Virtual Planetary Laboratory at UW
NAI Member

Instituto de Ciencias Nucleares

Universidad Nacional Autónoma de México

Biosignatures on habitable planets around other stars: Lessons from Earth

Antígona Segura Peralta
Instituto de Ciencias Nucleares
Universidad Nacional Autónoma de México

Collaborators

- Victoria Meadows, Washington State University
- James Kasting, Pennsylvania State University
- John Scalo, University of Texas, Austin
- David Crisp, NASA-JPL
- Martin Cohen, University of California, Berkeley
- Nancy Kiang, NASA Goddard Institute for Space Studies
- Giovanna Tinetti, university College London

A new generation of instruments

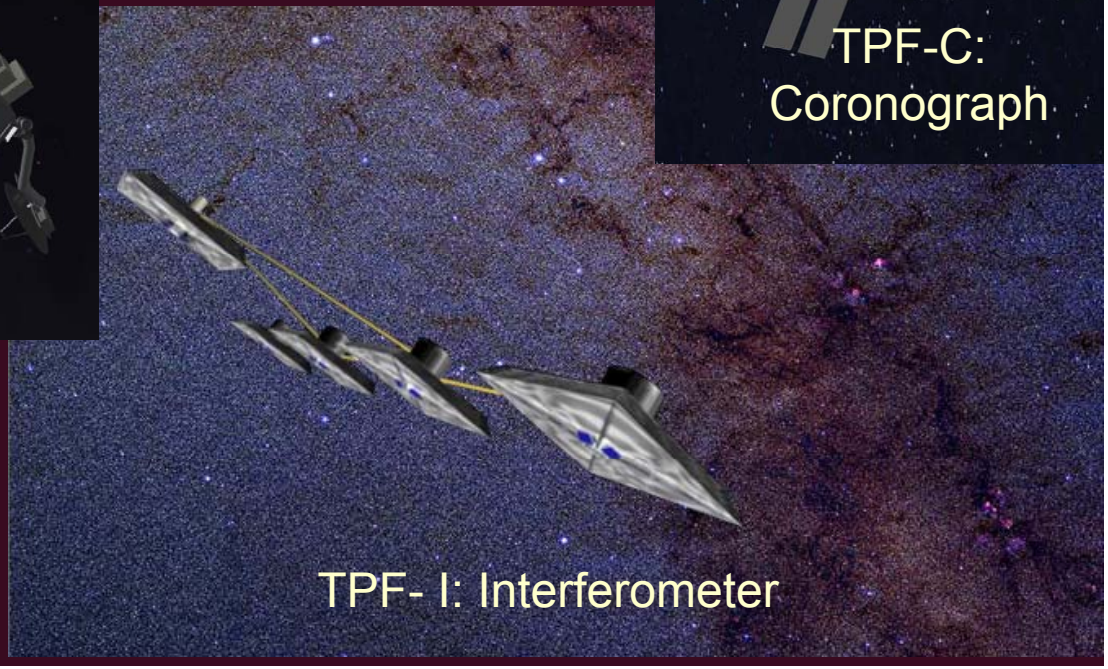
Kepler (NASA):

- Launch: 2009
- Photometer 0.95 m
- Detection of Earth-size planets

Terrestrial Planet Finder (NASA):

- ~100 nearby stars
- Visible and infrared spectroscopy

TPF-C: Coronograph



TPF- I: Interferometer

A new generation of instruments

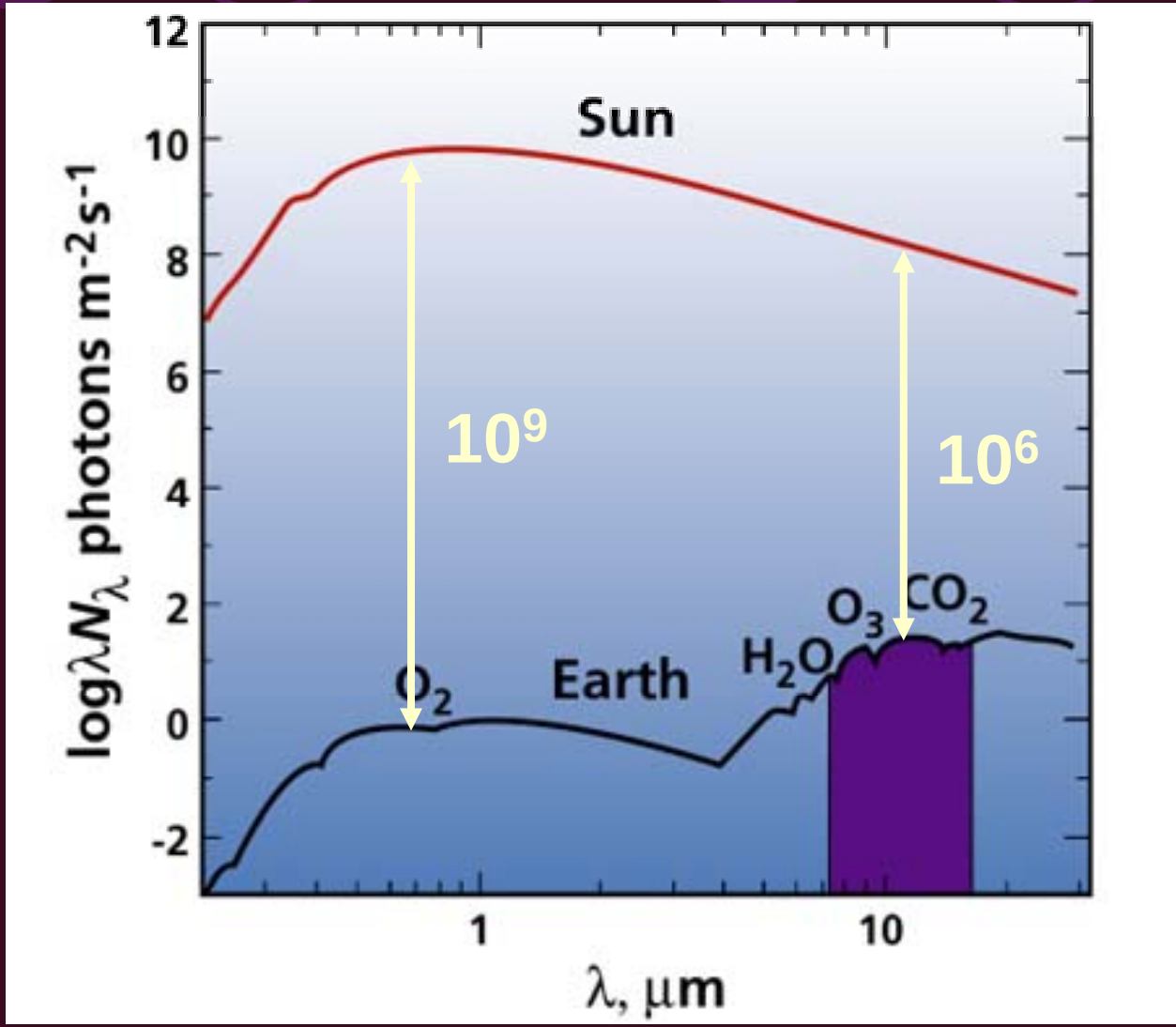
Corot (France):

- Launched December 2006.
- 27 cm Photometer

Darwin (ESA):

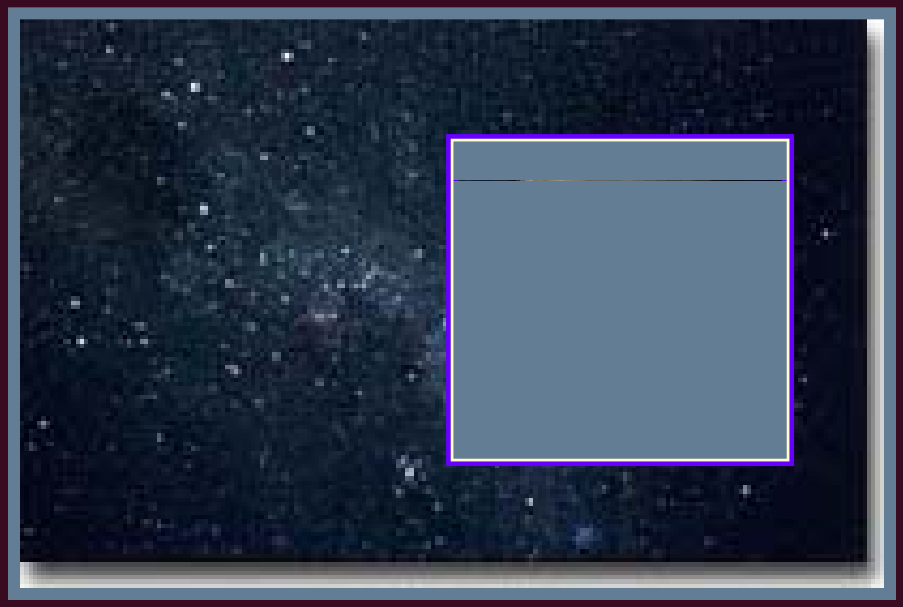
- Infrared interferometer

The problem of detecting Earth-size planets



Remote detection of life

- We will not be able to “resolve” the extrasolar planet
- Everything we learn about the planet will be obtained from disk-averaged data.
- The signs of life must be a global surface phenomenon
- Our interpretation is only as good as the effective emitting layer!



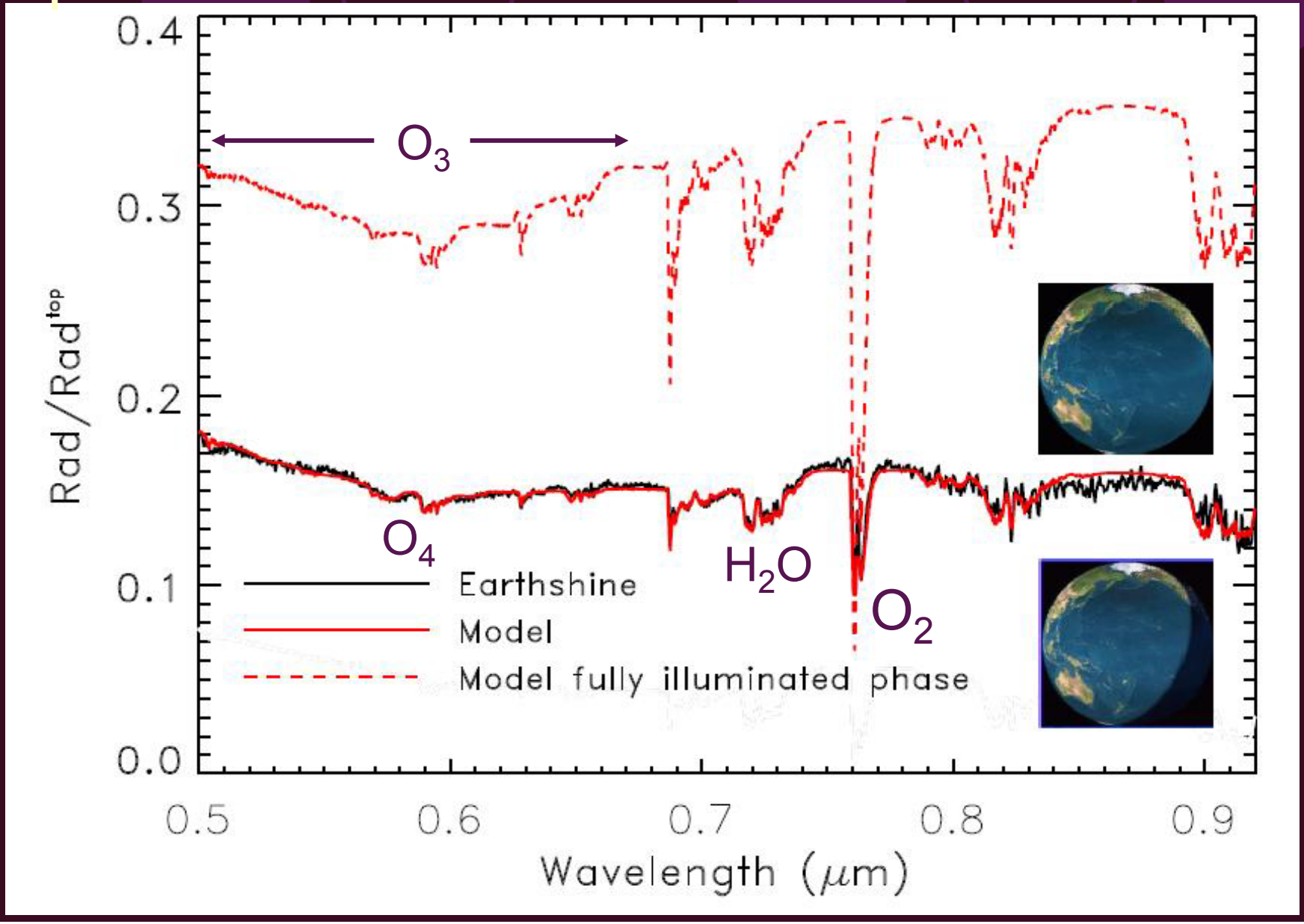
Earth: an habitable world

- Water: Good solvent, abundant in the universe
- Right distance from its star (Habitable Zone): It helps to maintain the right temperature if the planet has an…
- Atmosphere: Keeps a stable climate and provides the pressure for water to be liquid

Planet	T_{eff}	T_{surf}	Greenhouse effect
Venus	-43C	470C	513C
Earth	-17C	15C	32C
Mars	-55C	-50C	5C

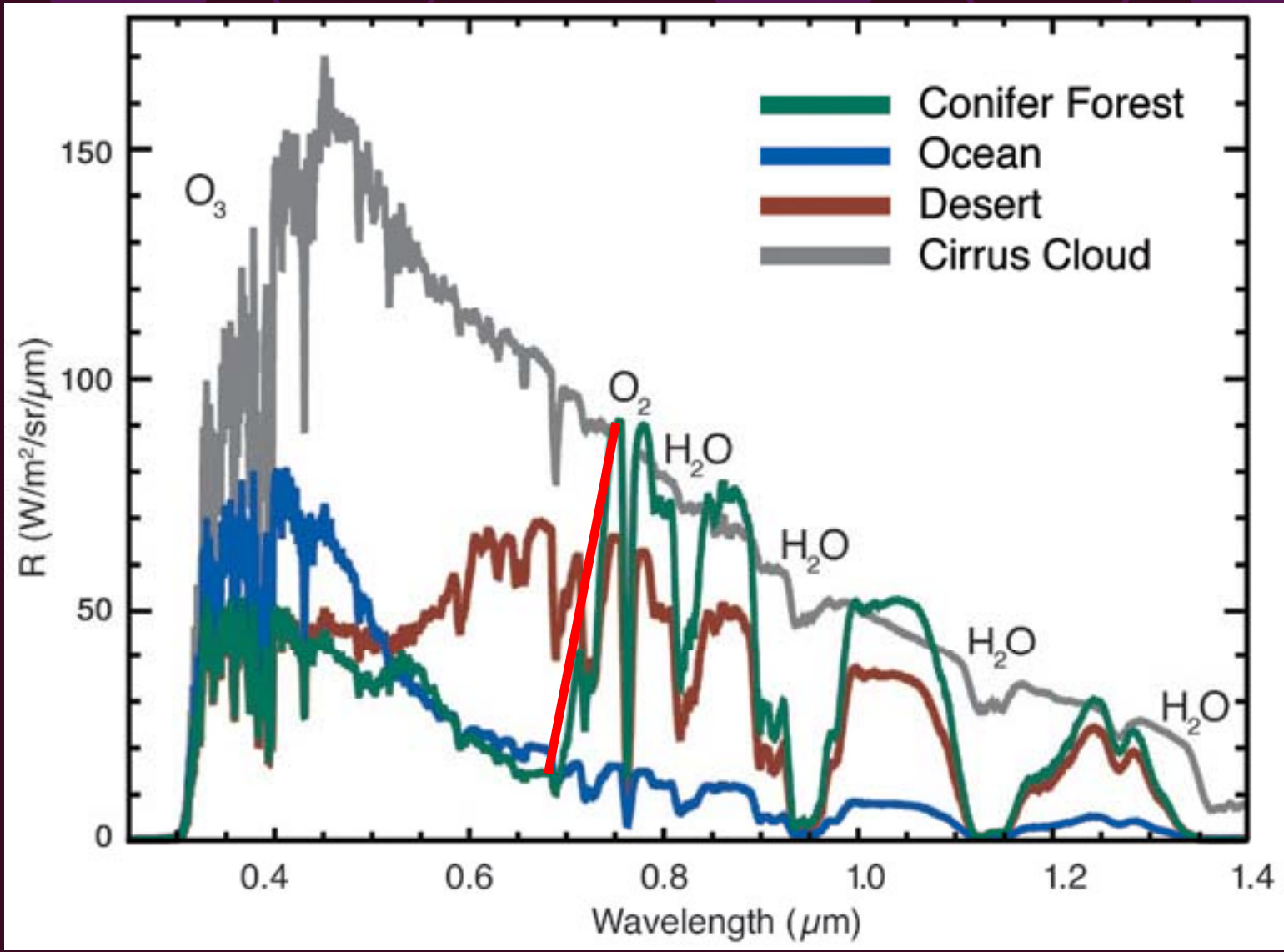
- Planetary mass: Helps to retain the planetary atmosphere and it is related to plate tectonics and magnetic field.

