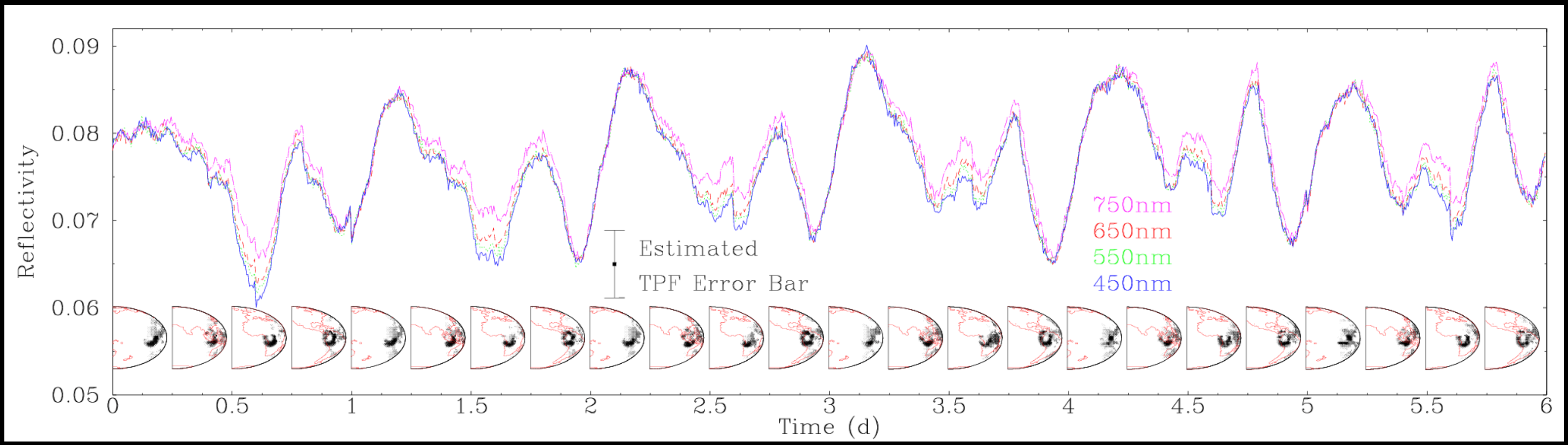
Petigura, Howard & Marcy: arXiv:1311.6806

