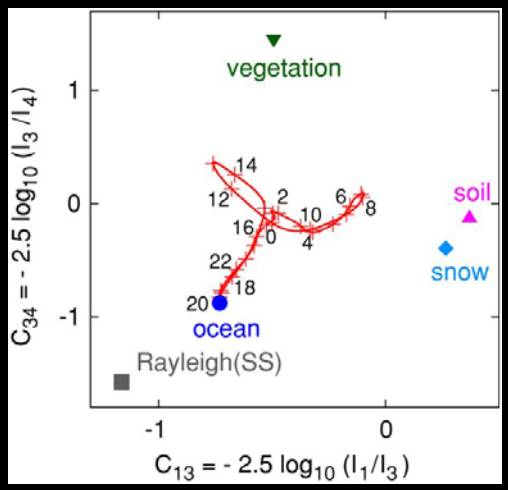
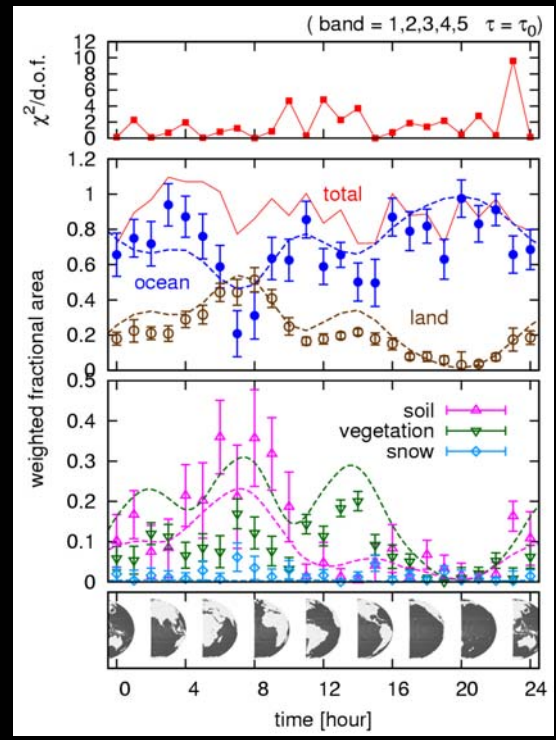
Colors of a second Earth: towards exoplanetary remote-sensing





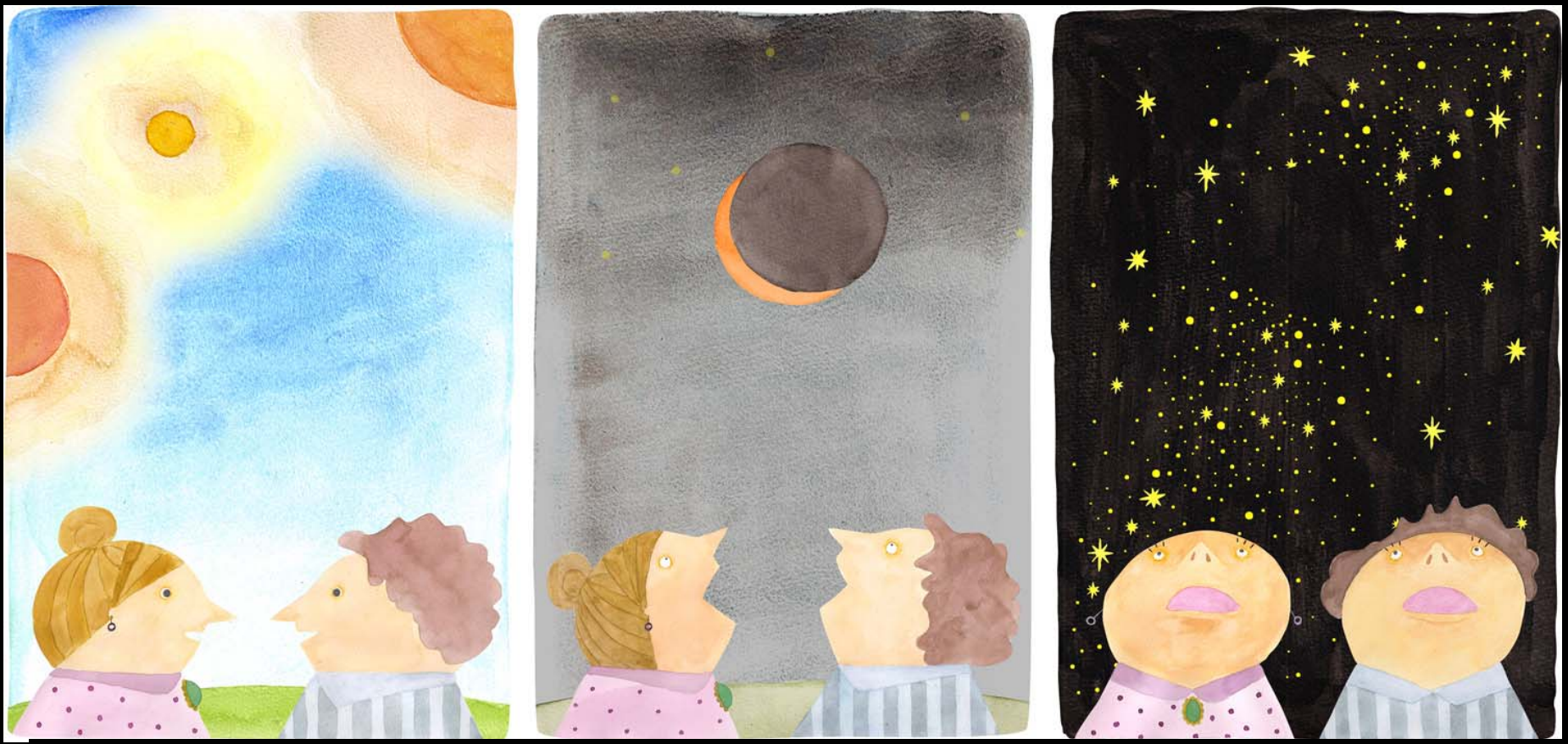
Yasushi Suto

Department of Physics, the University of Tokyo & Global Scholar, Department of Astrophysical Sciences, Princeton University

seminar at Centre de Recherche Astrophysique de Lyon

14:00 October 20, 2011@ENS-Big CECAM

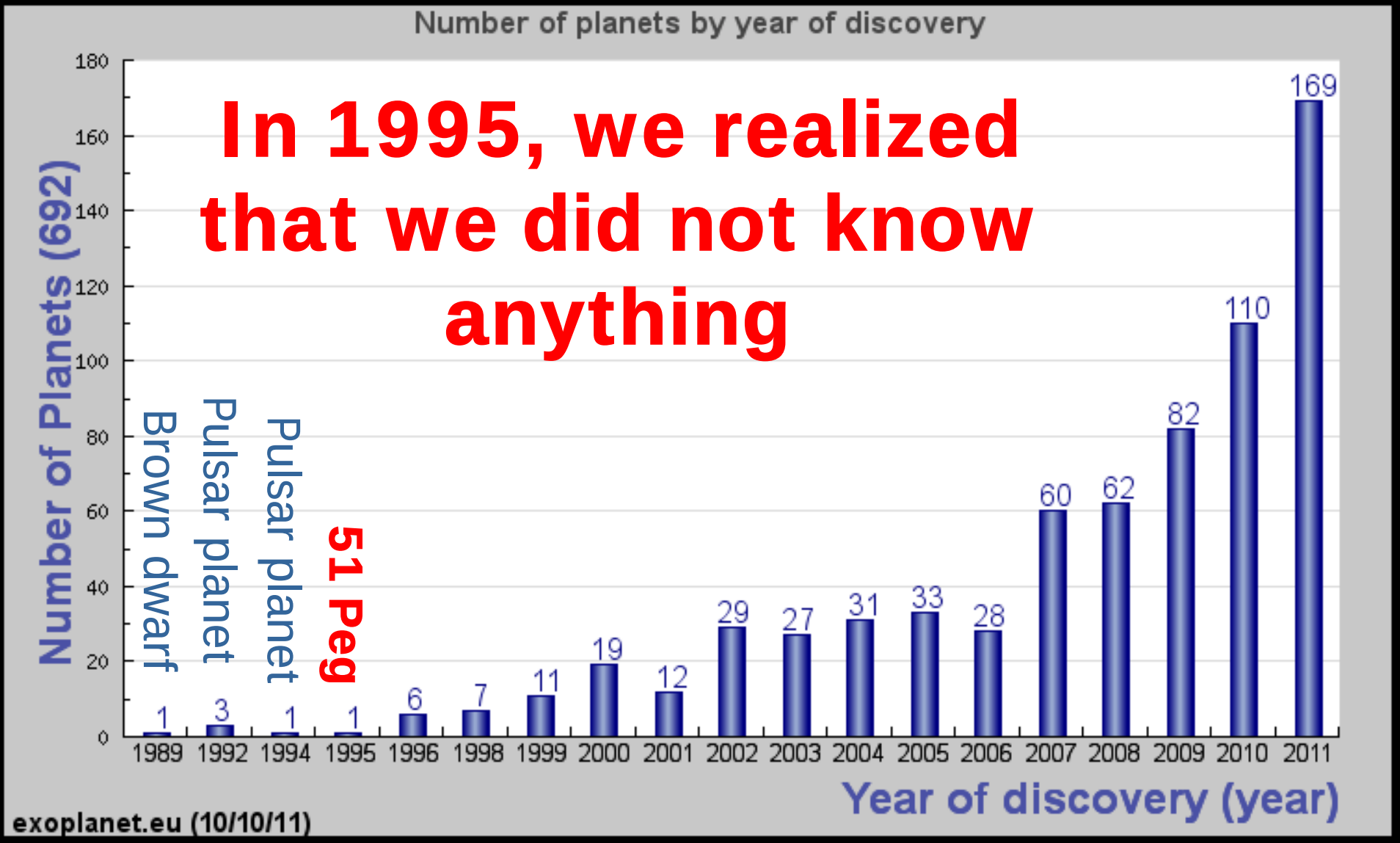
Nightfall: We didn’t know anything



(Alisa Haba)

- no “night” except the total eclipse due to another planet every 2049 years on a planet “Lagash”
- People realized the true world for the first time through the darkness full of “stars” *(Issac Asimov: Nightfall)*

History of exoplanet discovery



exoplanet projects in my group at the Univ. of Tokyo

- Constraining the stellar spin and the planetary orbital axes from the Rossiter-McLaughlin effect
  - analytic perturbation formulae (Ohta et al. 2005, ApJ, 622, 1118; Hirano et al. 2010, ApJ, 709, 458; 2011 ApJ, in press)
  - First accurate detection (Winn et al. 2005 ApJ, 631, 1215)
  - application to ring detection (Ohta et al. 2009, ApJ, 690, 1)
- Colors of a second earth
  - Estimating the fractional areas of surface components from simulated photometry data (Fujii et al. 2010 ApJ, 715, 866;2011 ApJ, 738, 184)

What we have learned so far...