Earthshine: Earth's disk averaged spectrum

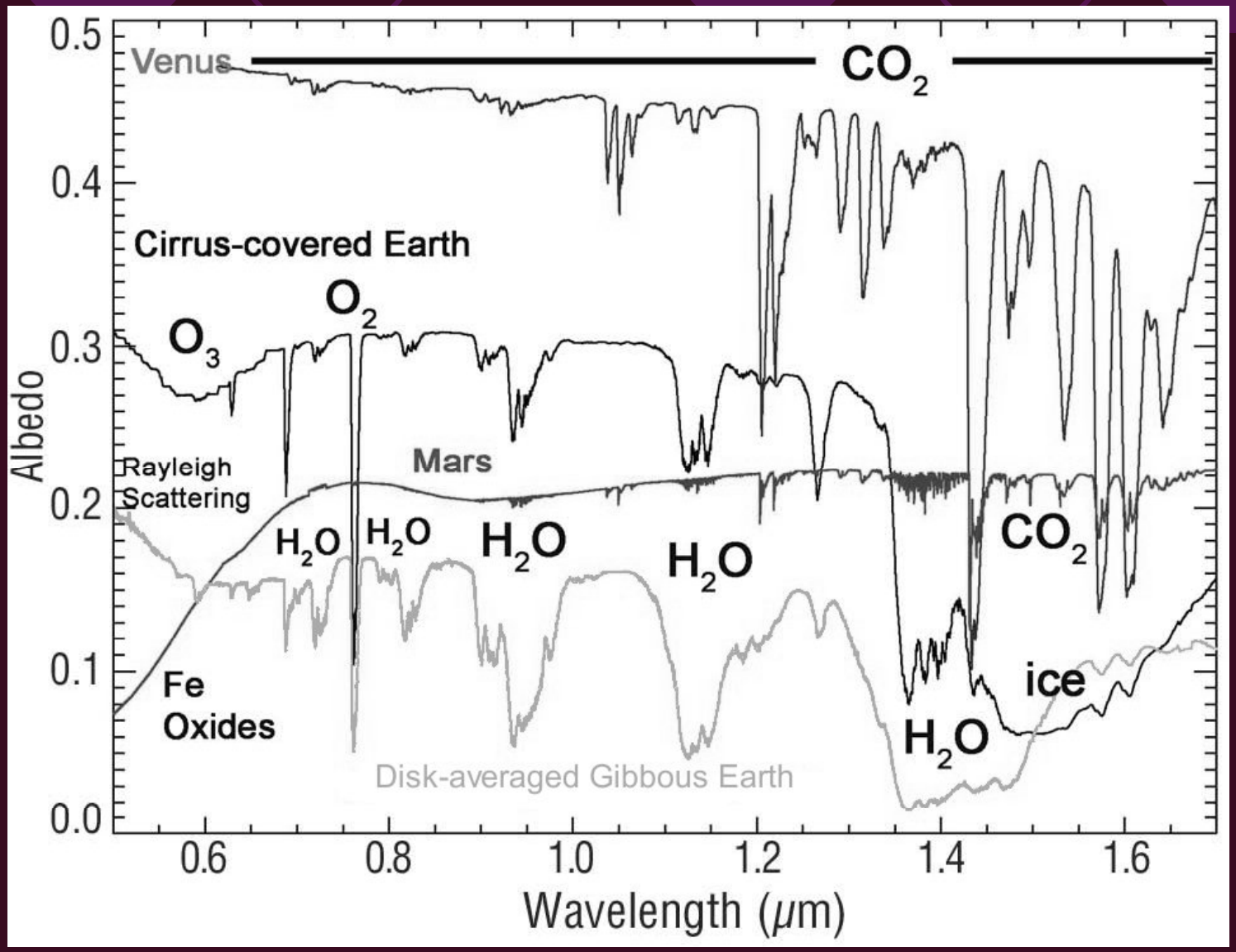


Data: Woolf, Traub and Jucks 2001
Models: Tinetti et al., 2006

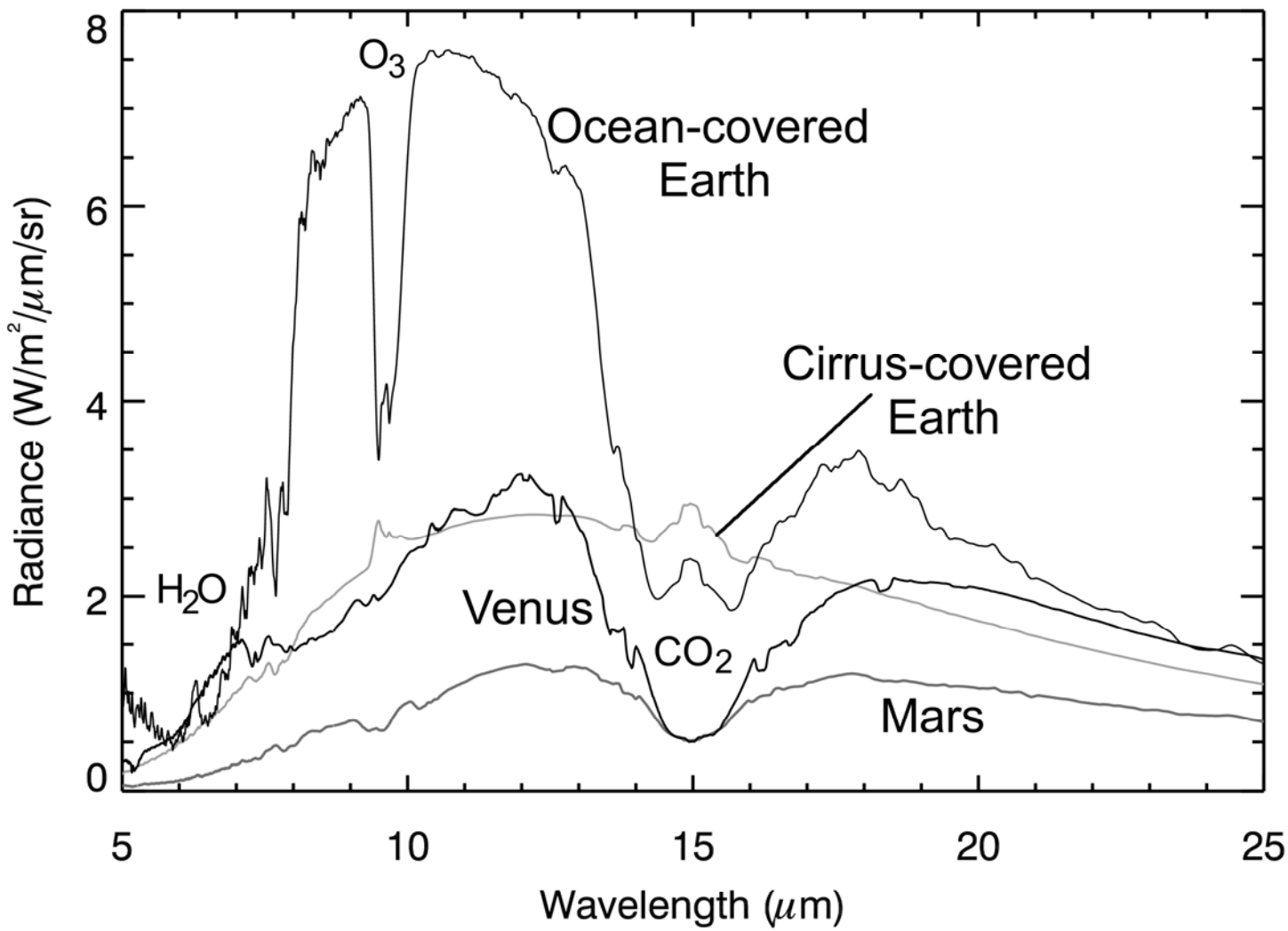
Present Earth: surfaces



Terrestrial Planets in the visible-NIR



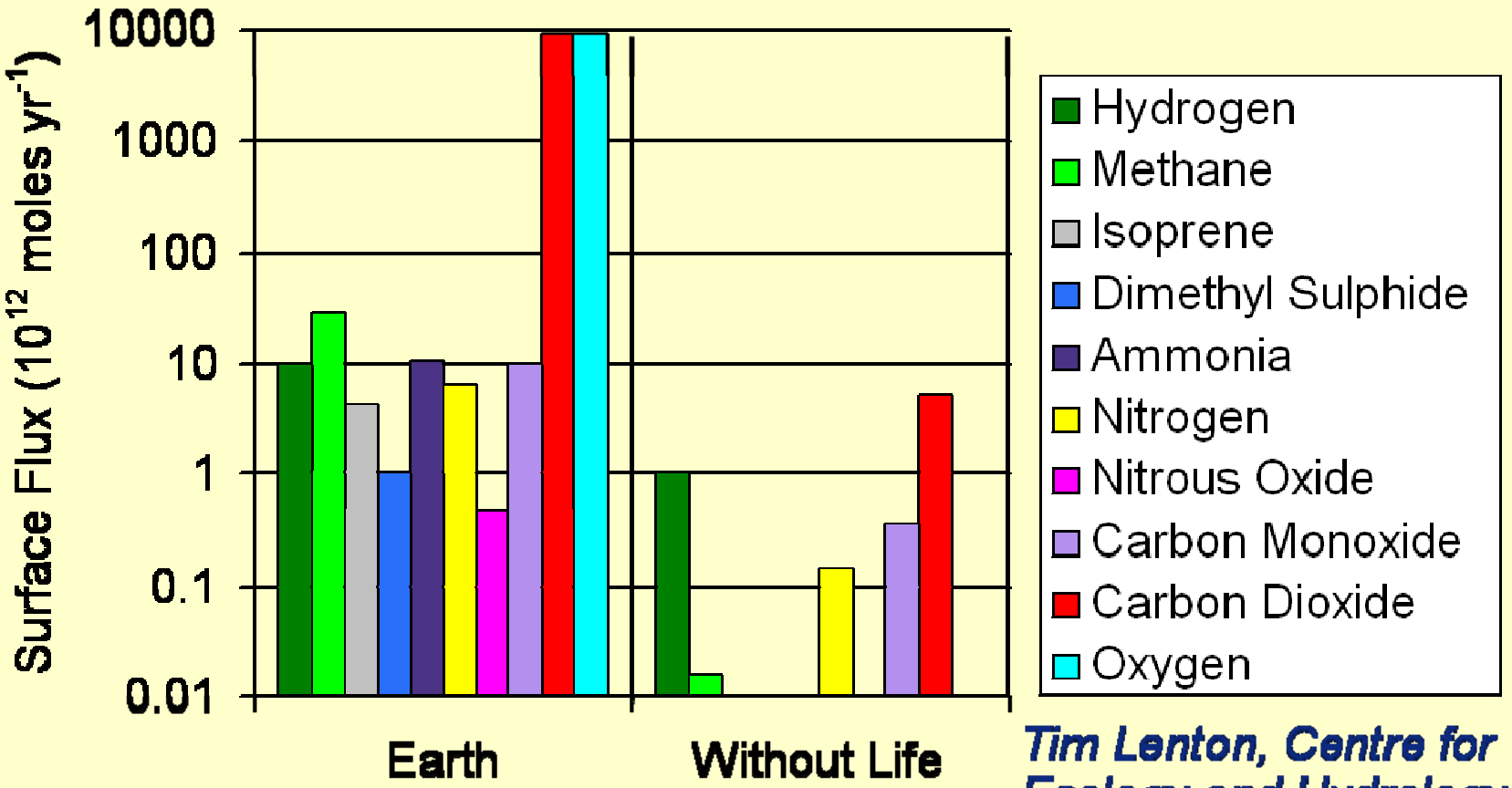
Terrestrial Planets in the mid IR



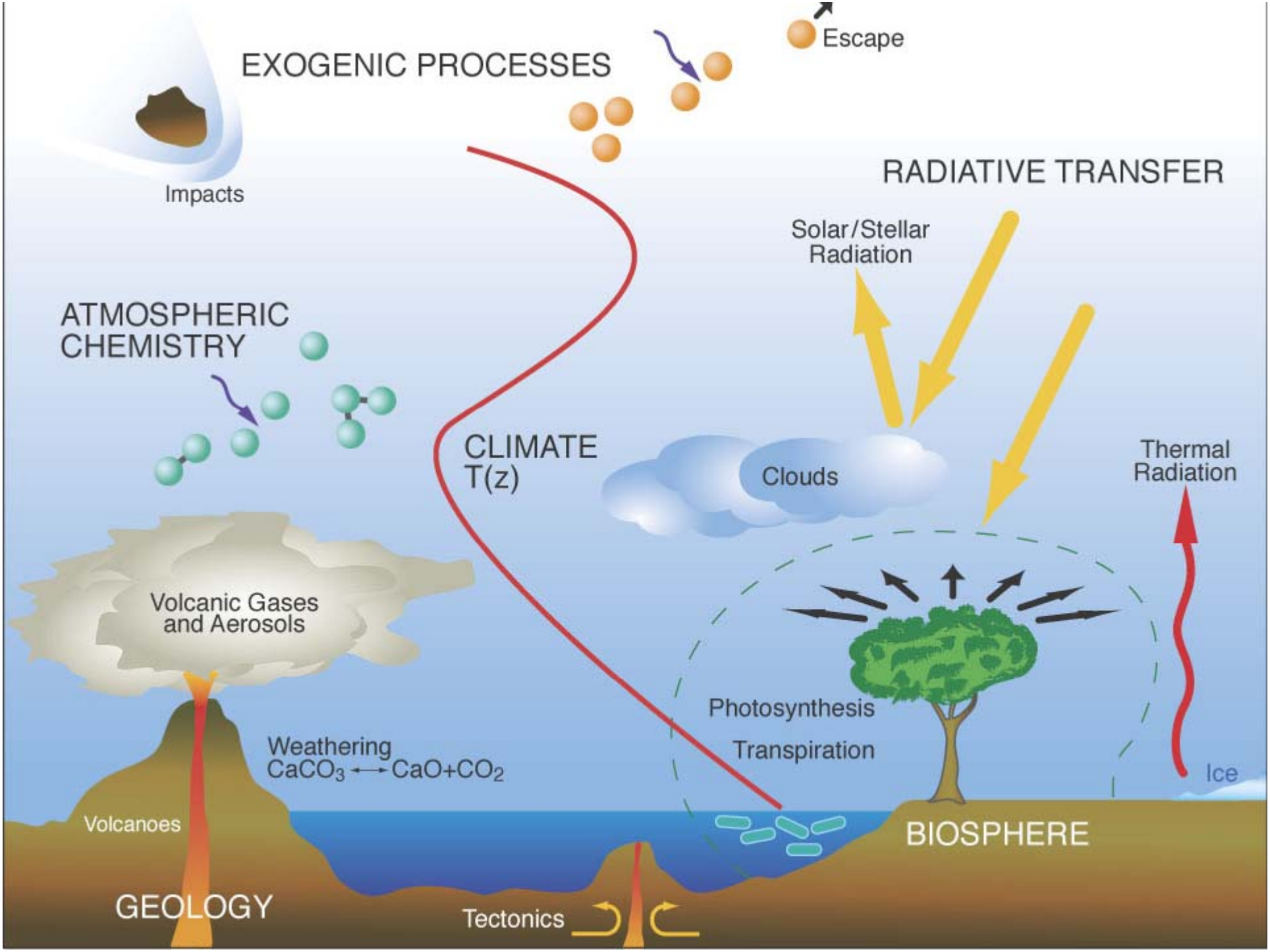
Biosignatures: Life´s footprints

- Astronomical Biosignatures are global-scale photometric, spectral or temporal features indicative of life.
- Earth shows us that life can provide global-scale modification of:
  - A planet's atmosphere
  - A planet's surface
  - A planet's appearance over time
- Biosignatures must always be identified in the context of the planetary environment
  - e.g. Earth methane and Titan methane, ammonia with oxygen, oxygen with liquid water.
- "Antibiomarkers"
  - e.g. H2, CO on Earth-like planets – mysterious "free lunches"