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

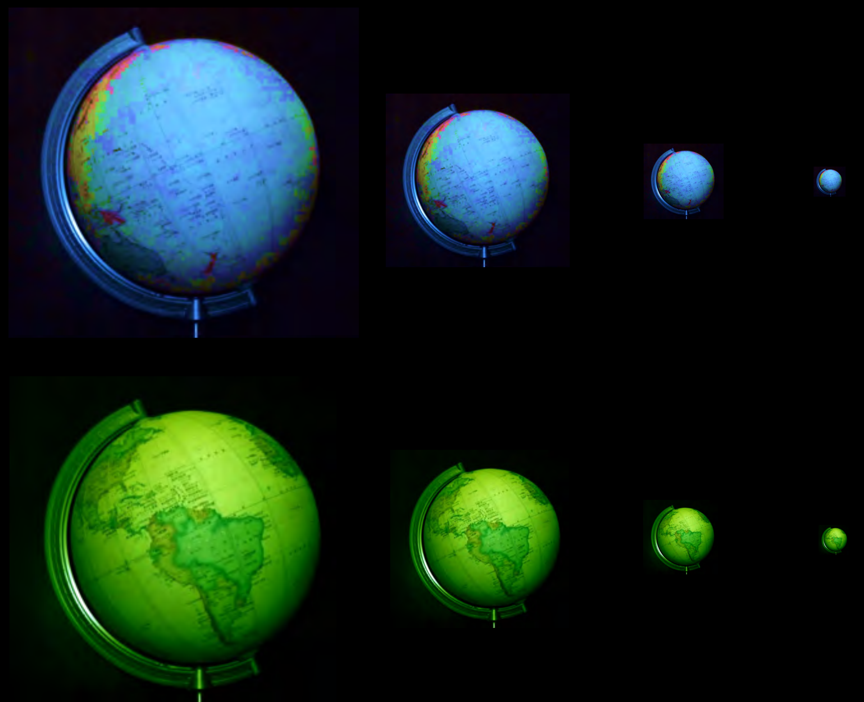
ApJ. 738(2011)184, arXiv:1102.3625

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

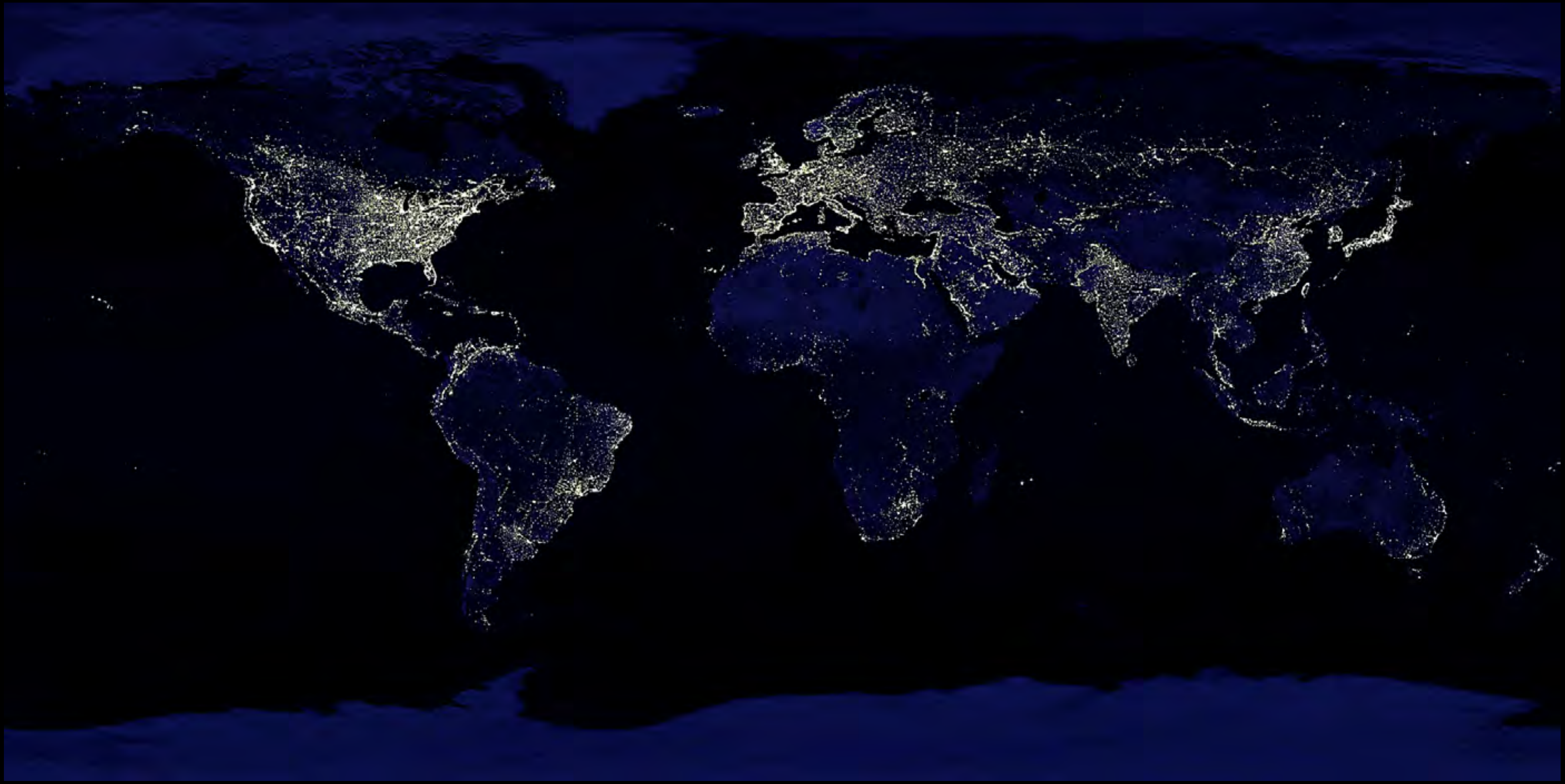
http://www.space.com/scienceastronomy/color-changing-planets-alien-life-100513.html