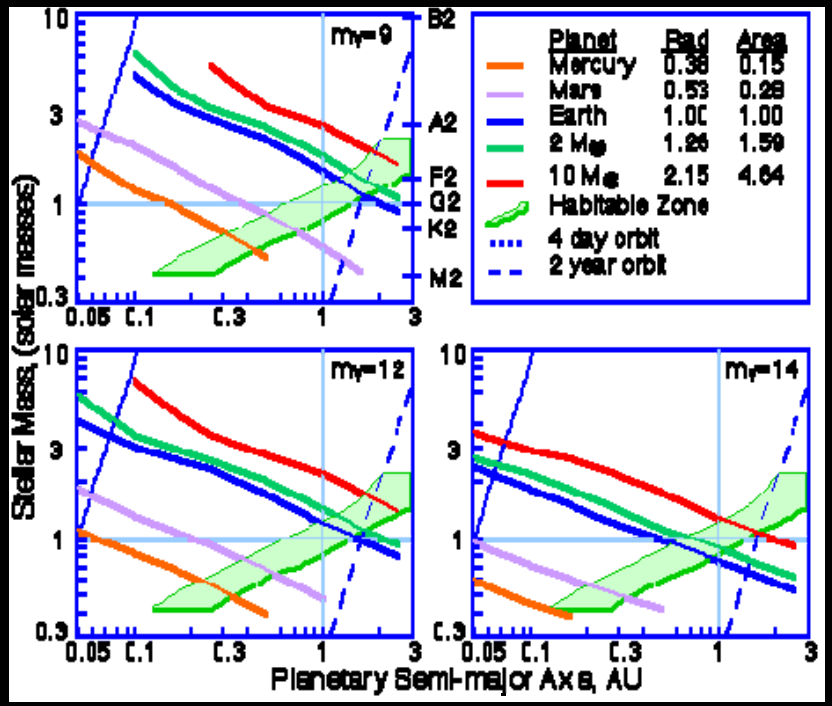
- Planets are not rare, but fairly common
  - >10 percent of sun-like stars have planets
- Diversity of planetary systems
  - Hot Jupiter, super earth,,,
  - Prograde/retrograde/polar-orbit planet
- Various observational approaches
  - High-dispersion spectroscopy (radial velocity), precise photometry (transit, micro-lens), direct imaging
  - Planetary atmosphere
  - Reflected light from planet

What's next ?

Kepler mission (March 6, 2009 launch)

Photometric survey of transiting planets

Searching for terrestrial (and habitable) planets



1st public data release
706 transiting planet candidates
(Borucki et al. arXiv:1006.2799)

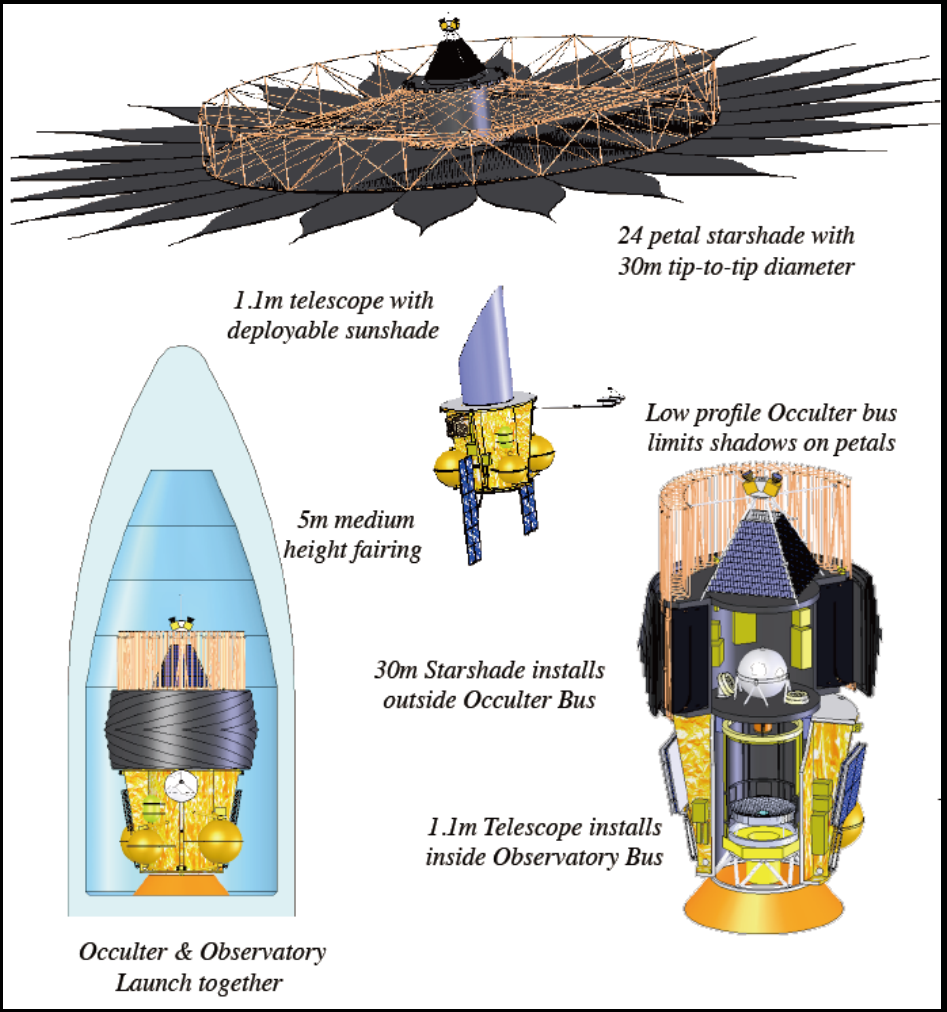
http://kepler.nasa.gov/

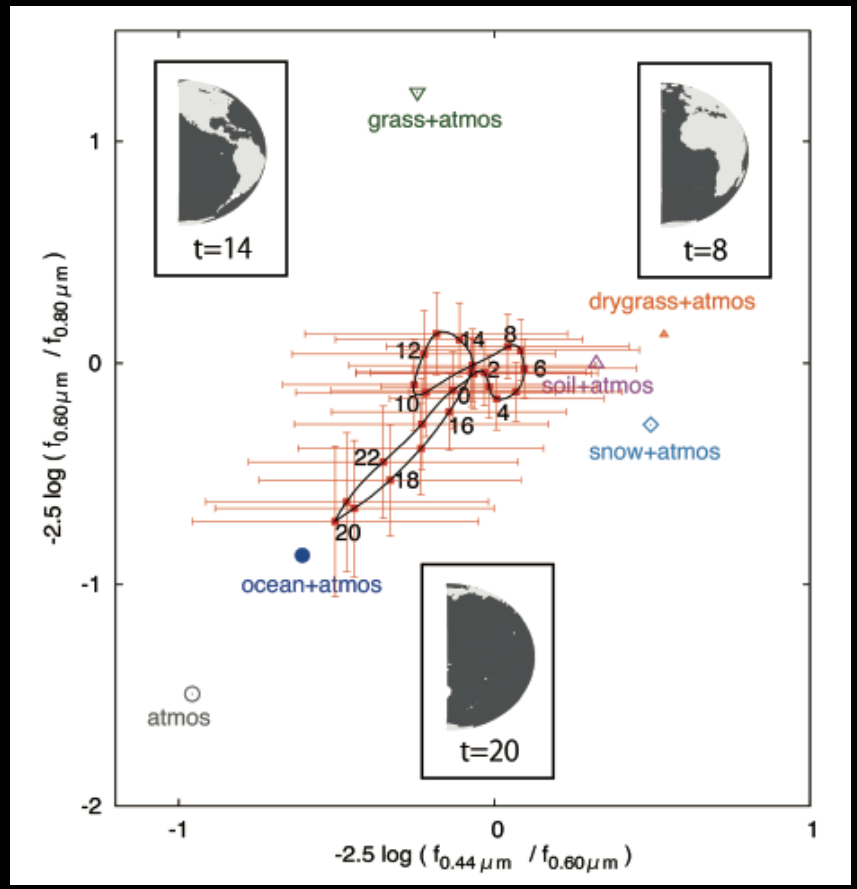
O_3: The Occulting Ozone Observatory

O_3: The Occulting Ozone Observatory

N. Jeremy Kasdin[1], David N. Spergel[1], P. Doug Lisman[2], Stuart B. Shaklan[2], Dmitry Savransky[1], Eric Cady[1], Edwin L. Turner[1], Robert Vanderbei[1], Mark W. Thomson[2], Stefan R. Martin[2], K. Balasubramamian[2], Steven H. Pravdo[2], Yuka Fujii[3], Yasushi Suto[3]

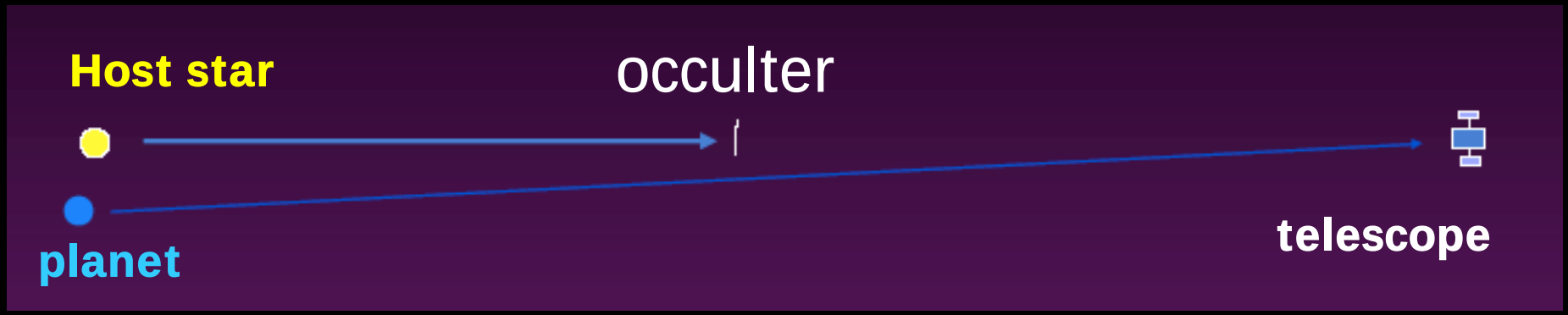
[1]Princeton University, [2]Jet Propulsion Laboratory, [3]University of Tokyo