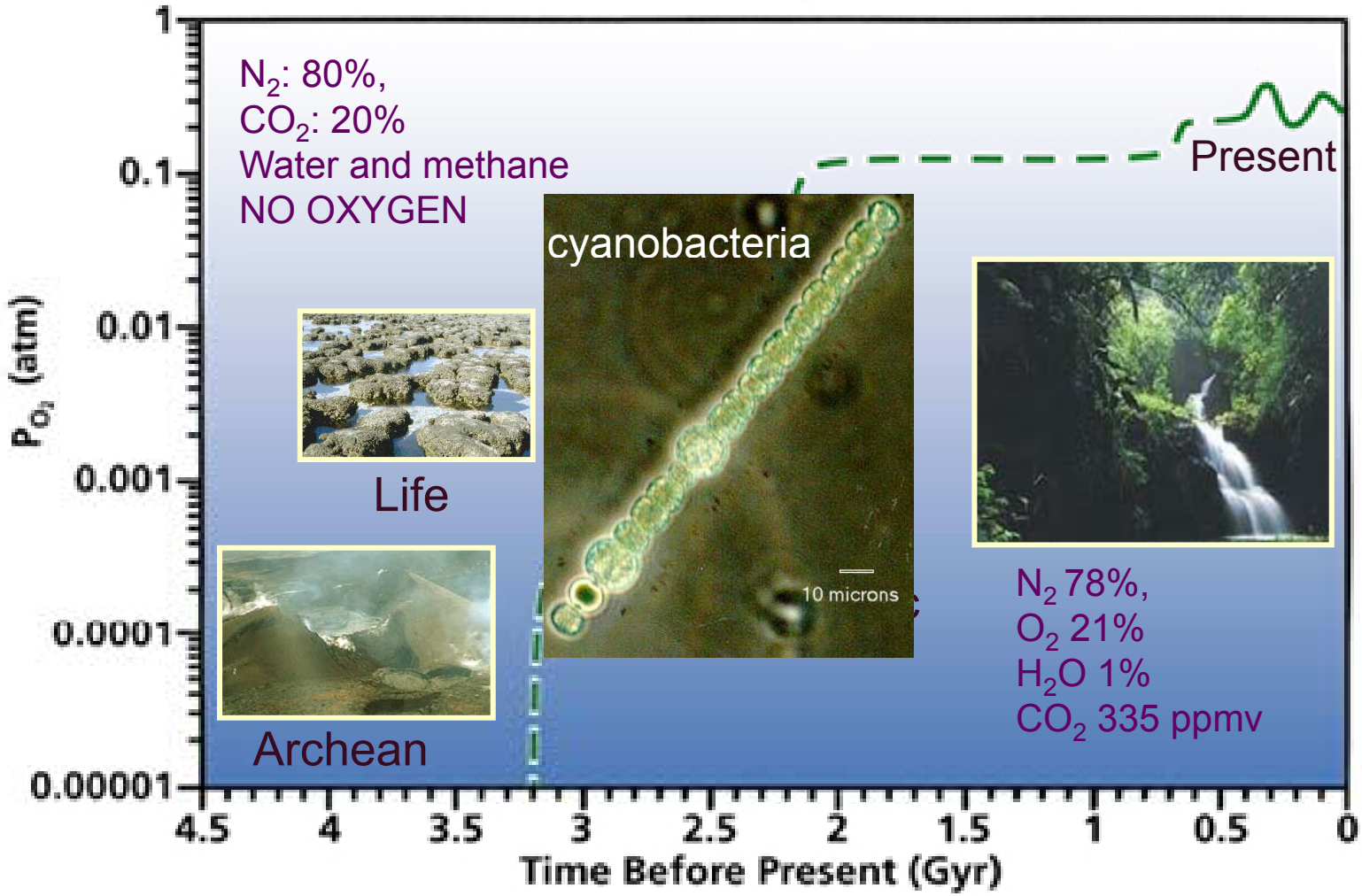
Possible biosignatures



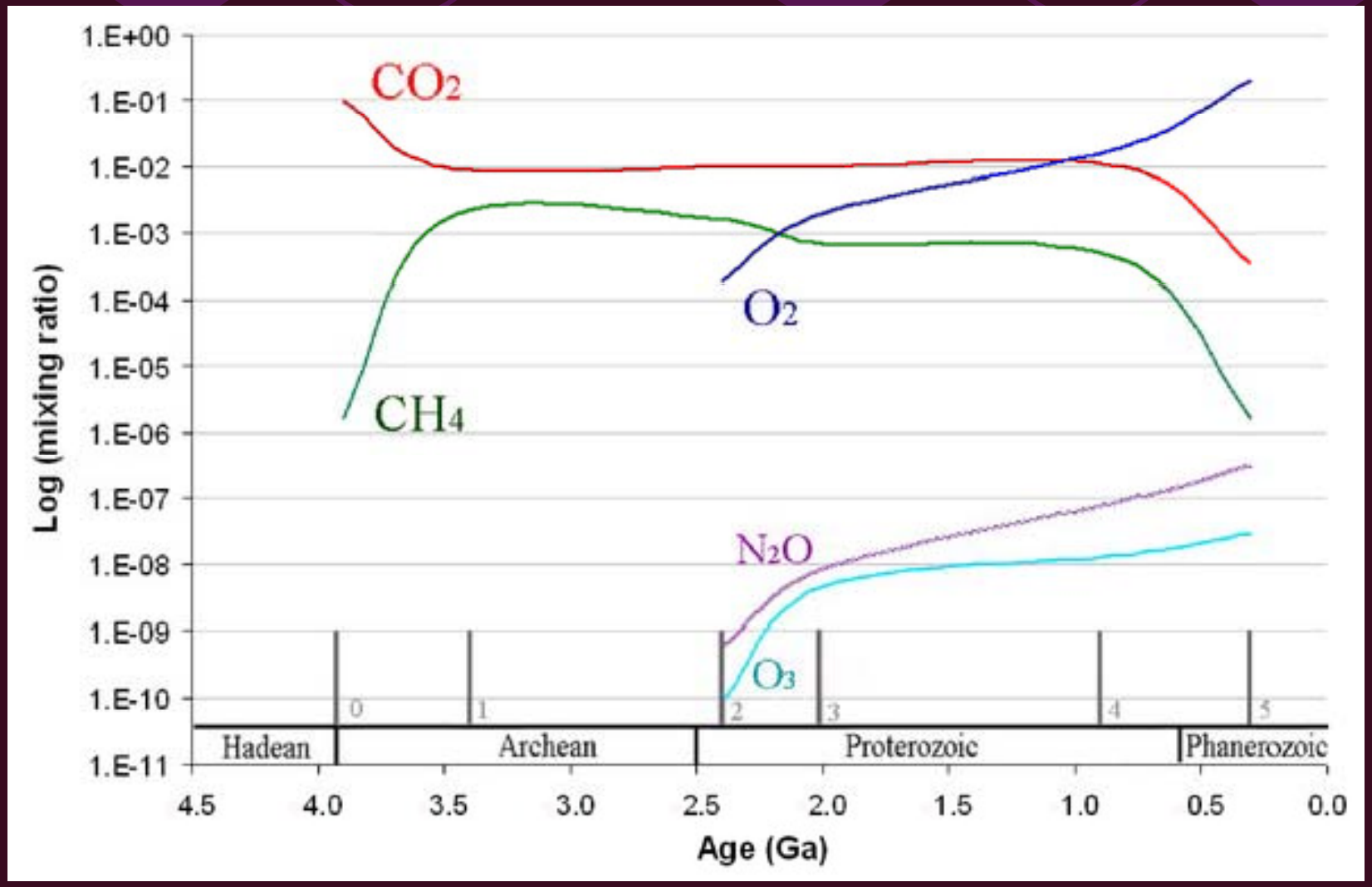
Tim Lenton, Centre for Ecology and Hydrology


EXOGENIC PROCESSES
Escape
Impacts
RADIATIVE TRANSFER
Solar/Stellar Radiation
ATMOSPHERIC CHEMISTRY
CLIMATE T(z)
Clouds
Thermal Radiation
Volcanic Gases and Aerosols
Photosynthesis
Transpiration
Weathering
$CaCO_3 \longleftrightarrow CaO+CO_2$
Ice
Volcanoes
BIOSPHERE
GEOLOGY
Tectonics

Oxygen on Earth

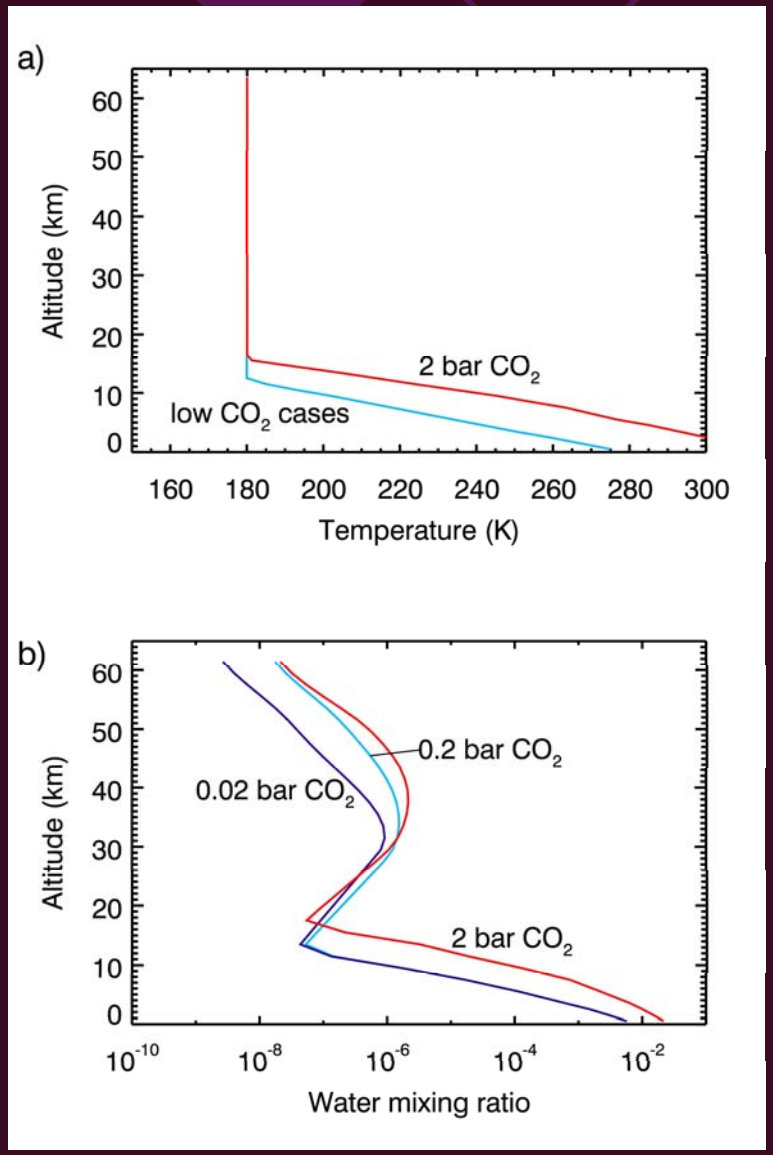


Earth on time



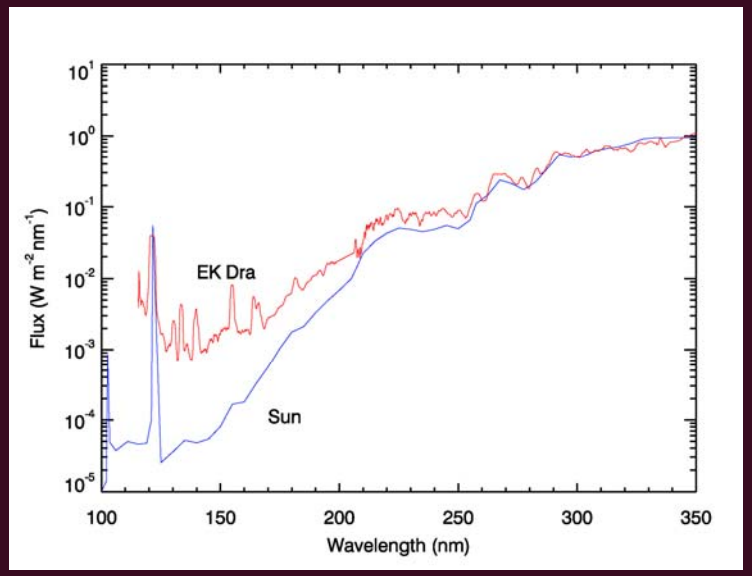
Kaltenegger et al. 2007

Early Earth: Archean (4 Ga)



Simulation of planets with high CO_2 atmospheres:

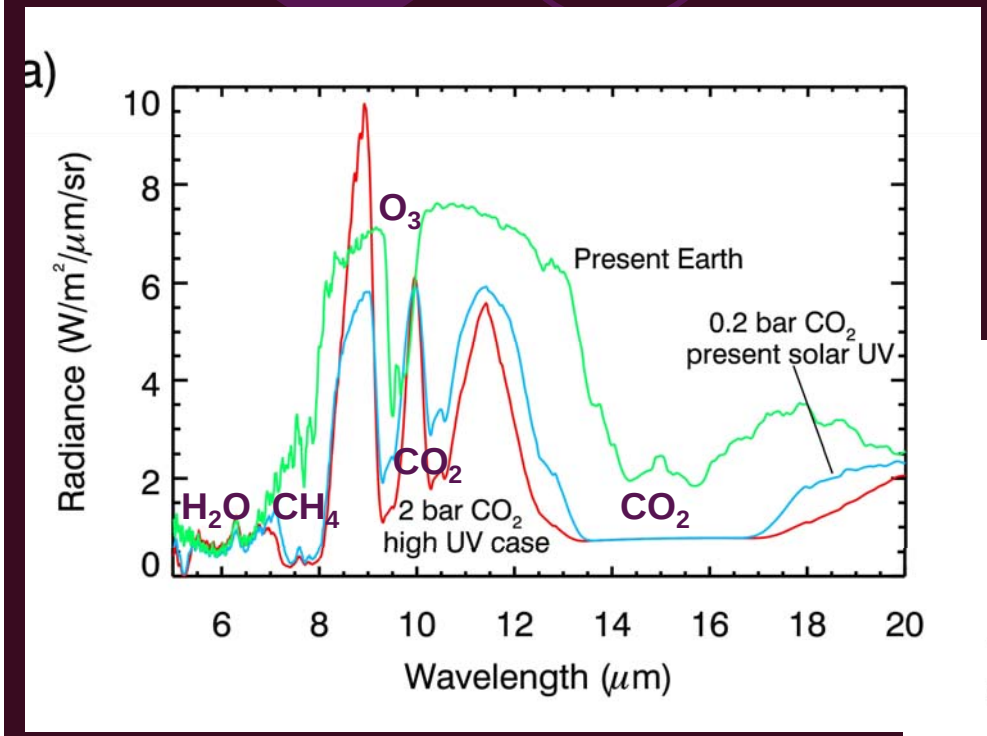
- 0.8 N_2, 0.02, 0.2 and 2 bars of CO_2
  - CH_4 surface flux= 2.8×10^{13} gr/yr (abiotic)
  - (Present CH_4 flux: 5.35×10^{14} gr/yr)



EK Dra: Sun-like star, age: 0.5 Ga

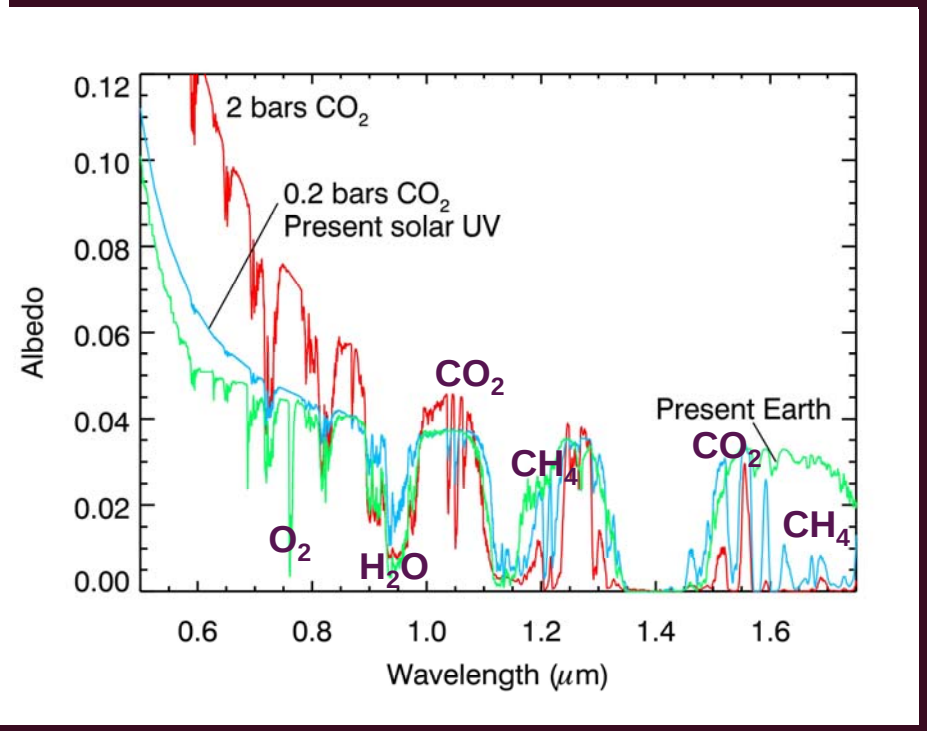
Segura et al. 2007 (A&A, 472, 665)