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



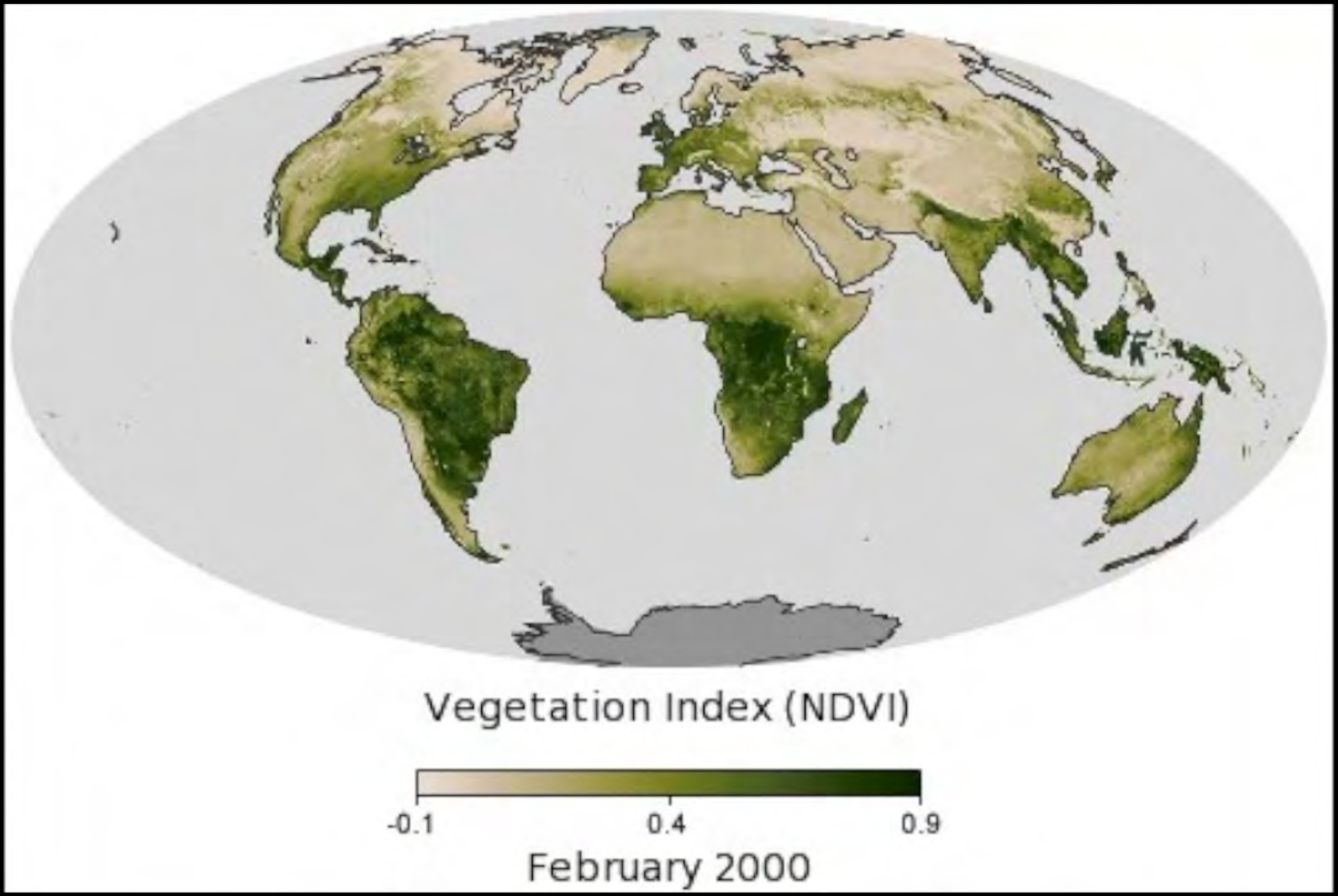
Earth at Night 2012



http://earthobservatory.nasa.gov/Features/NightLights/page3.php