- Princeton+JPL+…

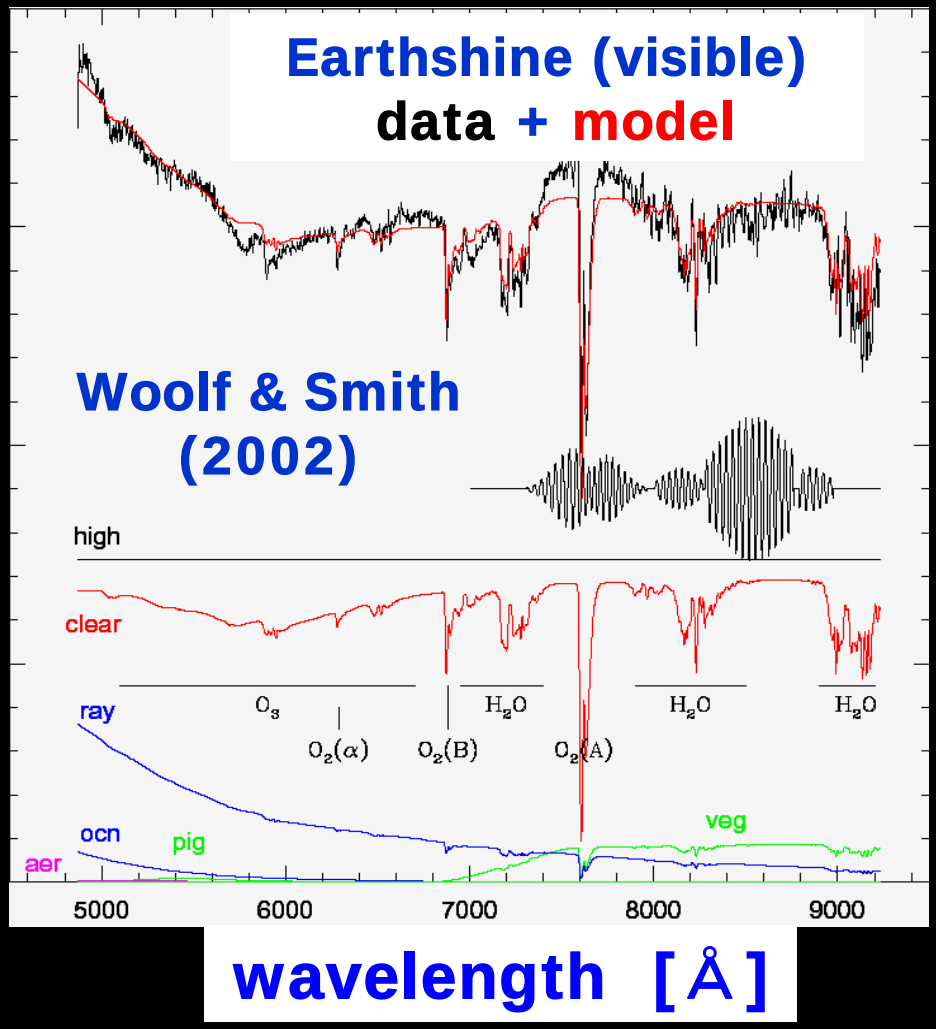
The New Worlds Mission: search for terrestrial planets



http://newworlds.colorado.edu/

- Visible-band mission with 2-4m apertuer@L2
  - Occulter mission @7x10^{4}km away
  - Photometric and spectroscopic monitor of planets
  - Search for biomarker
  - US+UK project; Univ. of Colorado

Conventional biomarkers (signature of life)

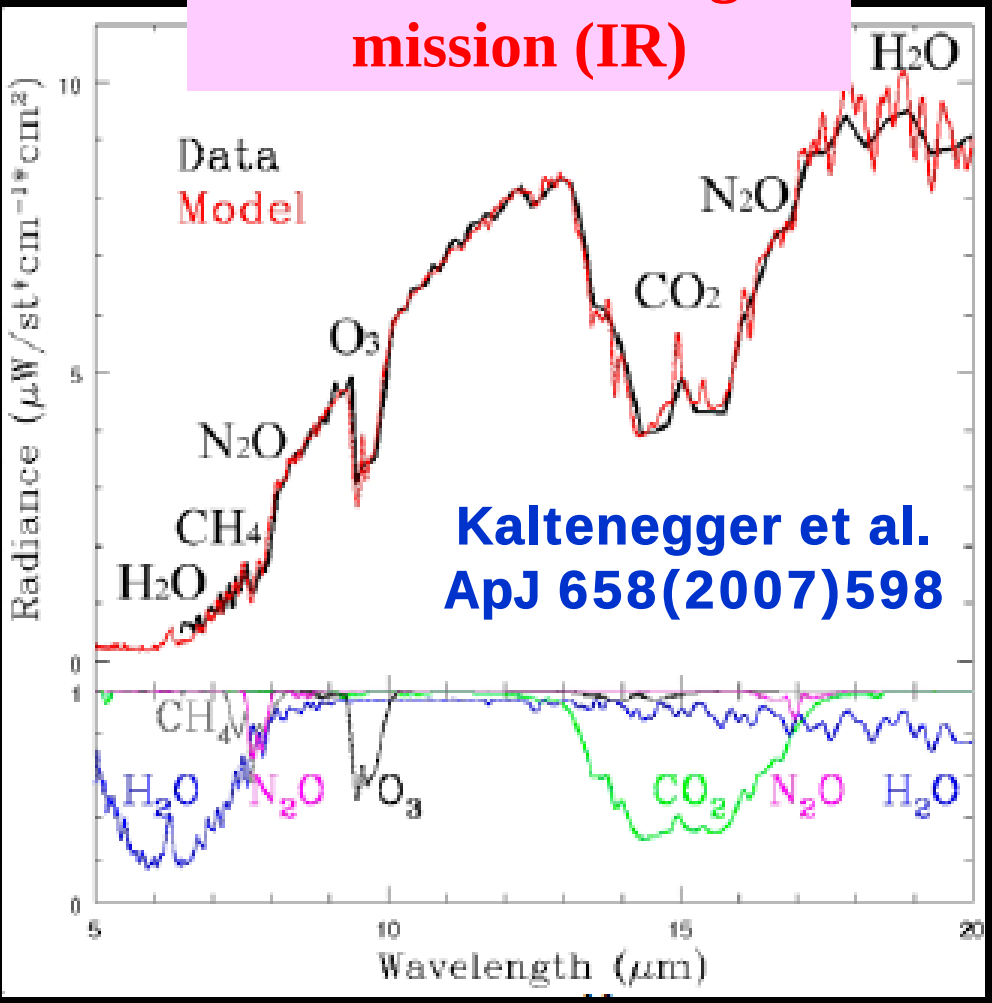


- O_2
  - A-band@0.76 μ m
  - B-band@0.69 μ m
- H_2O
  - 0.72, 0.82, 0.94 μ m
- O_3
  - Chappuis band @(0.5-0.7) μ m
  - Hartley band @(0.2-0.3) μ m

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

Earth's IR spectrum and biomarkers

Earth observing mission (IR)

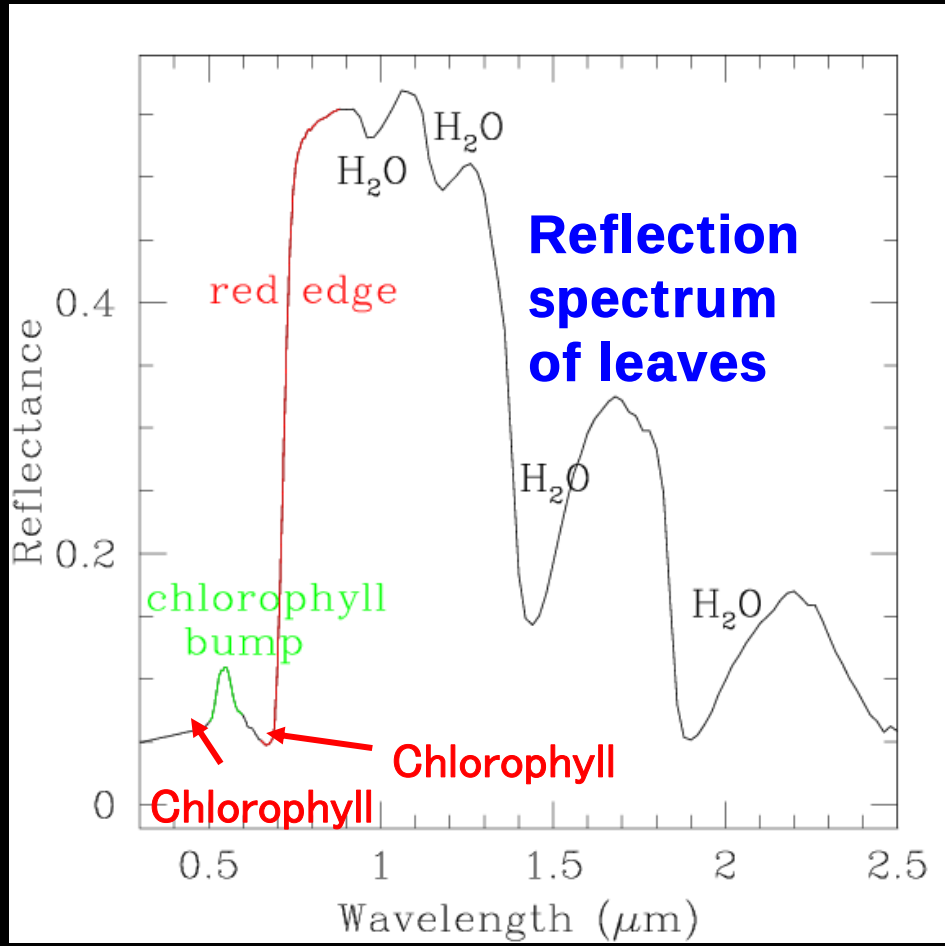


- O_3@9.6 μ m
  - Good tracer of O_2
- H_2O @<8 μ m,>17 μ m
- CH_4@7.7 μ m
  - Biotic origin?

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

Red edge of *(extrasolar) plants:* a biomarker in *extrasolar planets*

- **Red-edge**
  - Significant increase of reflectivity of leaves on Earth (terrestrial planets) for $\lambda > 7000$ Å
- An interesting and unique biomarker ?
- Widely used in the remote-sensing of our Earth



Seager, Ford & Turner
astro-ph/0210277

Vesto Melvin Slipher (1875-1969)

Red-edge as a biomarker (at least) in 1924 !