Early Earth: Archean (4 Ga)



Abiotic production of O_2: ~10^{19} cm^{-2}
(present Earth: 4.65 $\times 10^{24}$ cm^{-2})

Ozone from abiotic O_2: 10^{14}-10^{16} cm^{-2}
(present Earth: 8.61 $\times$ 10^{18} cm-2)



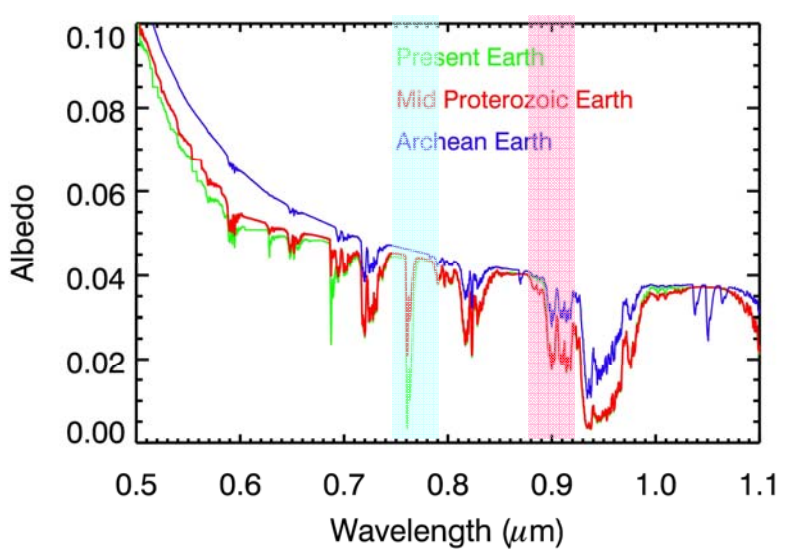
Abiotic O_2 does not produce a detectable signature

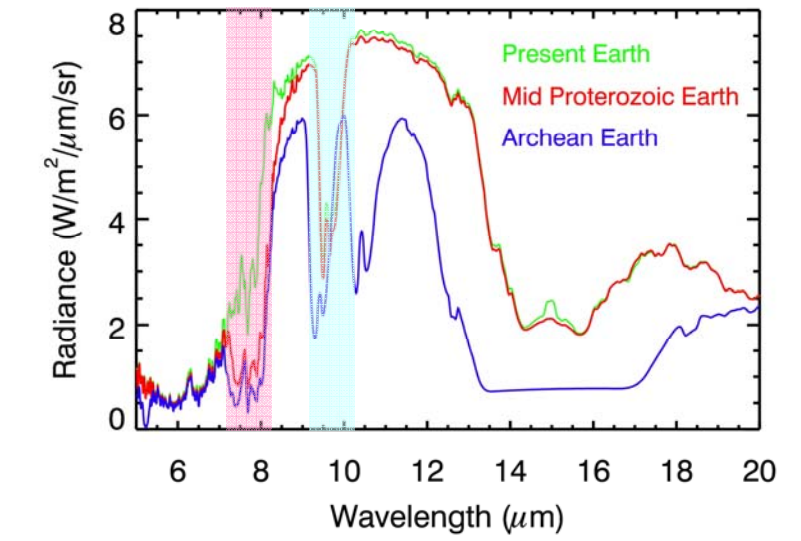
O_2 band (9.6 μm) masked by CO_2 (Selsis et al. 2002)

H_2O, CO_2 and CH_4 signatures clearly detectable

Segura et al. A&A, 2007

Mid Proterozoic Earth (2.3-0.8 Ga)



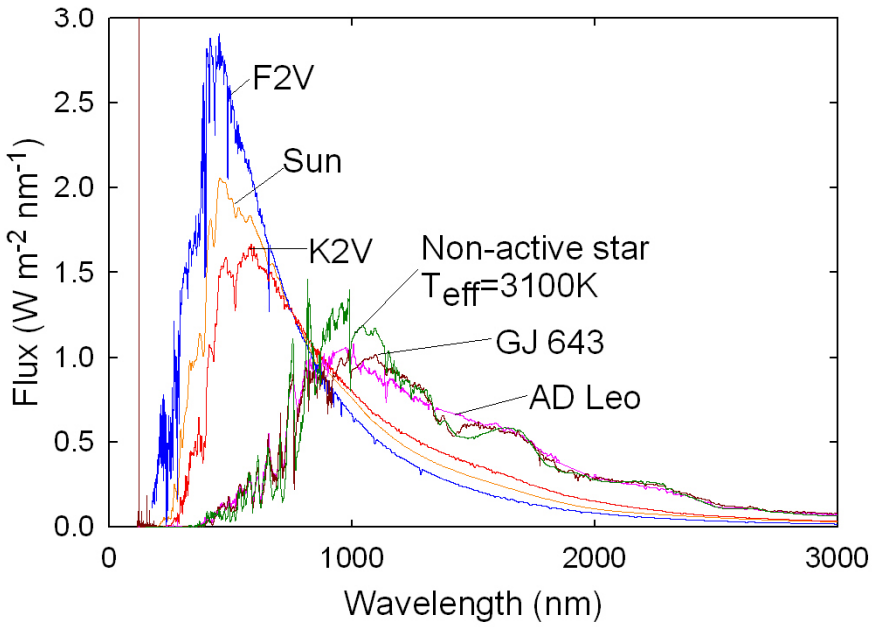


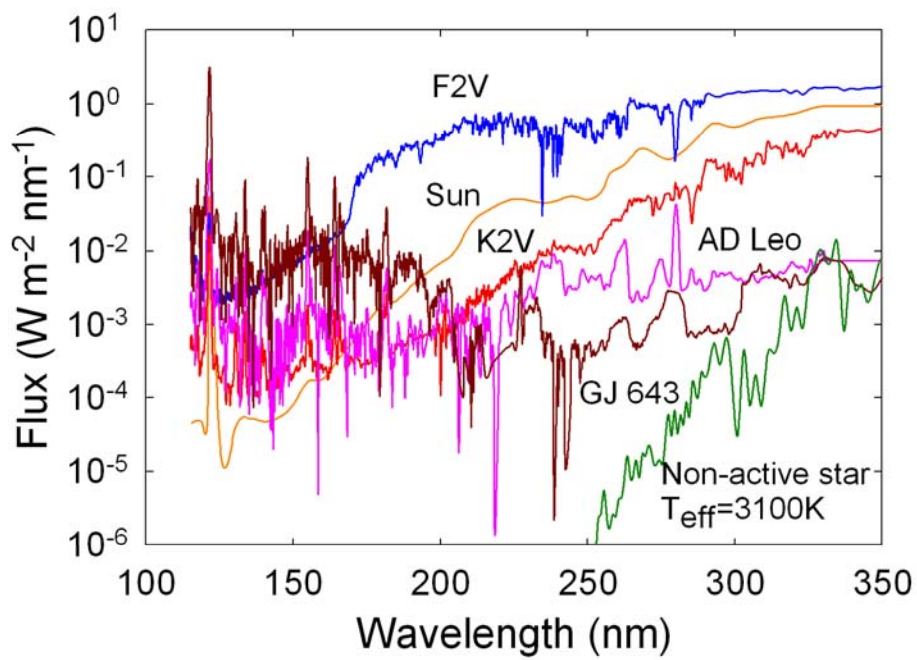
- In the MIR, Mid-Proterozoic Earth-like atmospheres show strong signatures from both CH_4 and O_3

- In the visible, the O_2 absorption is reduced, but potentially detectable, CH_4 is less detectable for the mid-Proterozoic case.

Earth around other stars

Stellar spectra at the distance of a planet in the habitable zone of each star





Segura et al, Astrobiology 2003

Simulations of Earth around other planets

- Climate model

  Radiative-convective 1-D model (Pavlov et al., 2000, *JGR* 105, 11981).

- Photochemical model

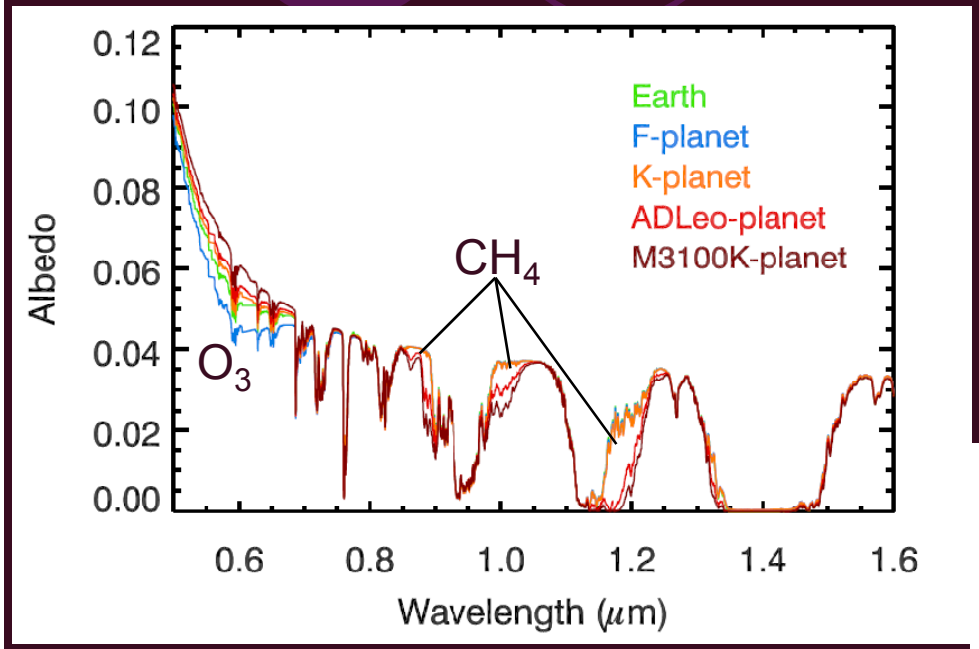
  1-D model for 55 chemical species linked by 219 reactions (Pavlov and Kasting, 2002, *Astrobiology* 2, 27).

- SMART radiative transfer model

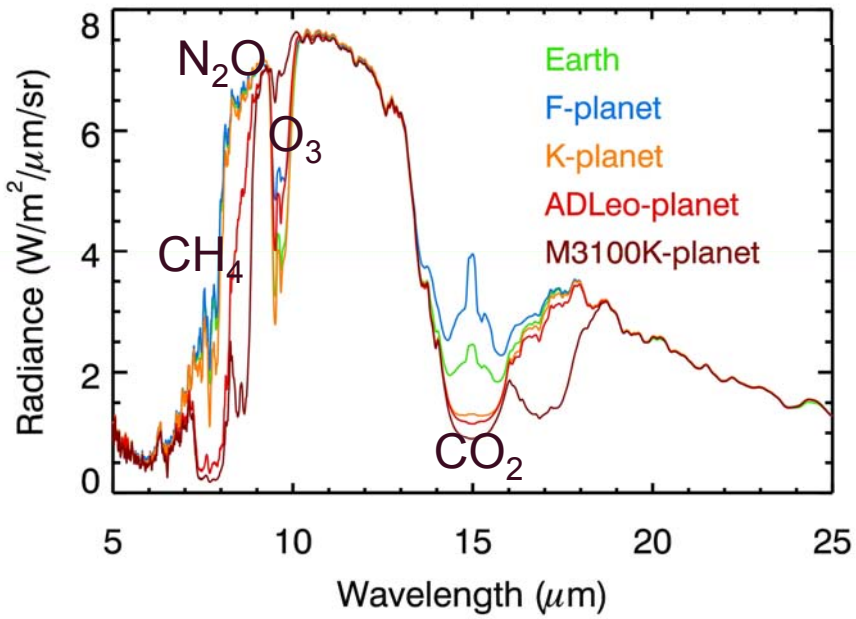
  Generates high-resolution, angle dependent synthetic planetary spectra (Meadows and Crisp, 1996, *JGR* 101(E2), 4595).

- Atmospheric composition of Earth-like planets
  - Present Earth concentrations for major species (N_2, O_2), and 355 ppm of CO_2
  - Surface pressure of 1 atm.
  - Fixed surface fluxes for biogenic compounds (H_2, CH_4, N_2O, CO, CH_3Cl). Meaning: Life is producing the same on those planets.

Earth around other stars

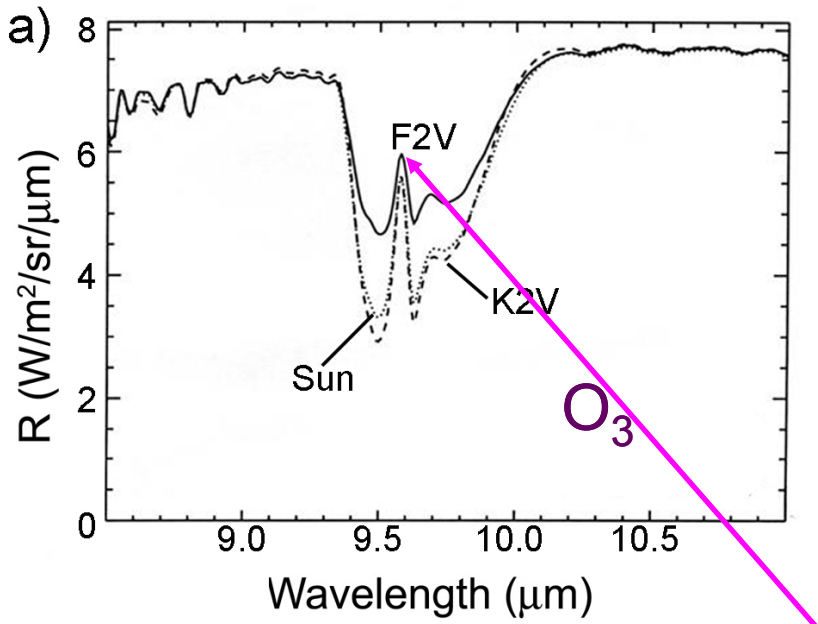


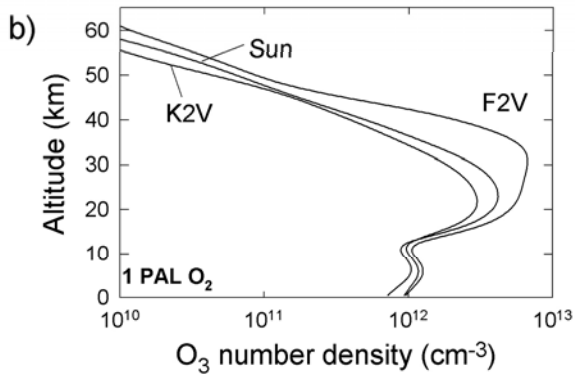
Visible-NIR: Small differences



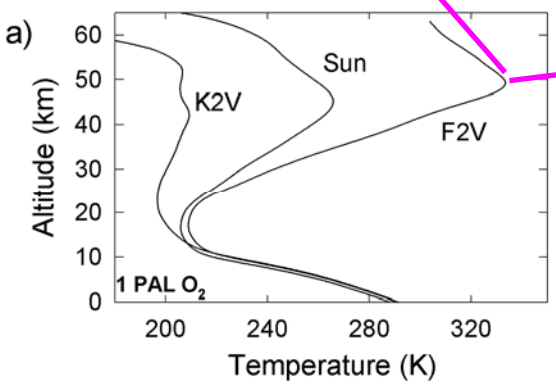
Mid-IR: Each planet has a characteristic spectrum