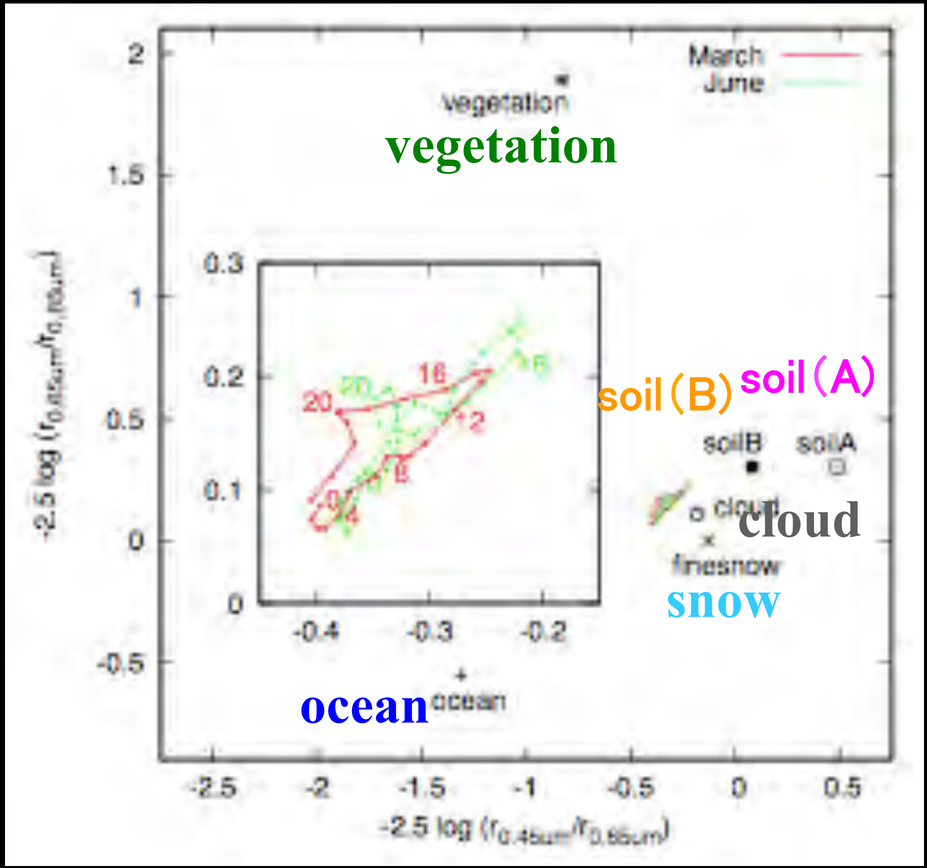
Night in Korea and Japan…

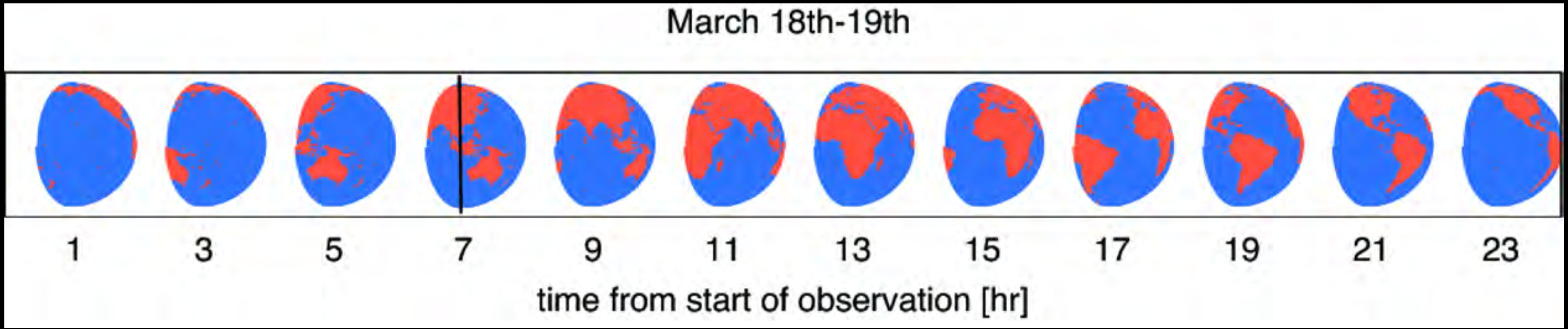
annual vegetation global map by the earth observing satellite Terra