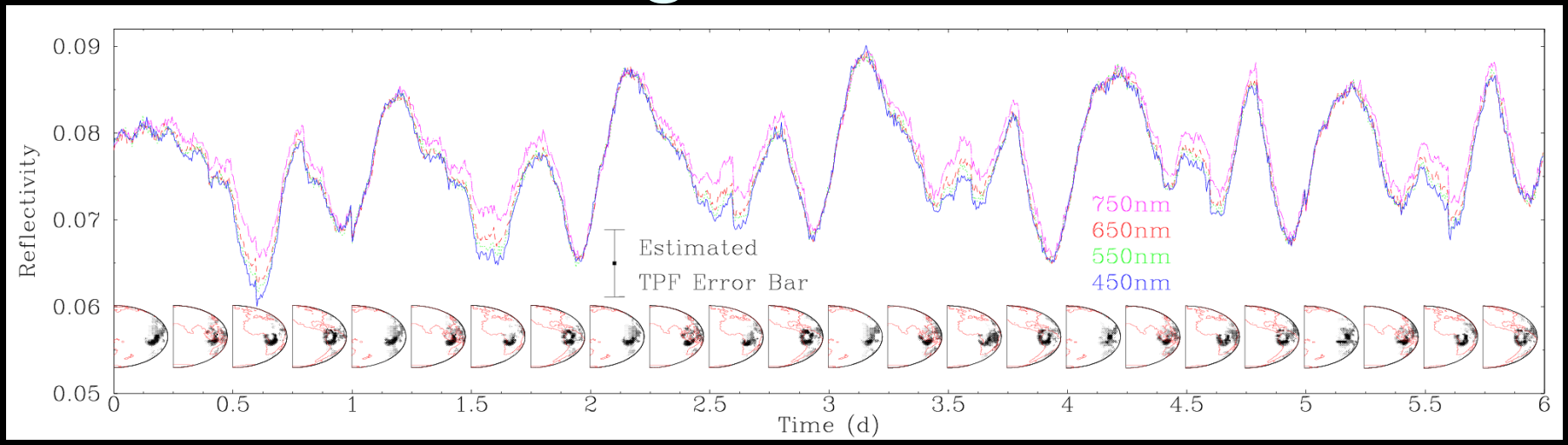
- Discovered redshifts of “spiral nebulae” now known as galaxies

“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 !

Expected daily change of the reflected light from the earth



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

- ***Assume*** **that the earth's reflected light is completely separated from the Sun's flux !**
  - **TPF (Terrestrial Planet Finder) in 10 years from now ?**
- ***Periodic change of 10 % level*** **due to different reflectivity of land, ocean, forest, and so on**
- **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

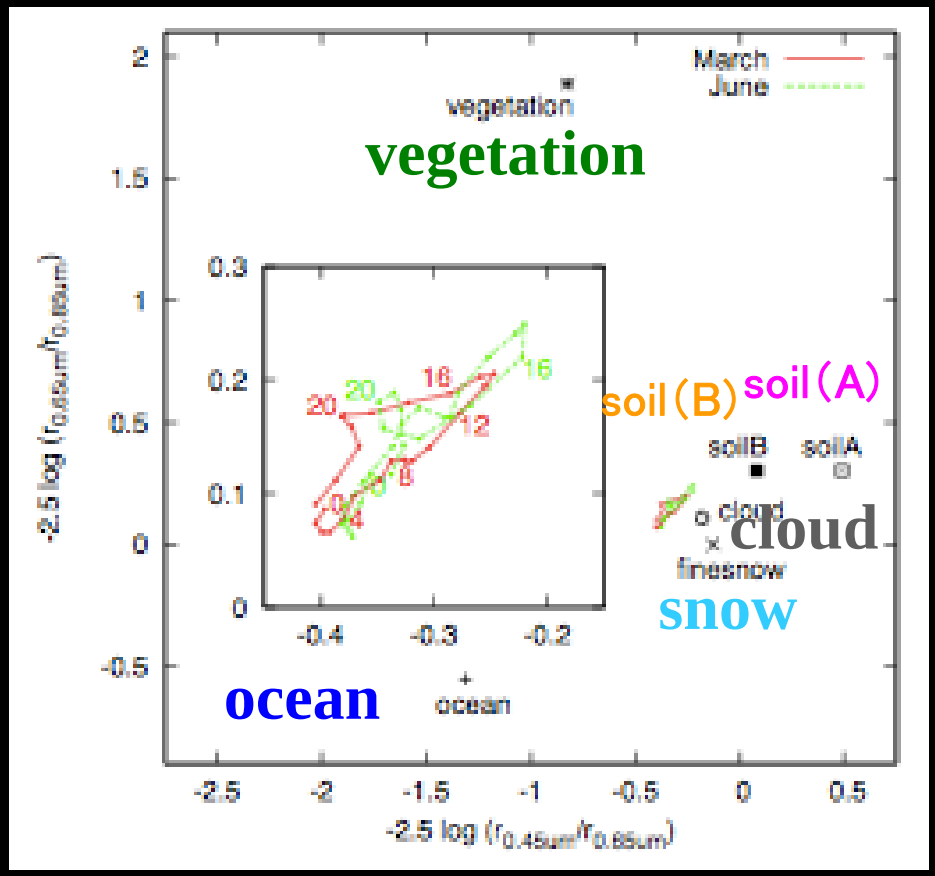
Colors of a Second Earth. II: Effects of Clouds on Photometric Characterization of Earth-like Exoplanets

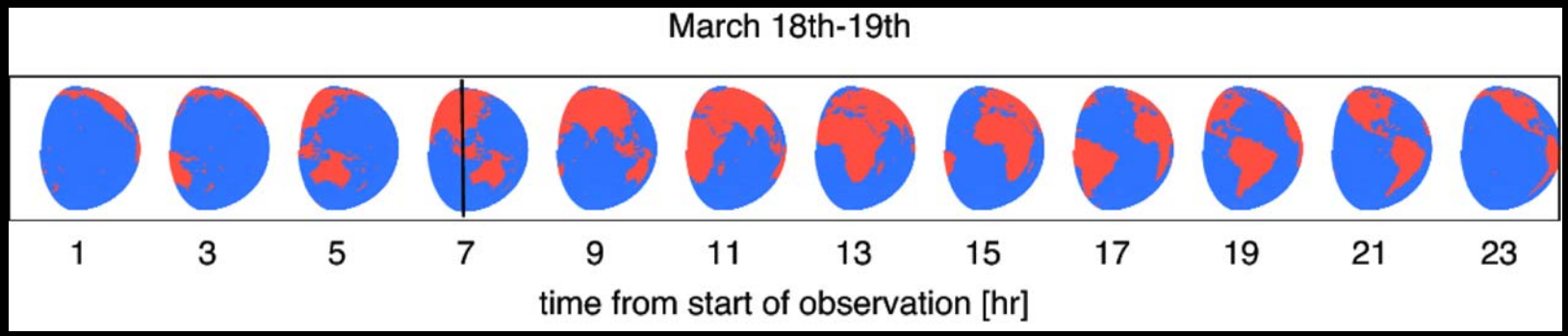
ApJ. 738(2011)184, arXiv:1102.3625

- 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.)

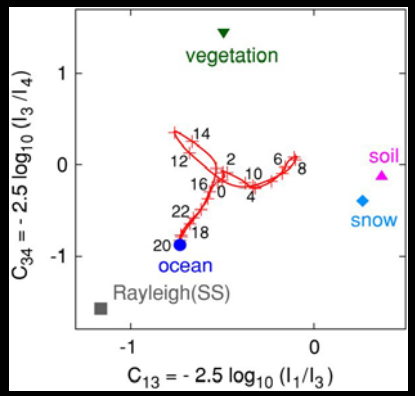
http://www.space.com/scienceastronomy/color-changing-planets-alien-life-100513.html