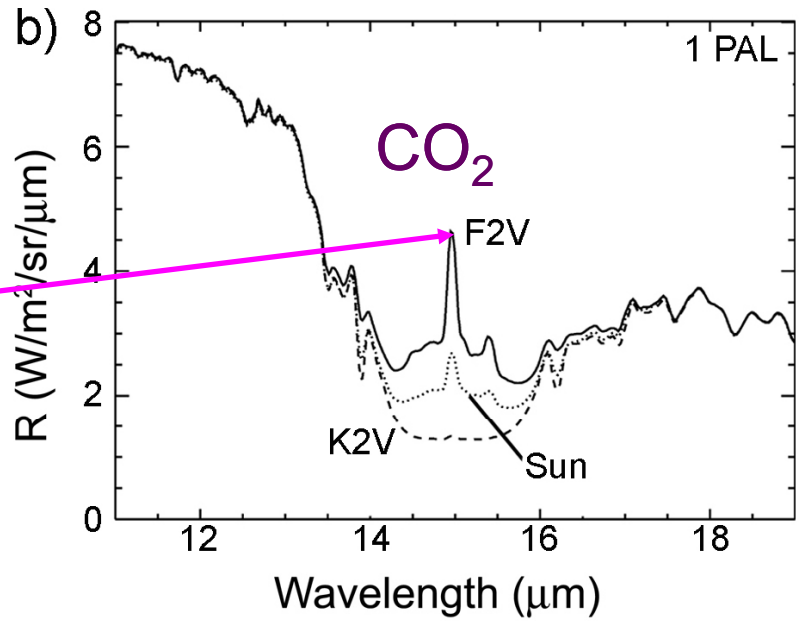
Earth around other stars





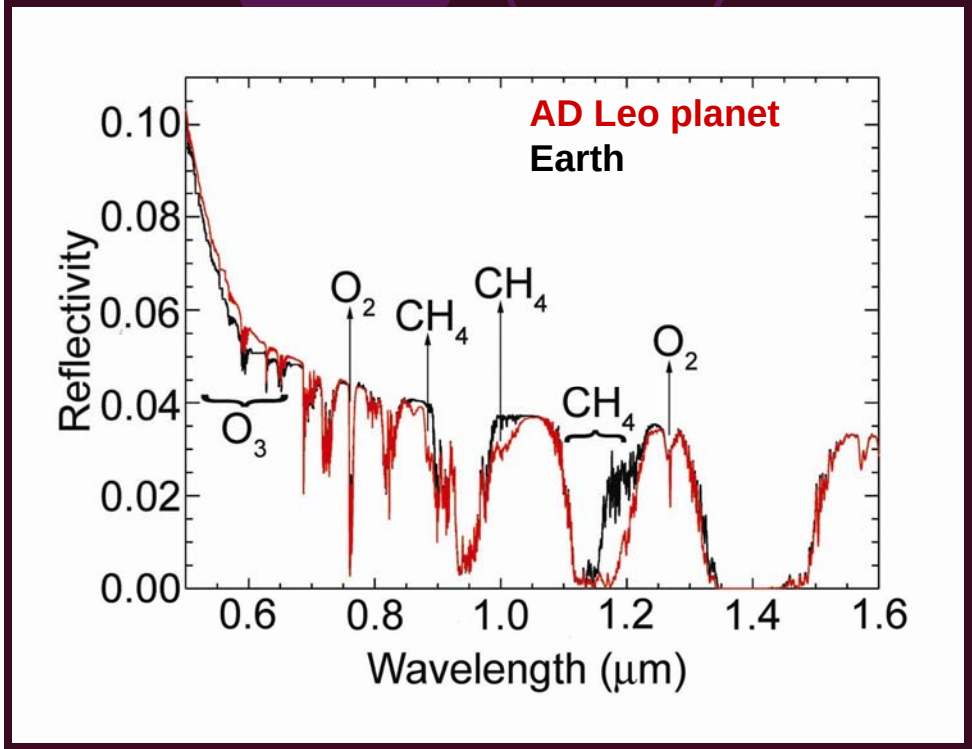
More does not mean more detectable

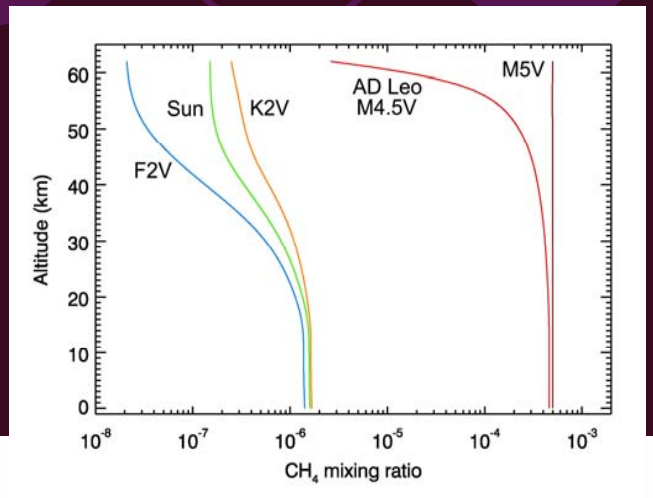


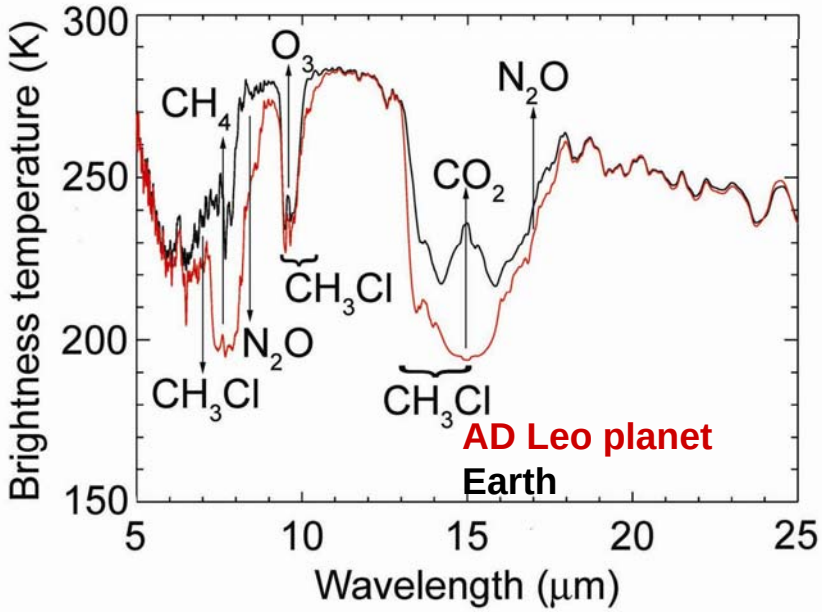


Segura et al, Astrobiology 2003

Earth around M stars







Methane

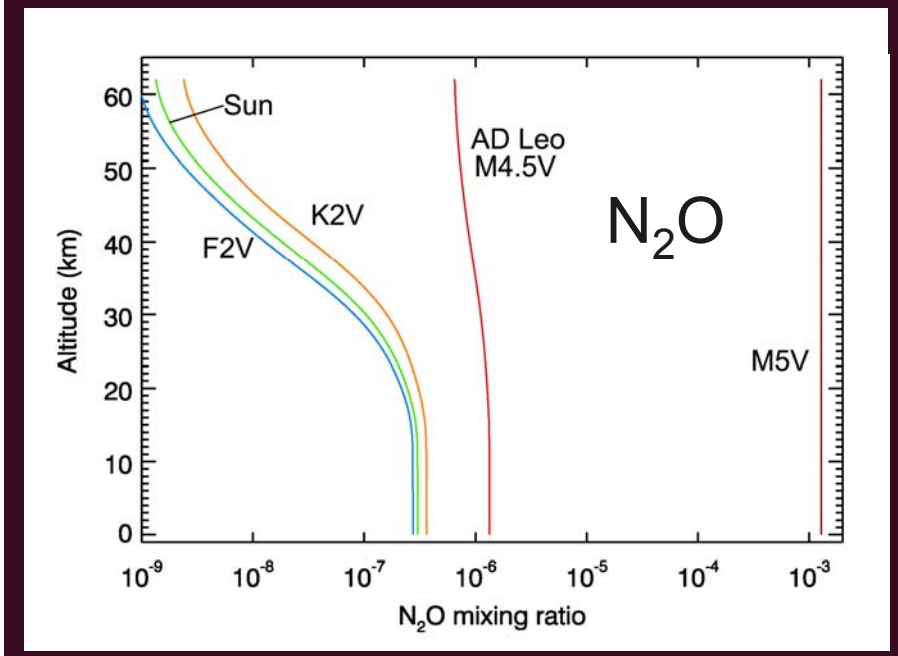
Earth surface flux = 9.5 x 10^{14} g/yr (1.6 ppm)

No-active M star: 2 x 10^{14} g/yr (500 ppm)

Abiotic: 2.8×10^{13} gr/yr (41-140 ppm depending on UV)

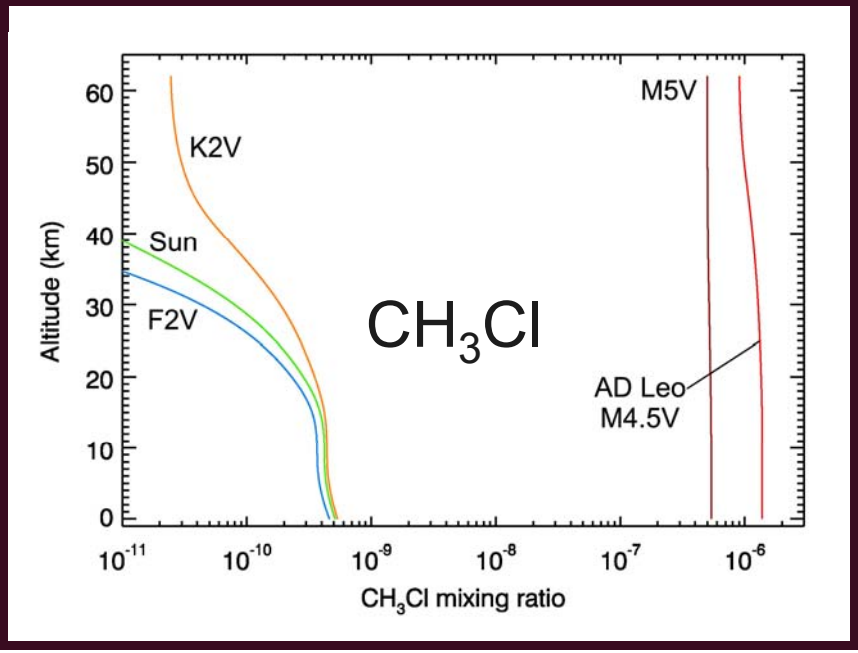
Segura et al, Astrobiology 2005

Earth around M stars



N_2O surface flux = 1.3 x 10^{13} g/yr

Sources: Oceans, soils, biomass burning, industrial sources, cattle and feedlots



CH_3Cl surface flux = 7.3 x 10^{12} g/yr

Sources: Biomass burning, tropical plants, planktonic algae (ocean), wood-rot fungi, wetlands, rice paddies.

One more lesson: Galileo experiment

NATURE · VOL 365 · 21 OCTOBER 1993

A search for life on Earth from the Galileo spacecraft

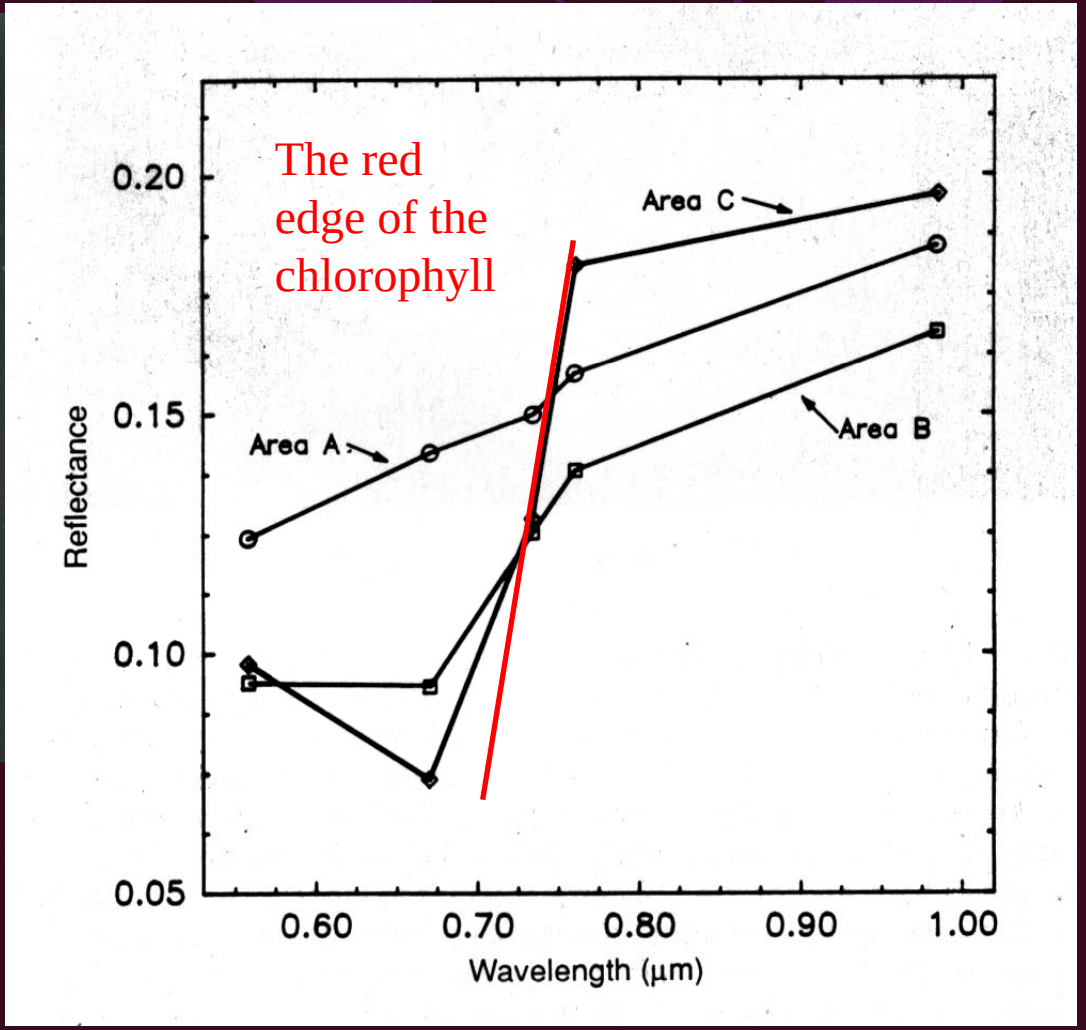
Carl Sagan*, W. Reid Thompson*, Robert Carlson†, Donald Gurnett‡ & Charles Hord§

* Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA
† Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA
‡ Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA
§ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

Galileo experiment

Earth in the near IR
(red, green, 1 μm)



Sagan et al. (1993)

Photosynthesis for physicists

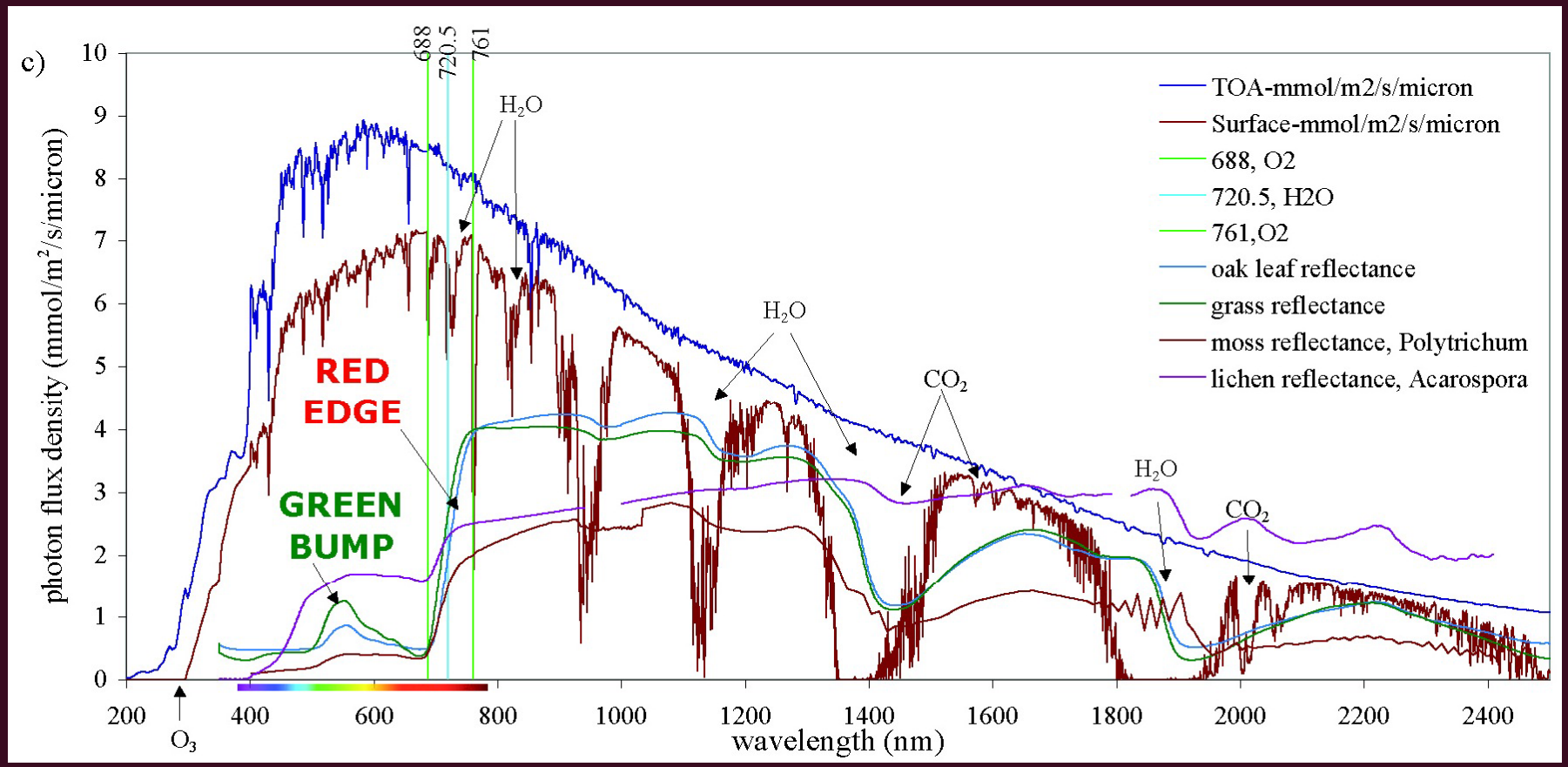
- General expression for photosynthesis:

$$CO_2 + 2H_2A + h\nu \xrightarrow[\text{pigments}]{} \underset{\text{carbohydrate}}{(CH_2O)} + H_2O + 2A$$