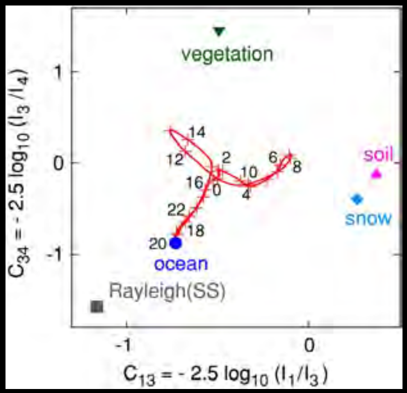
http://earthobservatory.nasa.gov/GlobalMaps/

Colors of our earth

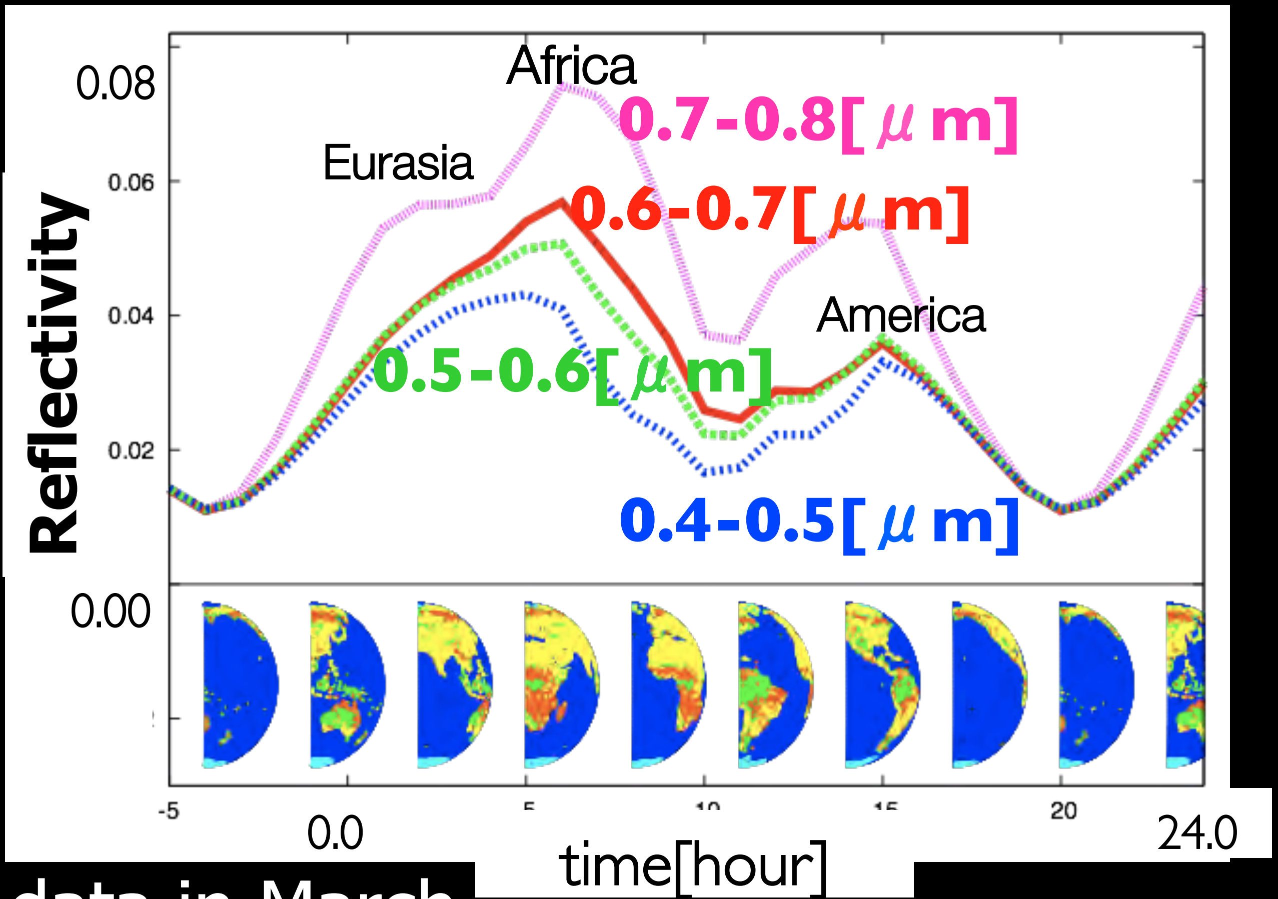




A pale blue dot ? Not really