Colors of our earth

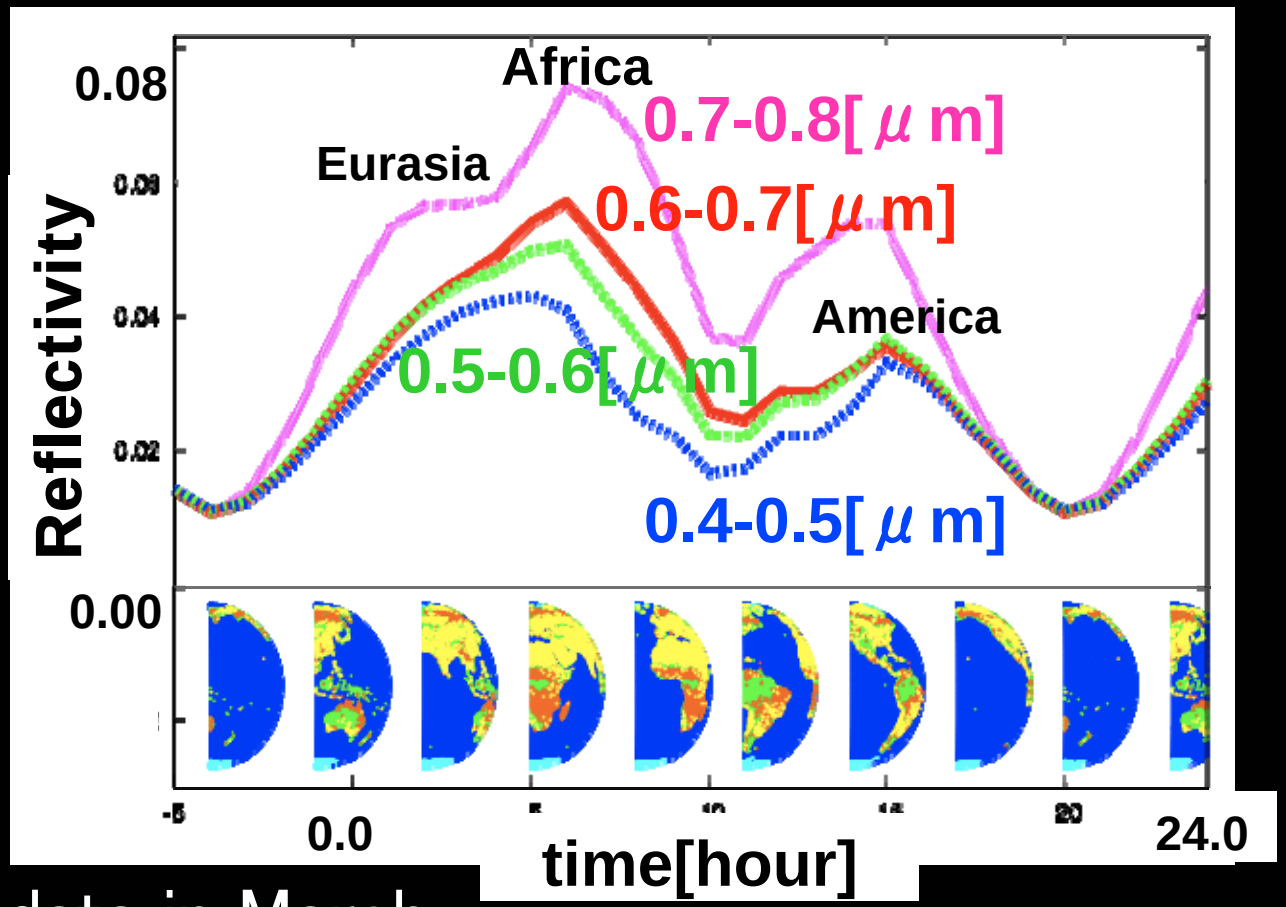




A pale blue dot ? Not really



Simulated photometric light-curves of Earth



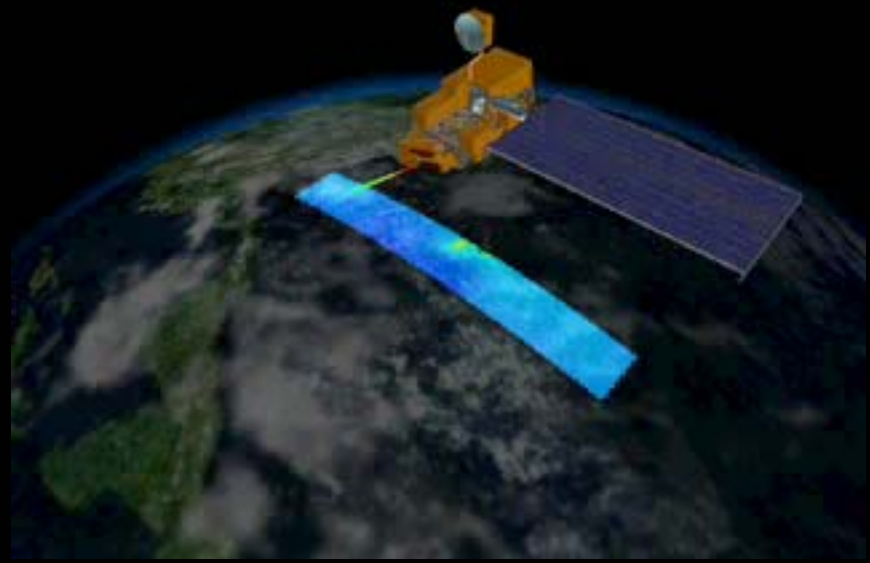
- Adopted Earth data in March
- Spin inclination = 0 (vernal equinox)
- cloudless

Fujii et al. (2010)

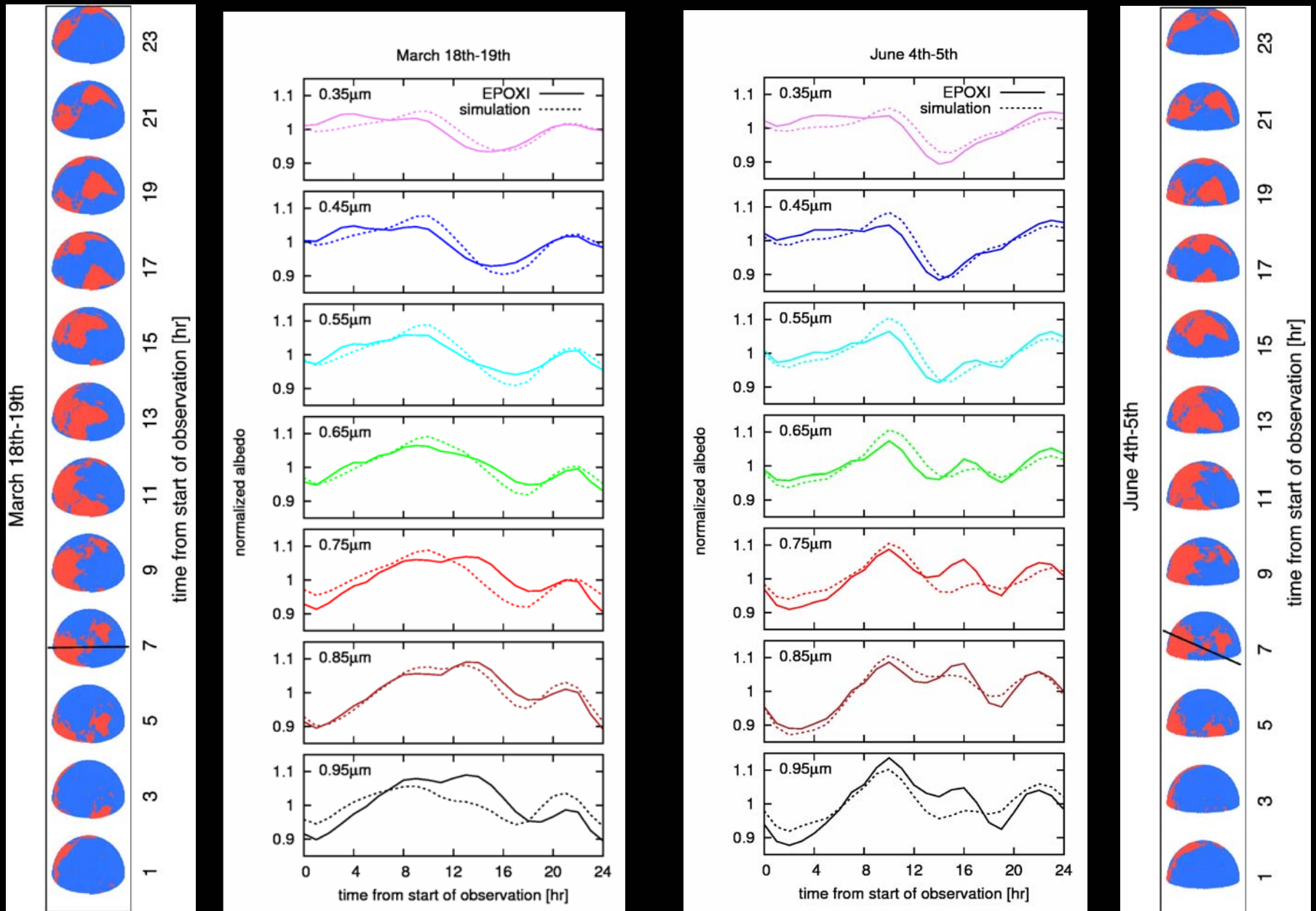
Forward procedure: reflected light model from the earth

- Simulated light-curves of the earth in 7 photometric bands
  - land: BRDF (Bidirectional Reflectance Distribution Function) model from earth-observing satellite Terra/MODIS on 2.5° x2.5° pixels
  - ocean: BRDF model of Nakajima & Tanaka (1983)
  - snow: real data of the month
  - cloud: real data of the day
  - Atmosphere and cloud: radiation transfer solved with rstar6b
- Comparison with the real data observed by EPOXI

Earth observing satellite Trace (Transition Region and Coronal Explorer) + detector Modis (Moderate Resolution Imaging Spectroradiometer)



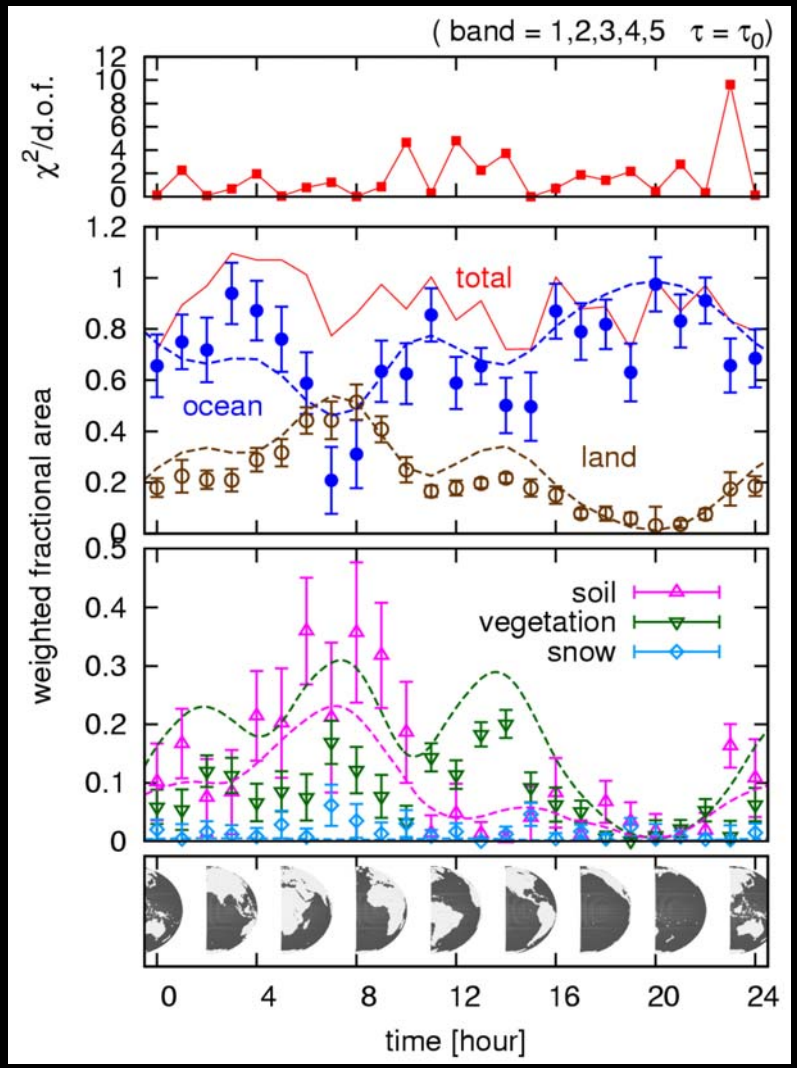
Simulated light-curves vs. EPOXI data



Inverse procedure: estimation of fractional areas of surface components

- Fitting the EPOXI data to a simplified model (isotropic scattering with ocean, soil, vegetation, snow and cloud)
  - Neglect light from the central star
  - Neglect the spin and orbital rotation during each exposure
  - A simple cloud model with the same optical depth τ（=10 fiducially）
  - US standard atmosphere: compositions, pressure and temperature profiles