CO_2 reduction by taking electros from the reductor

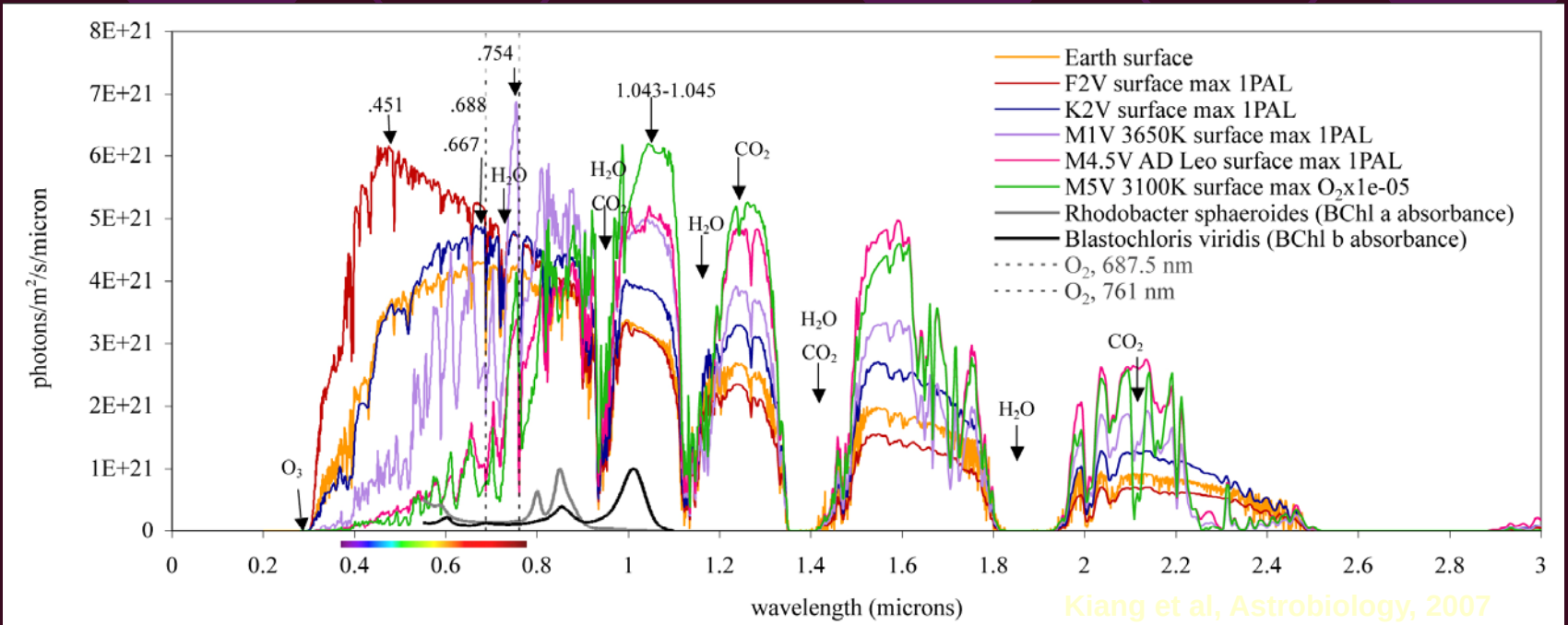
- H_2A is the reducing substrate:
  - H_2O, frees O_2
  - H_2, frees water
  - H_2S, frees S
  - Fe^{2+}, frees $Fe(OH)_3$

Photons vs. Plants



Kiang et al, Astrobiology, 2007

The color of alien plants



Kiang et al, Astrobiology, 2007

STAR TYPE	PHOTOSYNTHETIC PIGMENT COLOR	OXYGENIC/ ANOXYGENIC
F	cyan, green, yellow, orange, infrared	oxygenic
G	green, yellow, orange, infrared	oxygenic
K	green, yellow, orange, infrared	oxygenic
M	Black (no color)	oxygenic or anoxygenic

The Color of Plants on Other Worlds

Green aliens are so passé.

On other worlds, plants could be red, blue, even black

BY NANCY Y. KIANG

The prospect of finding extraterrestrial life is no longer the domain of science fiction or UFO hunters. Rather than waiting for aliens to come to us, we are looking for them. We may not find technologically advanced civilizations, but we can look for the physical and chemical signs of fundamental life processes: "biosignatures." Beyond the solar system, astronomers have discovered more than 200 worlds orbiting other stars, so-called extrasolar planets. Although we have not been able to tell whether these planets harbor life, it is only a matter of time now. Last July astronomers confirmed the presence of water vapor on an extrasolar planet by observing the passage of starlight through the planet's atmosphere. The world's space agencies are now developing telescopes that will search for signs of life on Earth-size planets by observing the planets' light spectra.

Photosynthesis, in particular, could produce very conspicuous biosignatures. How plausible is it for photosynthesis to arise on another planet? Very. On Earth, the process is so successful that it is the foundation for nearly all life. Although some organisms live off the heat and methane of oceanic hydrothermal vents, the rich ecosystems on the planet's surface all depend on sunlight.

Photosynthetic biosignatures could be of two kinds: biologically produced atmospheric gases such as oxygen and its product, ozone; and surface colors that indicate the presence of specialized pigments such as green chlo-

KEY CONCEPTS

- What color will alien plants be? The question matters scientifically because the surface color of a planet can reveal whether anything lives there—specifically, whether organisms collect energy from the parent star by the process of photosynthesis.
- Photosynthesis is adapted to the spectrum of light that reaches organisms. This spectrum is the result of the parent star's radiation spectrum, combined with the filtering effects of the planet's atmosphere and, for aquatic creatures, of liquid water.
- Light of any color from deep violet through the near infrared could power photosynthesis. Around stars hotter and bluer than our sun, plants will tend to absorb blue light and could look green to yellow to red. Around cooler stars such as red dwarfs, planets receive less visible light, so plants might try to absorb as much of it as possible, making them look black.

—*The Editors*

RED EARTH, GREEN EARTH, BLUE EARTH: Type M stars (red dwarfs) are feeble, so plants on an orbiting Earthlike world might need to be black to absorb all the available light (*first panel*). Young M stars fry planetary surfaces with ultraviolet flares, so any organisms must be aquatic (*second*). Our sun is type G (*third*). Around F stars, plants might get too much light and need to reflect much of it (*fourth*).

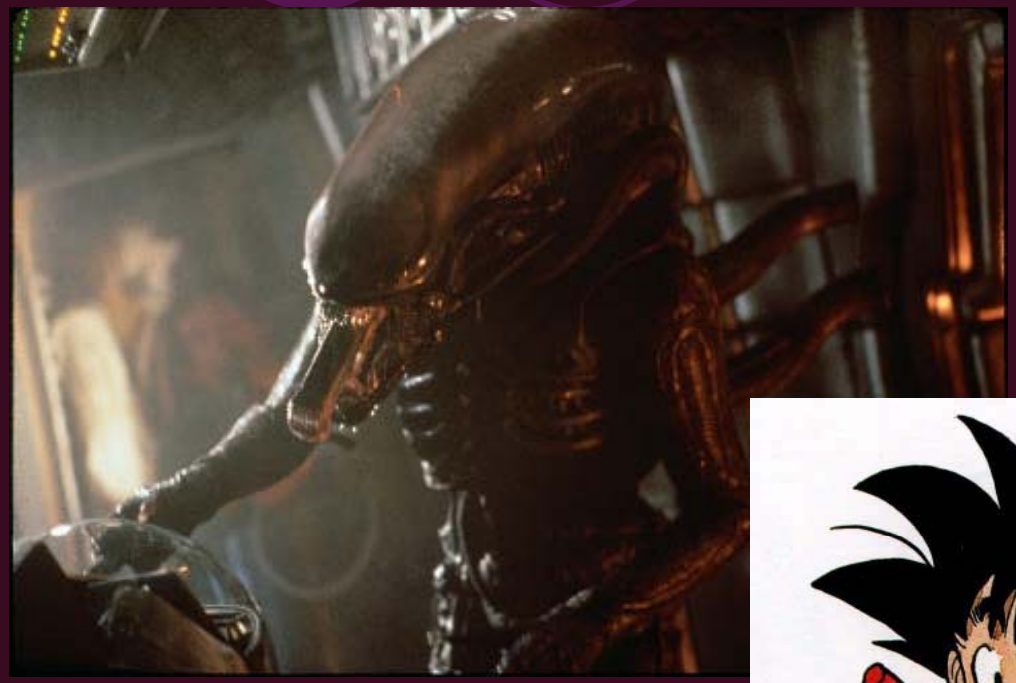
ILLUSTRATIONS BY MARK HUMPHREYS; Photodisc (bottom)

Scientific American, April 2008

Are plants detectable?

- Tinetti et al 2006:
  - Red edge detectable under certain conditions of geometry and illumination.
  - Plants can increase the albedo up to 50 %
  - Plants should cover at least 20% of the observed surface and the atmosphere should be cloud free in order to detect the red edge.
- Montañés-Rodríguez et al 2006:
  - The red edge is hard to detect but it may be possible under certain geometry conditions.

What we expect to find?



What we expect to find?

Microbial organisms that produce compounds like oxygen and methane

Plants pigments if they cover a fraction of the observed surface

Conclusions

- Many different aspects of the planet's environment will need to be combined to determine its habitability and discriminate biosignatures.
- This includes measurements of planetary characteristics, as well as interpretive models.
- Biosignatures must be identified in the context of their planetary environment.
- The Earth affords many examples of biosignatures, some of which may be enhanced in other planetary environments, others diminished.
- The planet's UV environment strongly affects its atmospheric chemistry and resultant spectrum, sometimes in non-intuitive ways!

EXTRAS

Chemistry on a habitable planet around an active M star

Methane destruction in Earth's troposphere

$$O_3 + h\nu\ (\lambda < 310\ \text{nm}) \rightarrow O_2 + O^1D$$

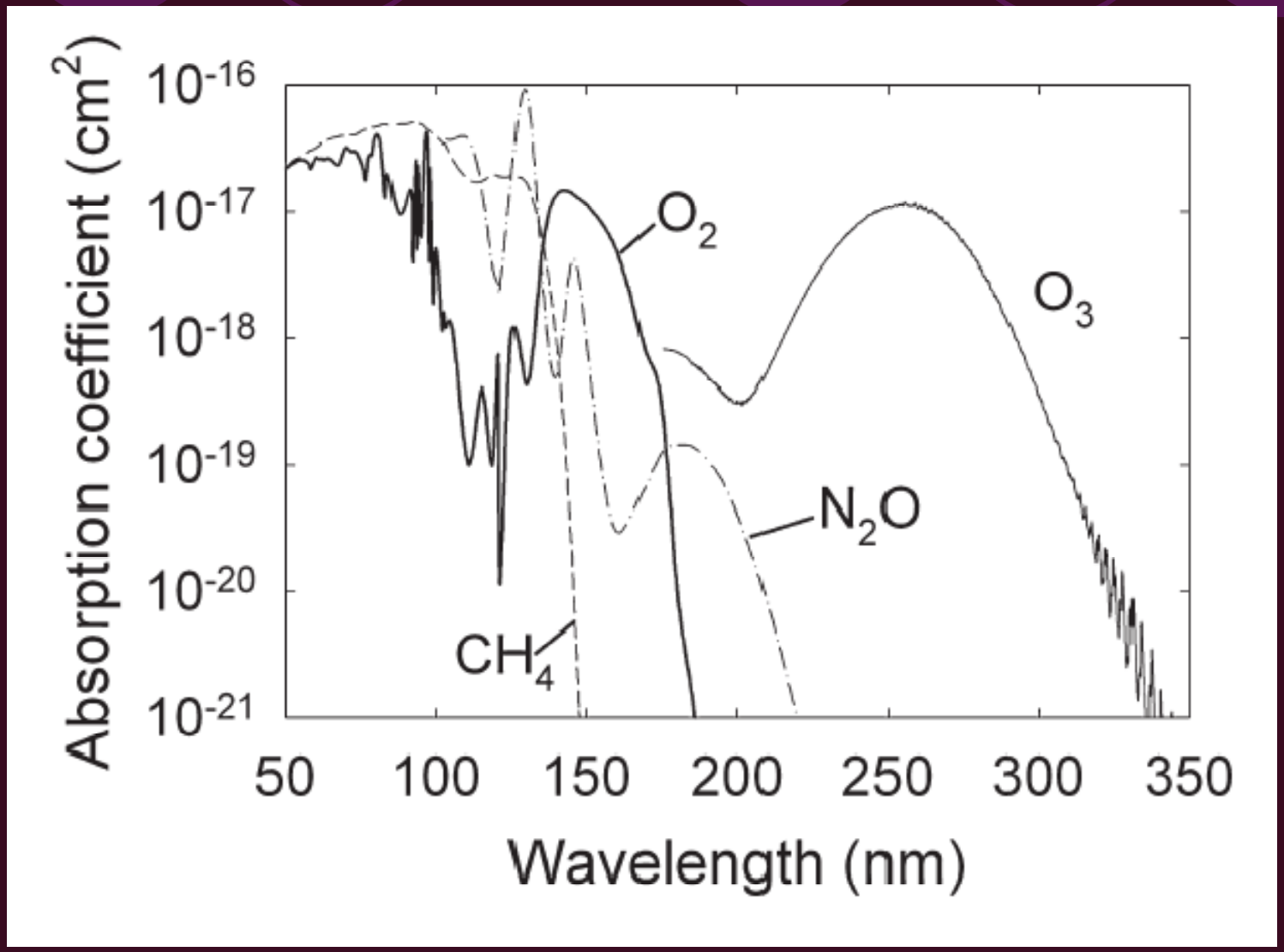
$$O^1D + H_2O \rightarrow 2\ OH$$

$$CH_4 + OH \rightarrow CH_3 + H_2O$$

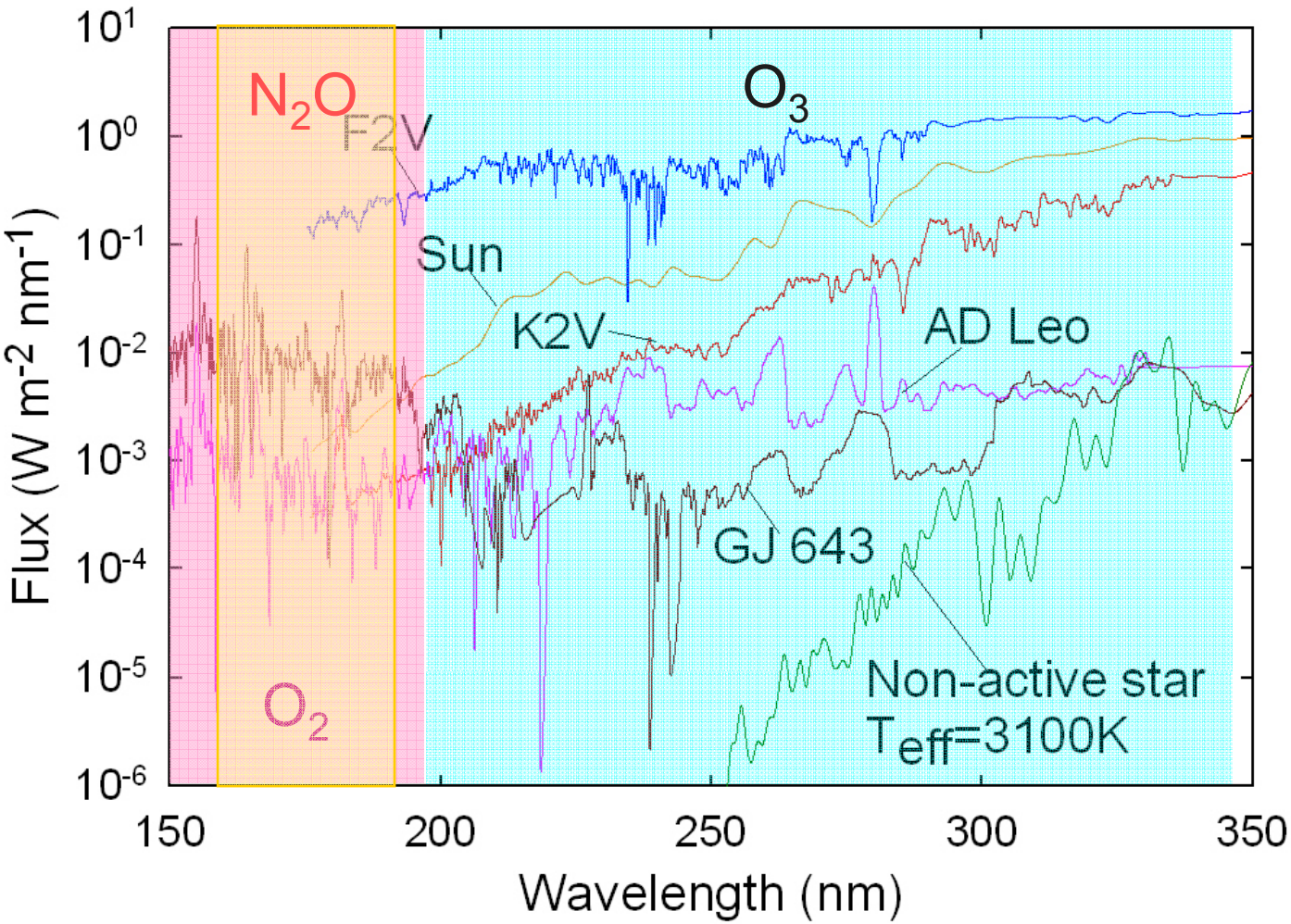
$$CH_3 + O_2 + M \rightarrow CH_3O_2 + M$$