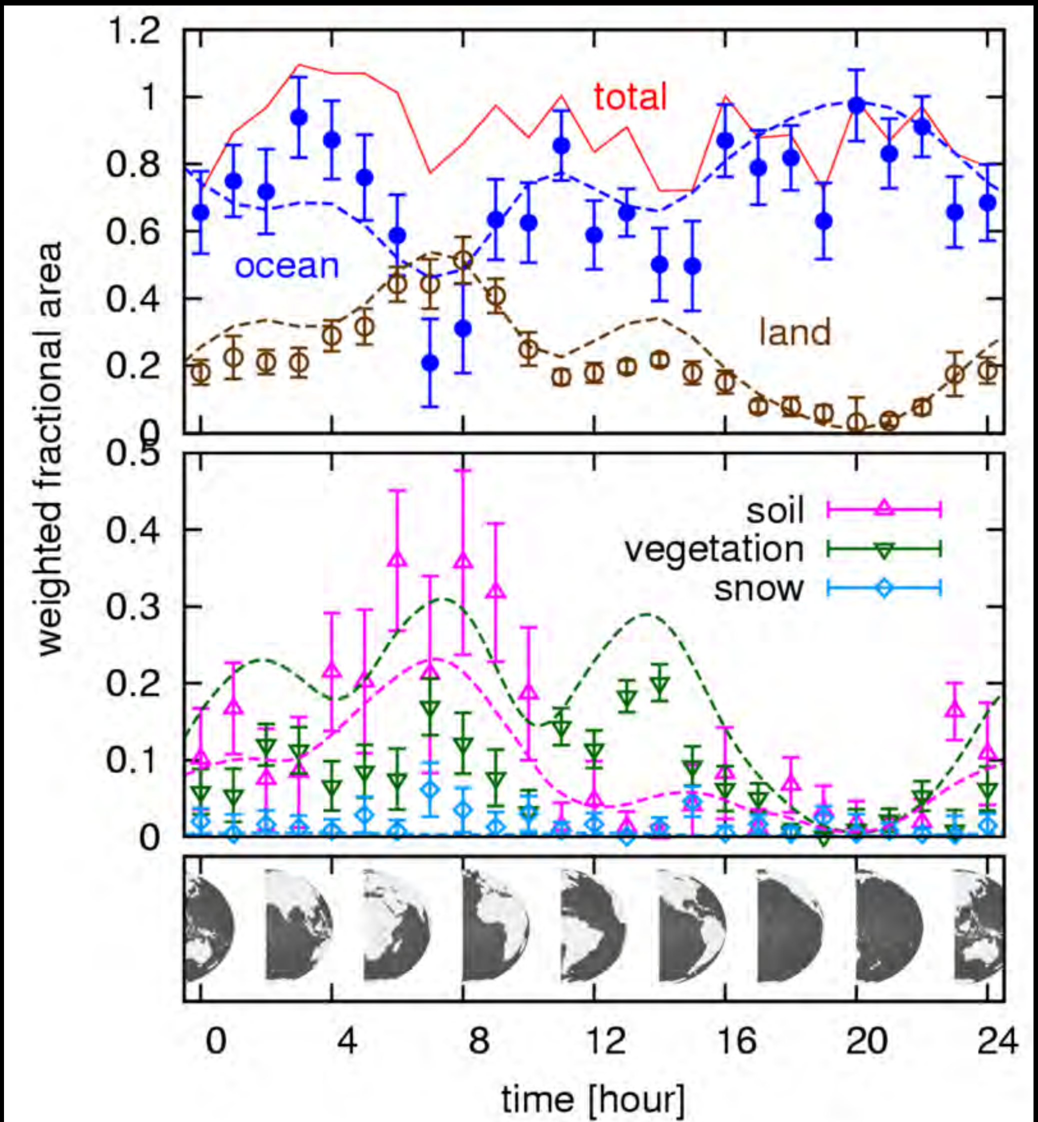
Simulated photometric light-curves of Earth



- Adopted Earth data in March
- Spin inclination = 0 (vernal equinox)
- cloudless