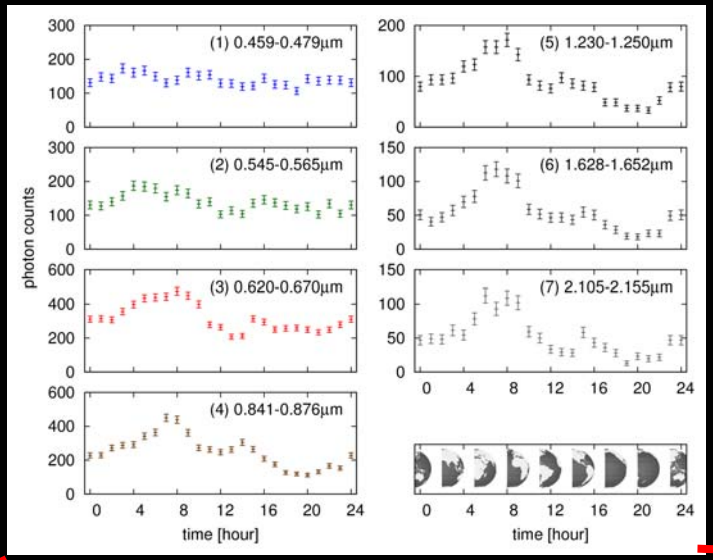
Cloudless case



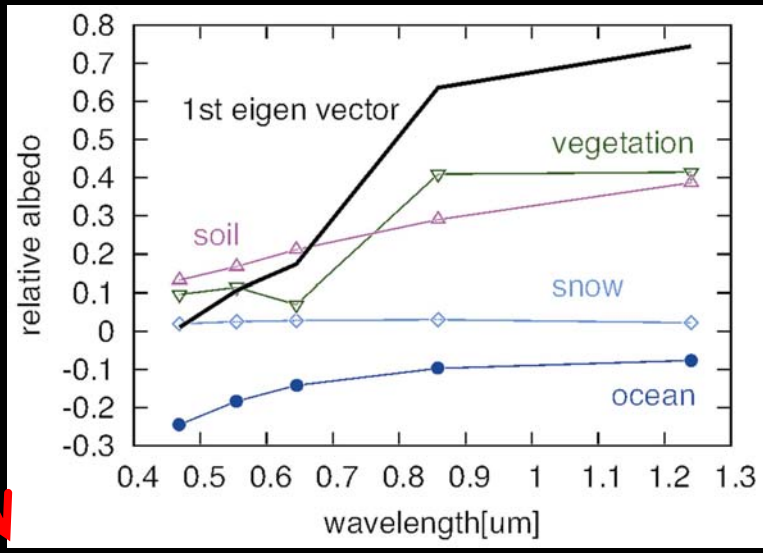
Fujii et al.（2010）

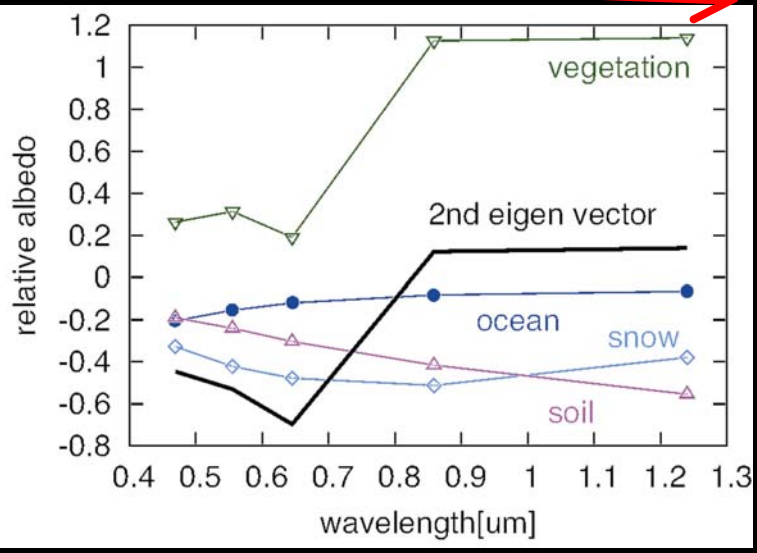
- Input data
  - 5 light-curves using anisotropic scattering (BRDF) model
  - 2 week observation of a cloudless Earth at 10 pc away
- Inversion assumptions
  - Ocean, soil, vegetation and snow only (with atmosphere)
  - Isotropic scattering assumed
- Results
  - Estimated areas (symbols) vs Surface classification data (dashed line)
  - Reasonably well reproduced.
  - Can identify vegetation !

PCA (principal component analysis)



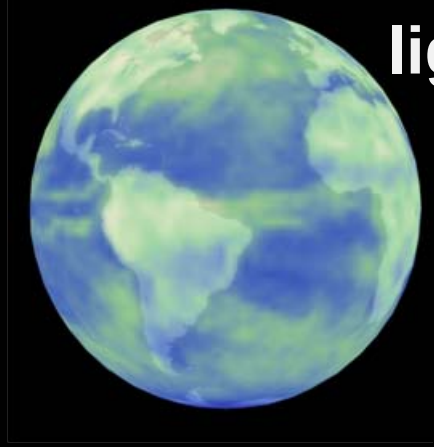
- 1st eigen vector
  - ≒ soil + vegetation – ocean
- 2nd eigen vector
  - ≒ vegetation – soil – ocean – snow



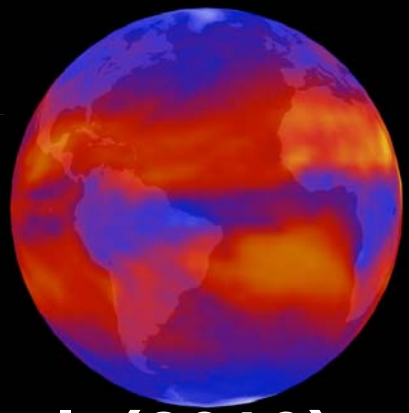


Reconstruction of planetary surface areas with clouds

reflected light

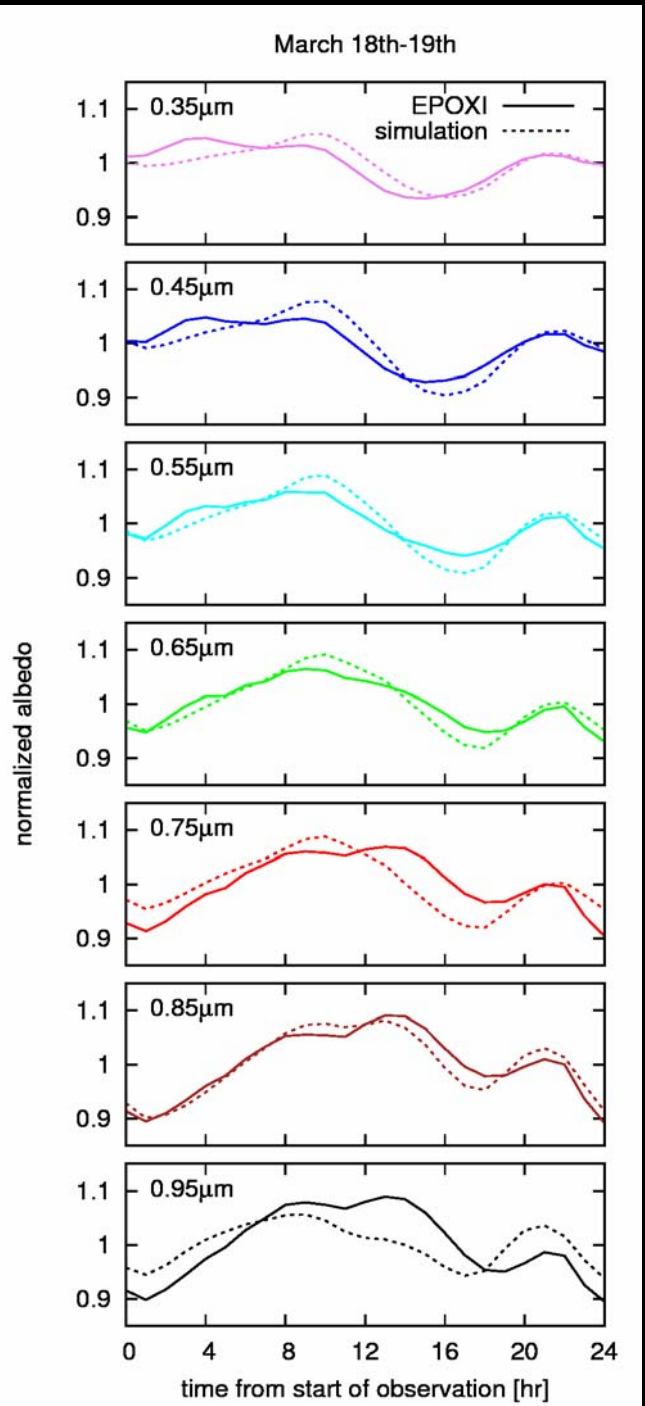


emission light

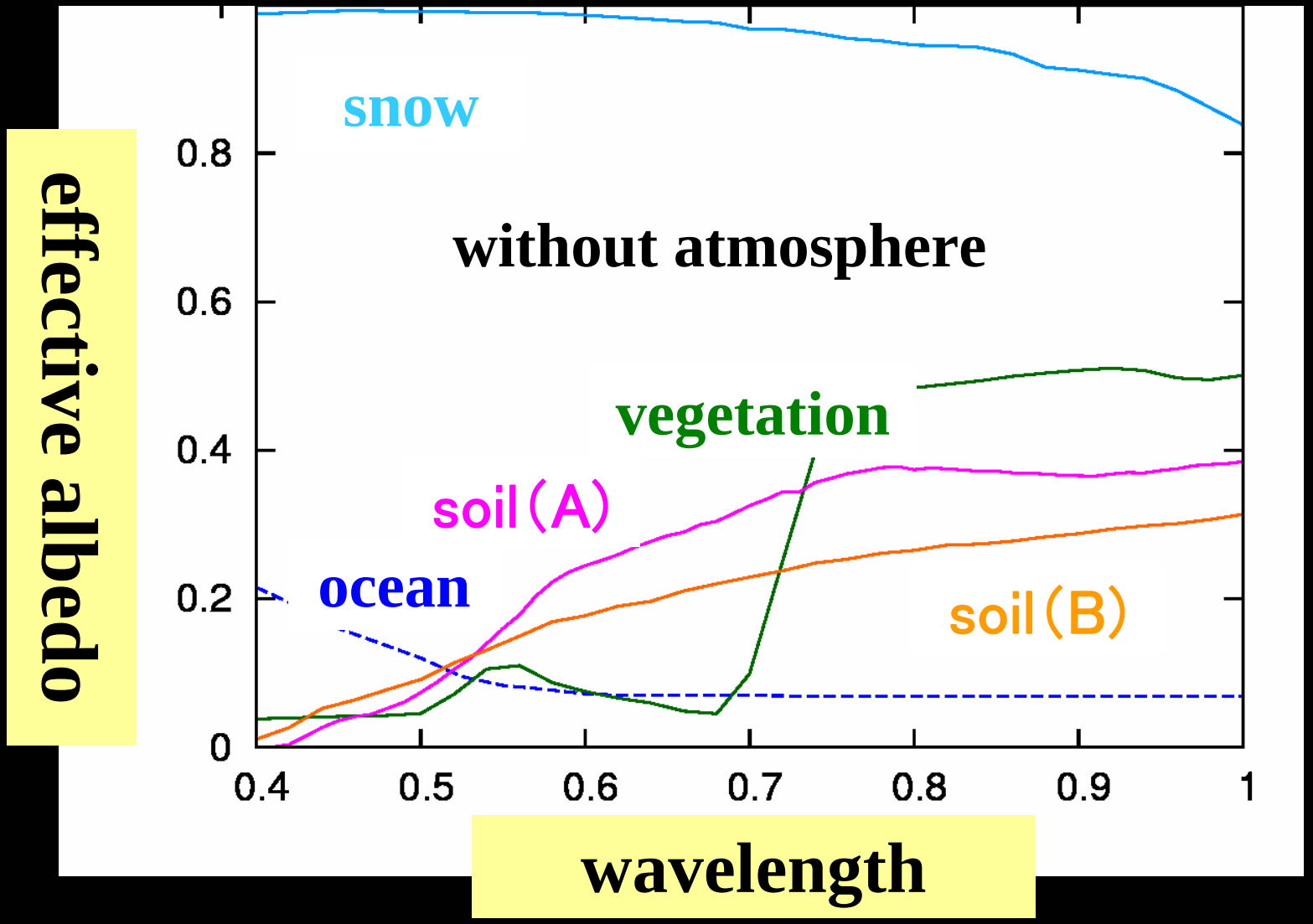


Vazquez et al. (2010)