$$\rightarrow \ldots \rightarrow CO\ (\text{or}\ CO_2) + H_2O$$

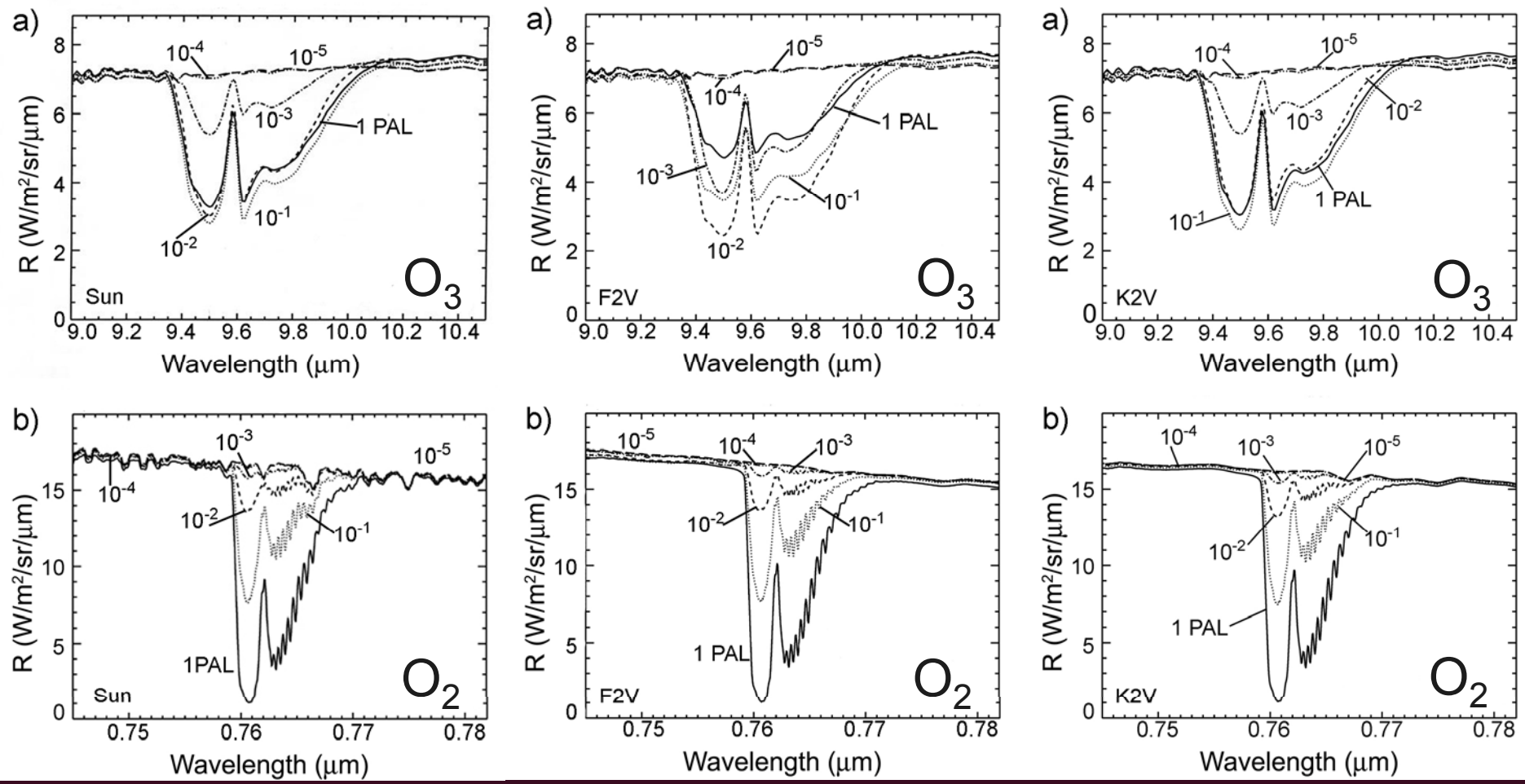
Coeficientes de absorción en el UV



Photolysis of O_2 and O_3



O_2 and O_3 signature in planets with different O_2 levels circling around F, G and K stars



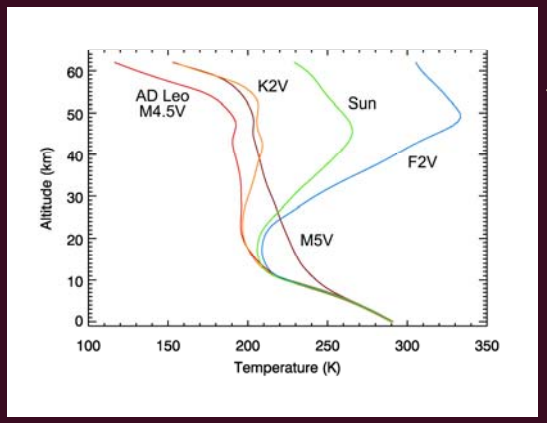
Spectra from F, G, K and M stars

Radiative-convective 1-D model (Pavlov et al., 2000, *JGR* 105, 11981).

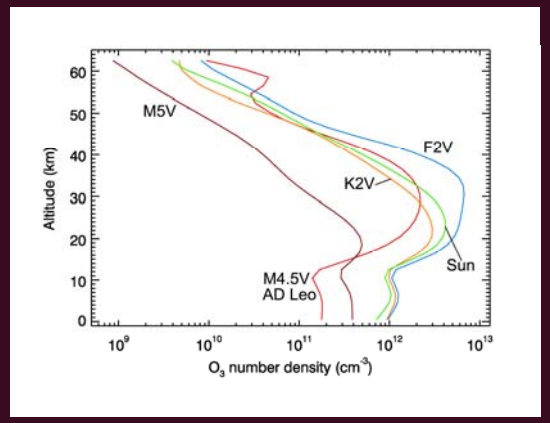
Temperature, tropospheric H_2O →

← Ozone, stratospheric H_2O

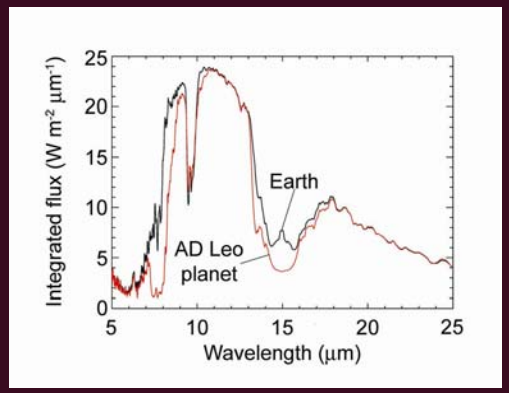
1-D photochemical model for 55 species linked by 219 reactions (Pavlov and Kasting, 2002, *Astrobiology* 2, 27).



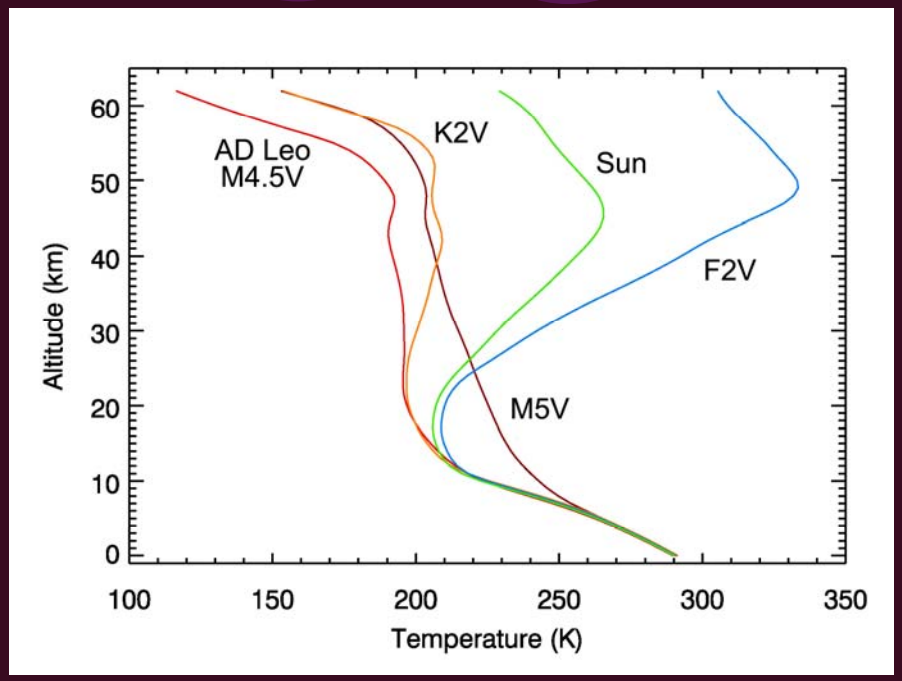
Profiles of Earth-like planets

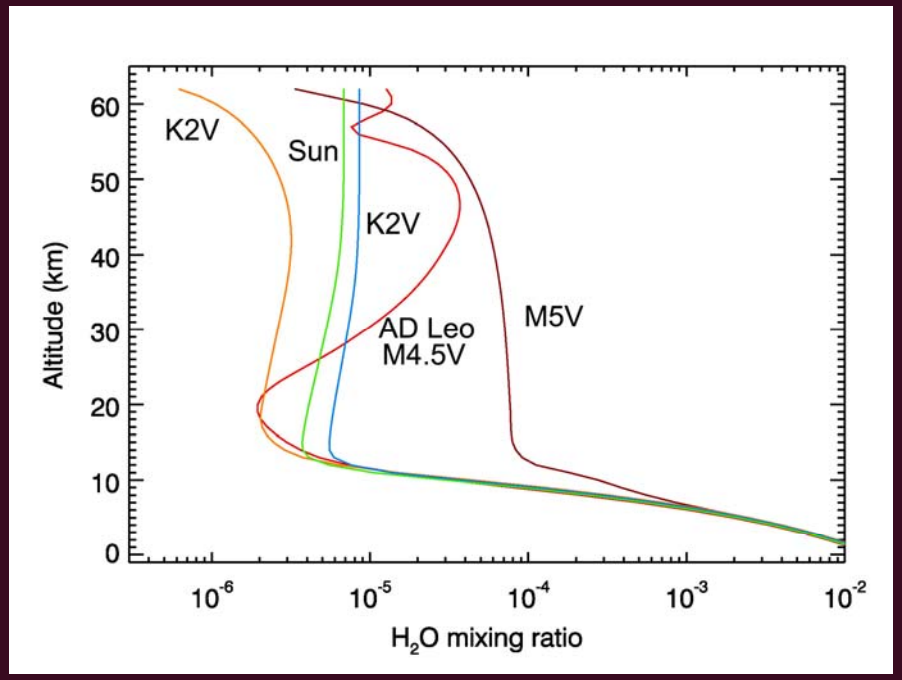


SMART radiative transfer model (Meadows and Crisp, 1996, *JGR* 101(E2), 4595).



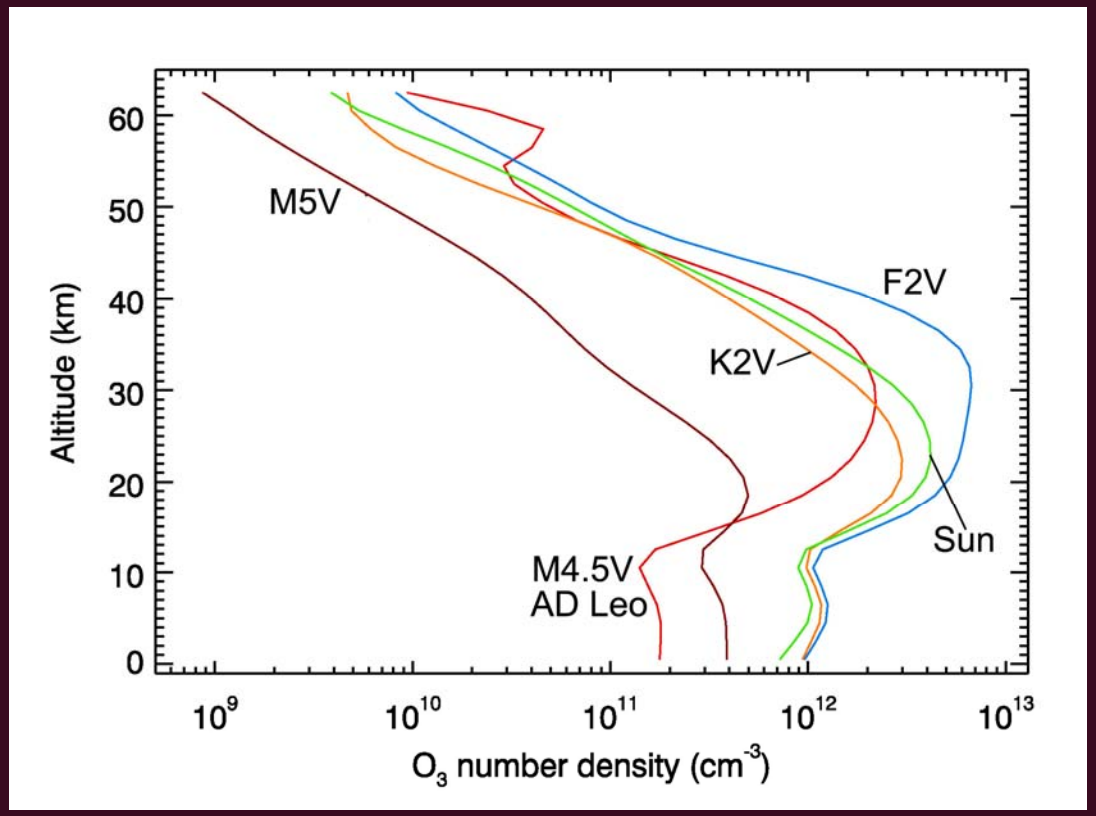
Temperature and H_2O profiles





From Segura et al. (2003, 2005)

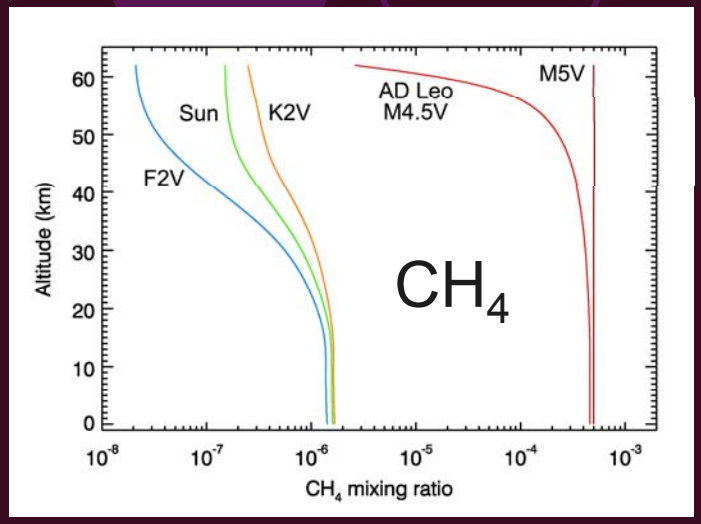
O_3 profiles



Parent star	O_3 column depth (cm^{-2})
Sun	8.4×10^{18}
F2V	1.6×10^{19}
K2V	6.6×10^{18}
AD Leo	4.4×10^{18}
M 3100	1.2×10^{18}