Fujii et al. (2010)

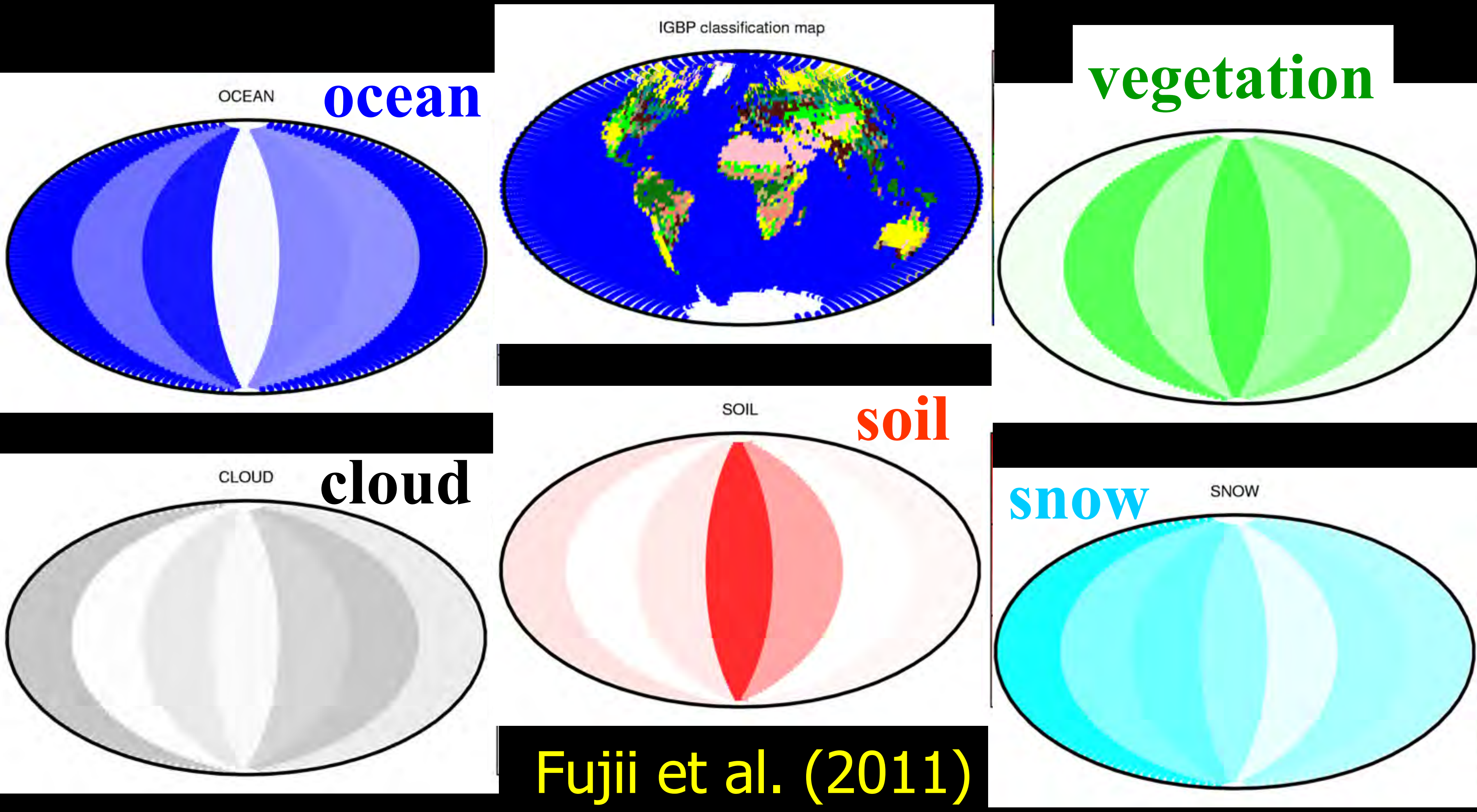
Estimating fractional areas of surface components from colors of a second earth