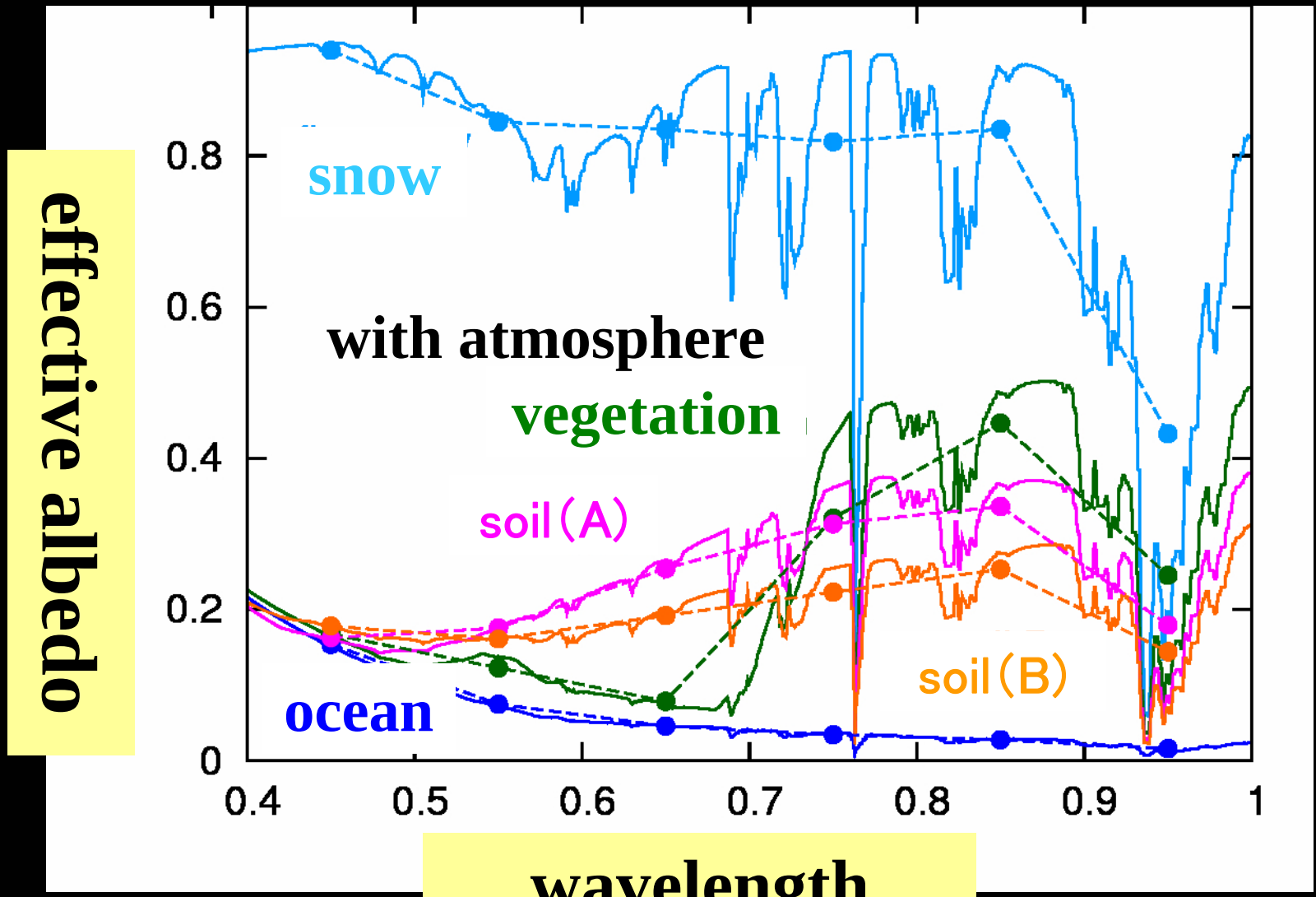
Fujii et al. (2010)



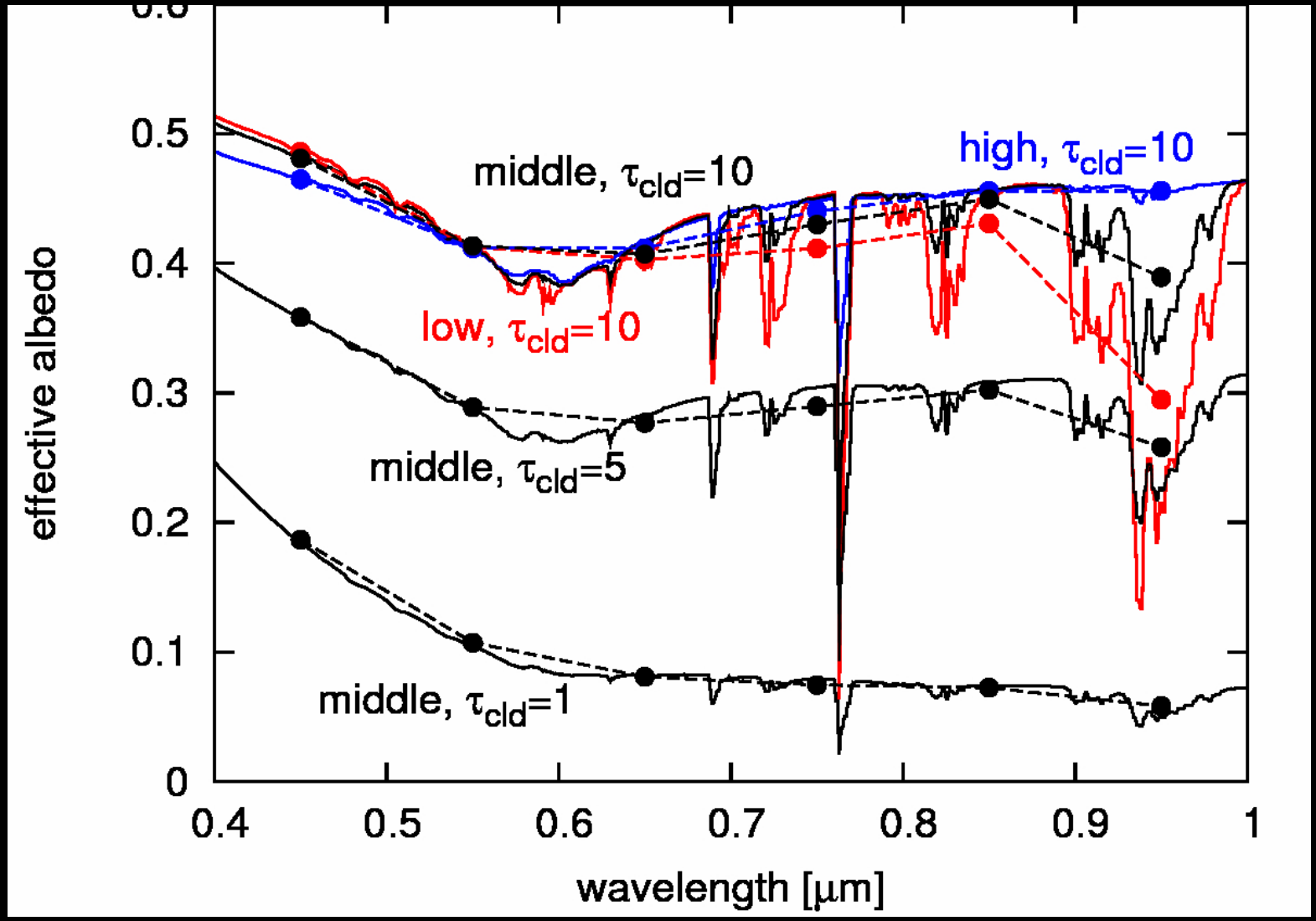
Albedo of surface components: isotropic approximation w/o atmosphere



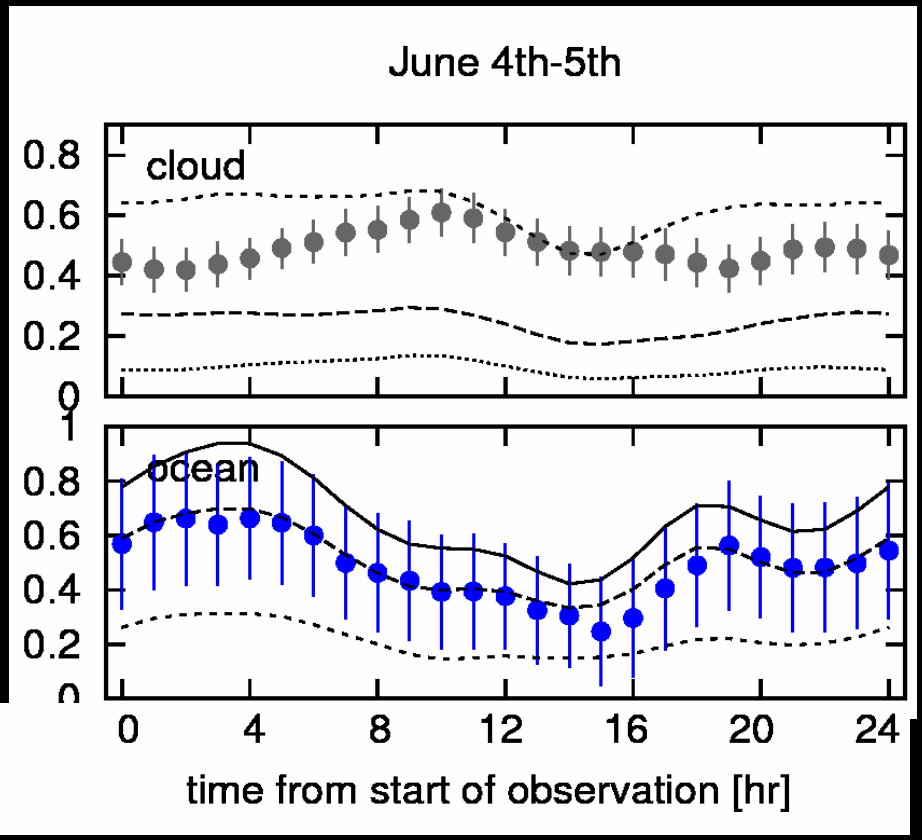
Albedo of surface components: isotropic approximation with atmosphere

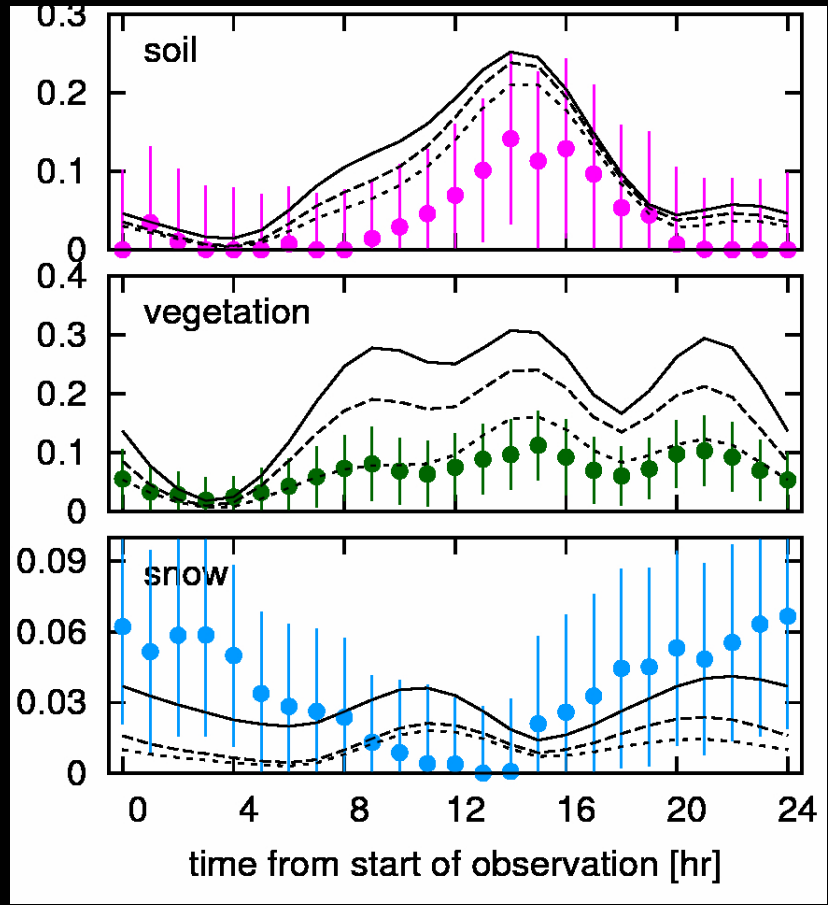


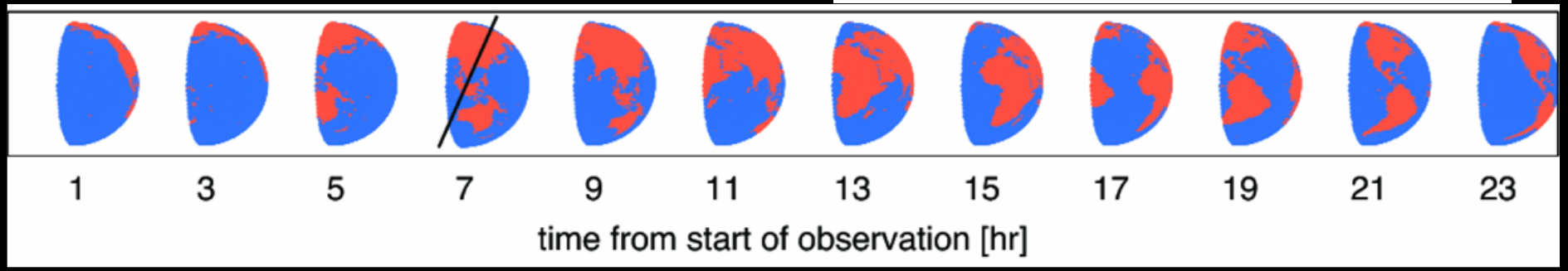
Albedo spectra of clouds: model dependence



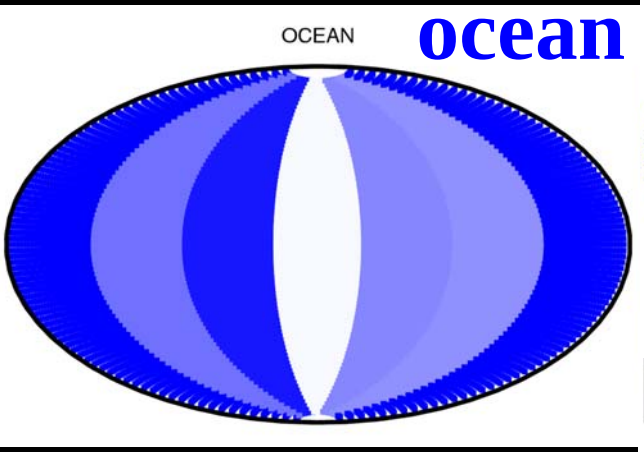
Fractional areas estimated from EPOXI data



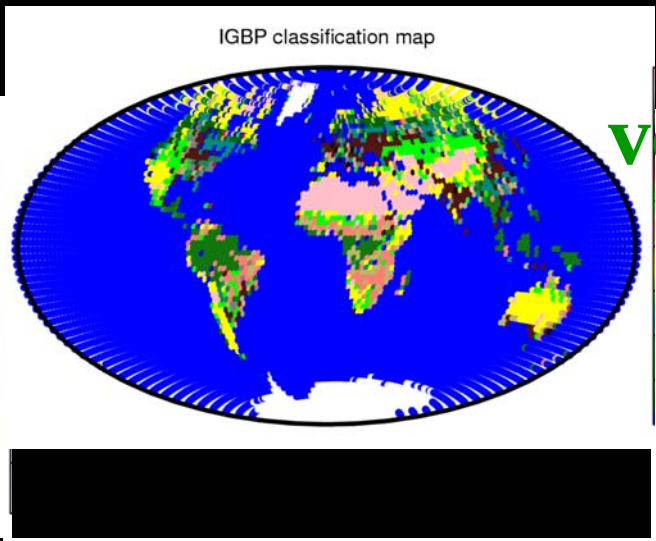




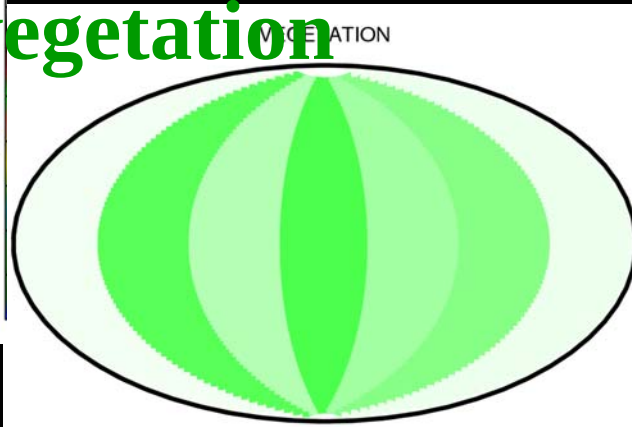
Surface latitude map estimated from EPOXI data

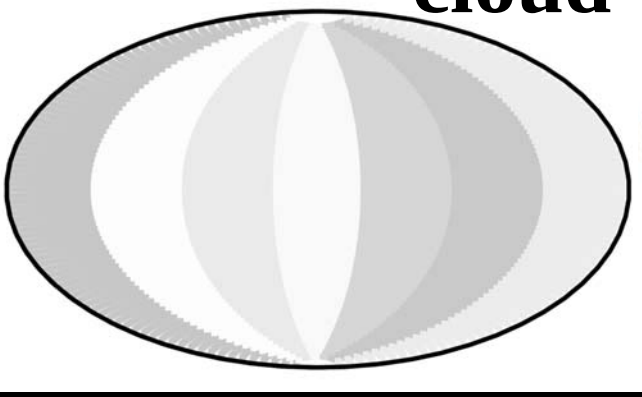


ocean

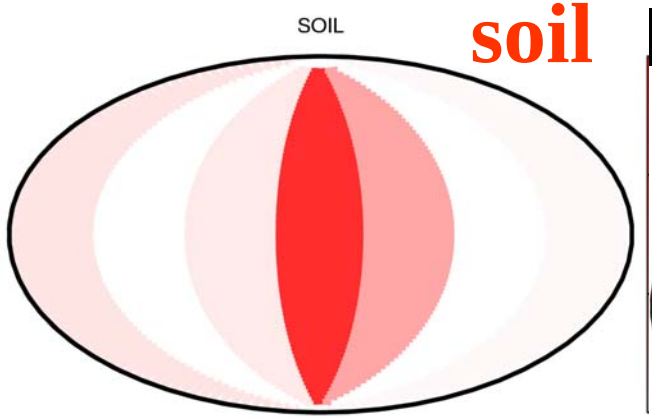


vegetation



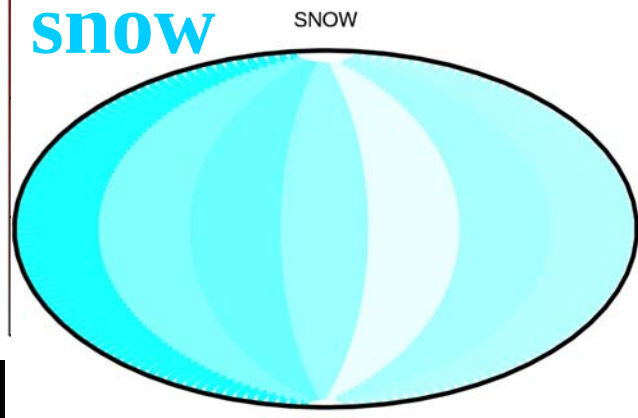


cloud



soil

snow



The color of plants on other worlds
N.Kiang, Sci.Am.(2008)

Le Petit Prince:
(par Antoine de Saint Exupéry)

Si quelqu'un aime une fleure qui n'existe qu'à un exemplaire dans les millions et les millions d'étoiles, ça suffit pour qu'il soit heureux quand il les regarde. Il se dit: "Ma fleur est là quelque part . . . "