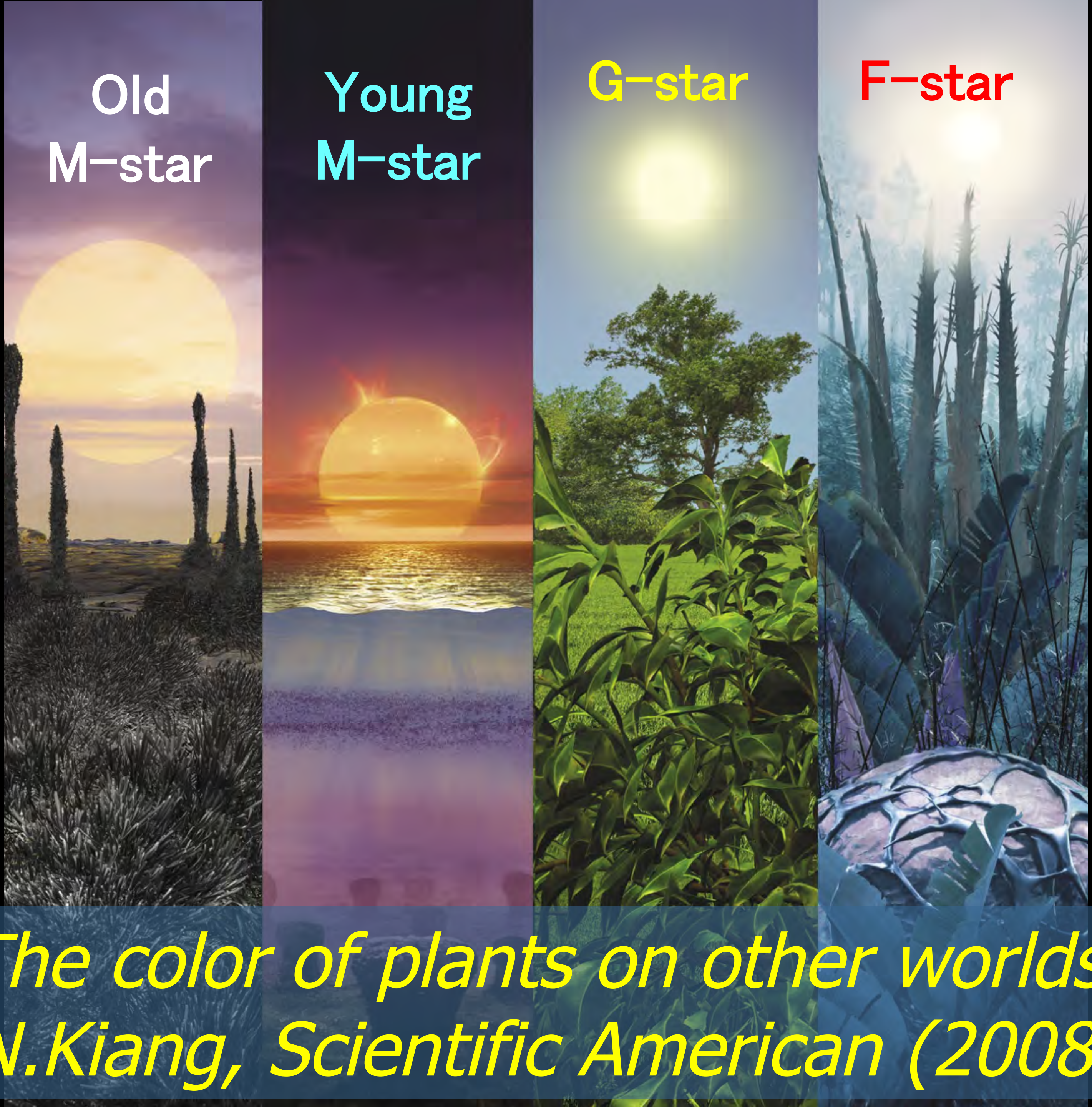
- 2 week observation of a cloudless Earth at 10 pc away
- Reasonably well reproduced
- possible to identify vegetation !

Fujii et al. (2010)

Surface latitude map estimated from real satellite data with cloud model



Fujii et al. (2011)



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

Summary:
A pale blue dot? Not really !

- Future direct imaging of daily change of colors of another earth is challenging, but would reveal the presence of ocean, land, cloud, and/or even vegetation on their surface
- Detection of a second Earth may not be a mere fairly tale nor a science fiction any more
- Detection of oxygen, water vapor, and even the red-edge may be a promising path towards astrobiology