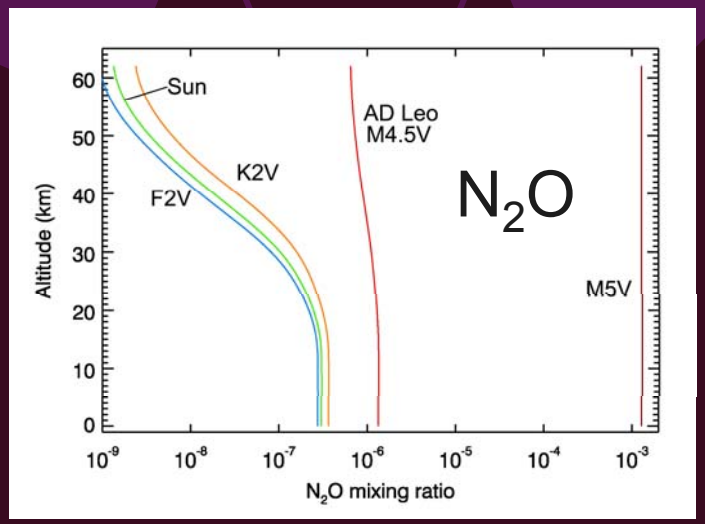
More UV more $O_3 \Rightarrow$ effective protection of the surface

Biosignatures



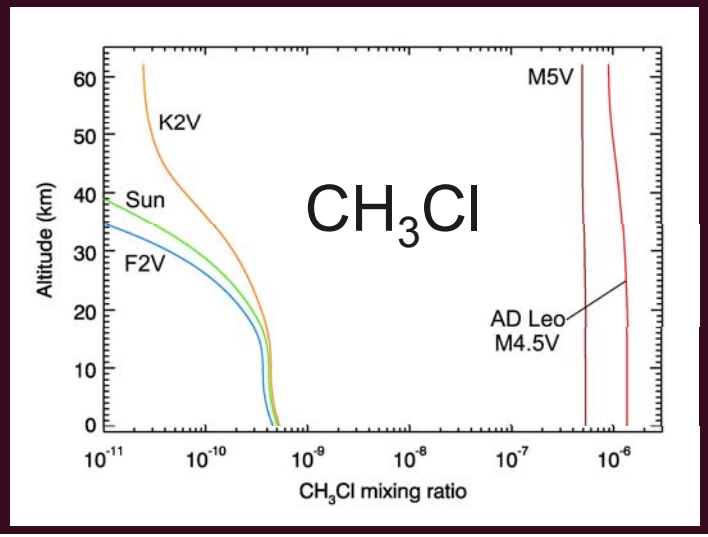
Methane flux = 9.5 x 10^{14} g/yr, except for non active M (2 x 10^{14} g/yr)

Sources: Wetlands, termites, oceans, waste decomposition, fossil fuels, biomass burning, domestic ruminants, rice paddies.



Nitrous oxide flux = 7.3 x 10^{12} g/yr

Sources: Biomass burning, tropical plants, planktonic algae (ocean), wood-rot fungi, wetlands, rice paddies.



Methyl chloride flux = 1.3 x 10^{13} g/yr

Sources: Oceans, soils, biomass burning, industrial sources, cattle and feedlots

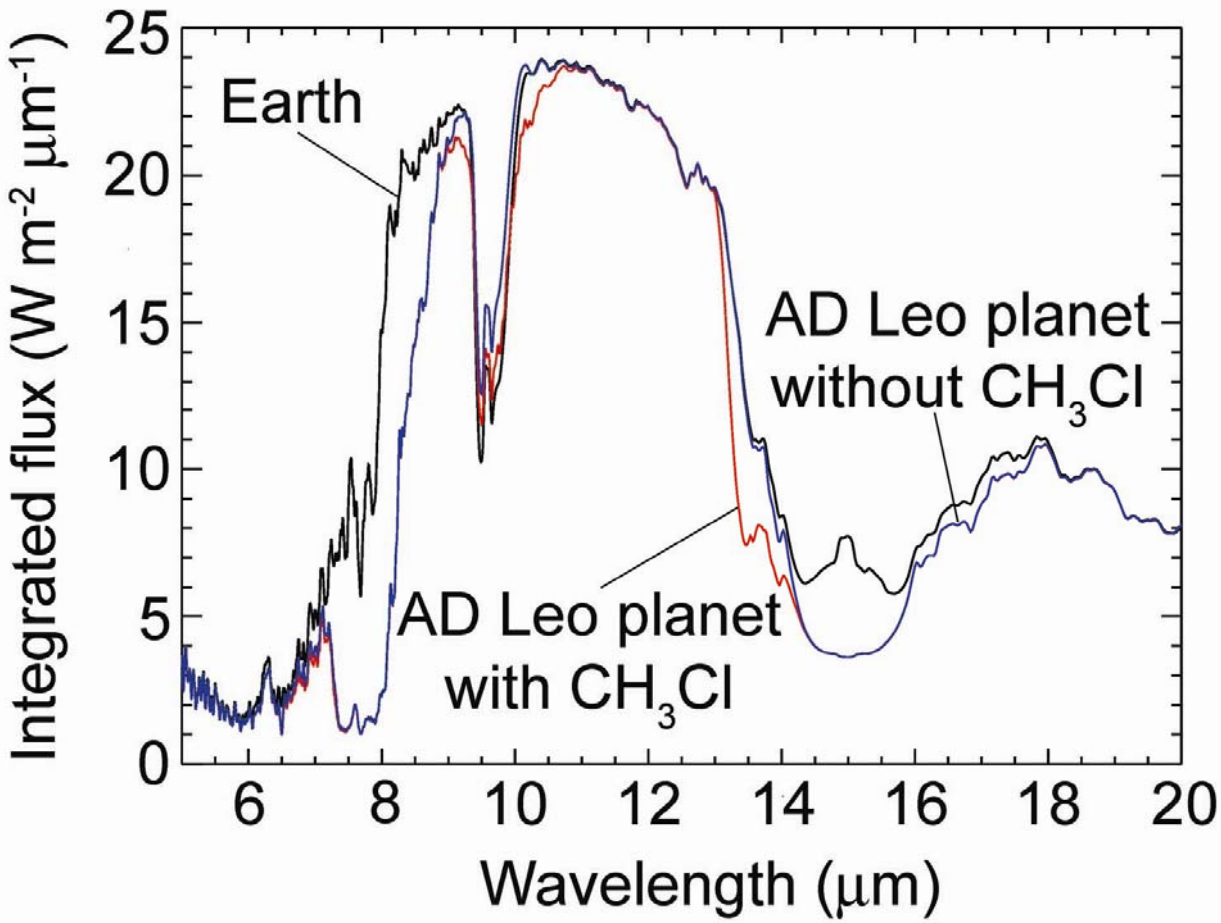
Biosignatures on F, G, K and M planets

Parent star	Lifetime (yr)		
	CH_4	CH_3Cl	N_2O
Sun	4.4	0.6	2×10^2
F2V	3.9	0.5	1×10^2
K2V	15	2	3×10^2
M3.5V	1×10^3	2×10^3	7×10^2
M5V	6×10^3	6×10^2	7×10^5

CH_4 and CH_3Cl have much longer lifetimes on planets around M stars due to the particular slope of the incoming UV

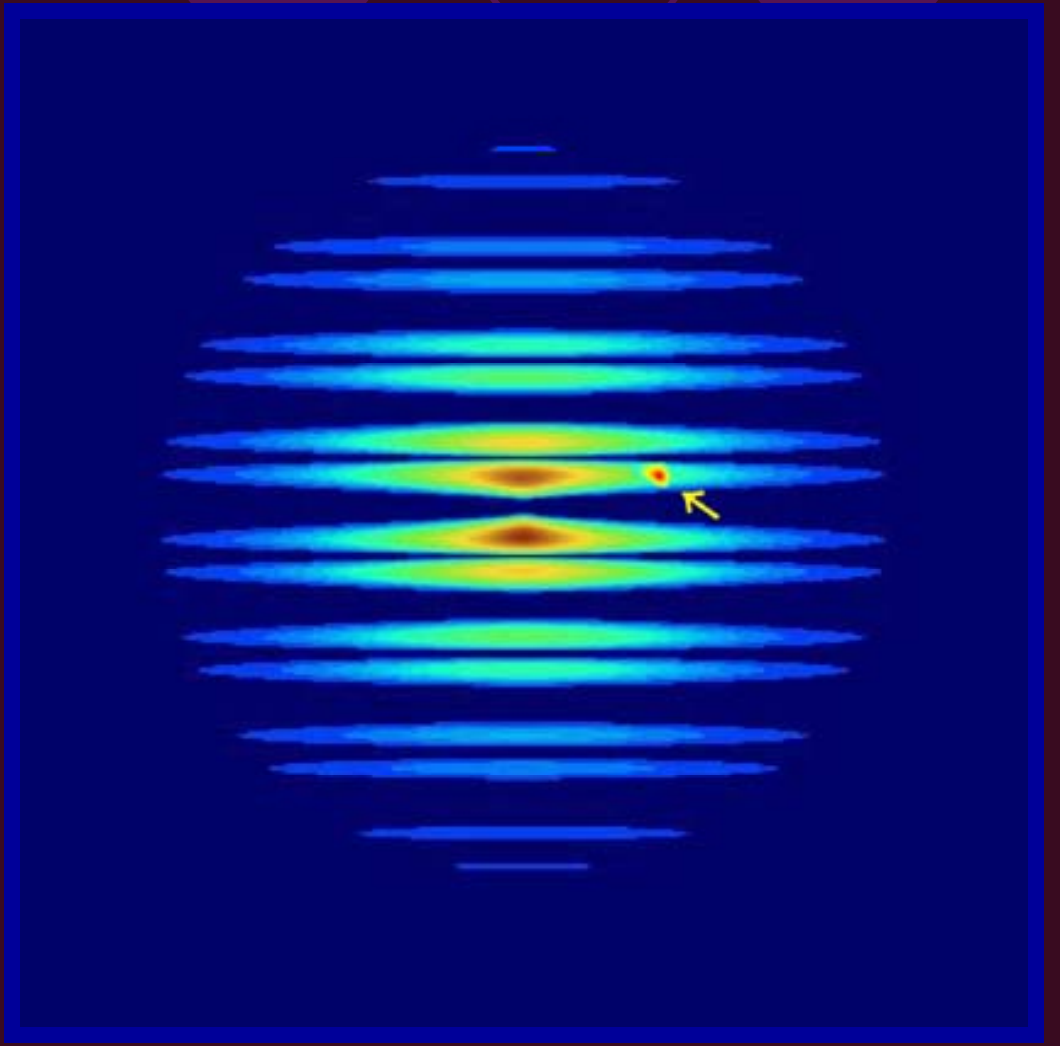
N_2O depends directly on the incident stellar UV

Methyl chloride



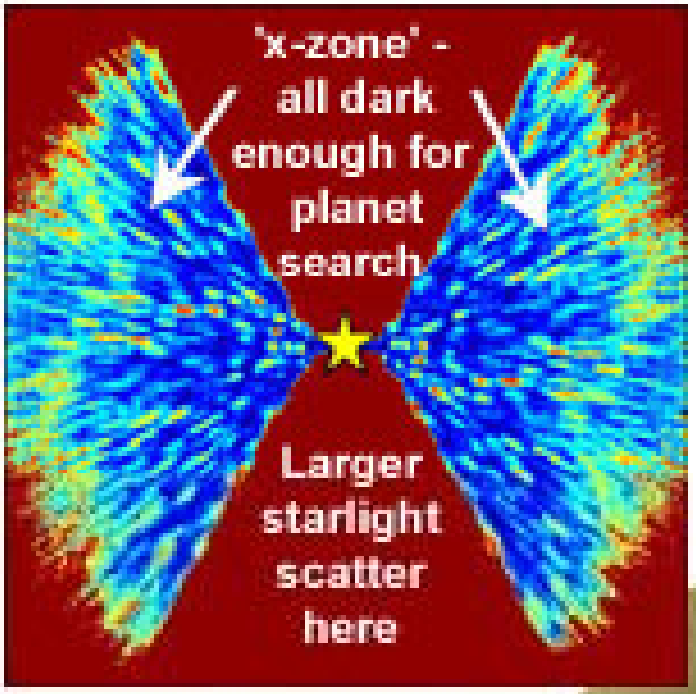
Infrared Nulling Interferometer

- Uses multiple mirrors to simulate the angular resolution of a much larger telescope.
- Two architectures
  - “free-flyer” in precision formation
  - fixed structure (“TPF on a stick”).
- Uses destructive interference to place the star in a “null”, reducing its light by a factor of a million



Visible Light Coronagraph

- A coronagraph blocks the light from a bright object so that fainter nearby things can be seen.
- Implemented on large optical telescope.
- The coronagraph must minimize both the direct light from the star, and minimize the telescope diffraction pattern to maximize angular resolution.
- Current designs use “masks” to simulate a telescope of a different configuration to preferentially scatter light in a restricted area on the focal plane.



Abiotic Production of O_2 and O_3 on High CO_2 Terrestrial Atmospheres*

Antígona Segura
Instituto de Ciencias Nucleares, Univesidad Nacional Autónoma de México
Formerly at JPL/Caltech
Victoria S. Meadows
University of Washington
Formerly at Infrared Processing and Analysis Center, California Institute of Technology
James Kasting
Department of Geosciences, Pennsylvania State University
Martin Cohen
Radio Astronomy Laboratory, University of California, Berkeley
David Crisp
NASA Jet Propulsion Laboratory

Members of the NASA Astrobiology Institute's Virtual Planetary Laboratory

*The contents of this talk are part of a paper accepted in A&A and available at arXiv:0707.1557

O_2 and O_3 as biosignatures

- For a planet with water and located in the habitable zone of its star, high concentrations of O_2 and O_3 are considered good signs of the presence of life (e.g Owen 1980; Angel 1986; Leger et al. 1993)

- But O_2 and O_3 can accumulate in a planet:

  - Runaway greenhouse (Venus)
  - Frozen Mars-like planet

  } Outside the habitable zone

- And it has been proposed that in a planet with no life and liquid water (CO_2-N_2 atmosphere) the reaction:

$$H_2O + h\nu \rightarrow H_2 + O$$

may lead to a high level of O_2 and O_3 because

H_2 escapes,

O recombines into O_2 and O_3

$\Rightarrow$ accumulation of O_2 and O_3

$\Rightarrow$ false positive of life??

Previous work on Abiotic O_2

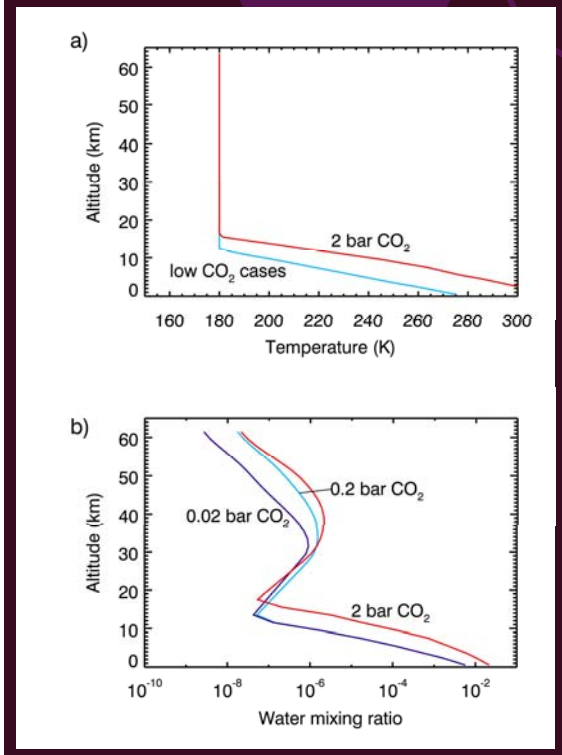
Authors	O_2 amount	Source	False positive?
Berkner & Marshall (1964, 1965, 1966, 1967)	10^{-4}-10^{-3} PAL	O_2 needed to block UV	O_2: No O_3: Maybe
Brinkman (1969)	0.27 PAL	1/10 of the H atoms	Yes
Walker ([illegible])	[illegible] PAL	H_2 escapes at diffusion limit rate Hunten (1973)	[illegible]
Selsis et al. (2002)	0.1 PAL (super O_3 layer ~2 Earth)	Photochemical reactions	IR: No Vis: Yes (O_2 band at 0.76 μm)

PAL = Present Atmospheric Level = 0.21 bars O_2

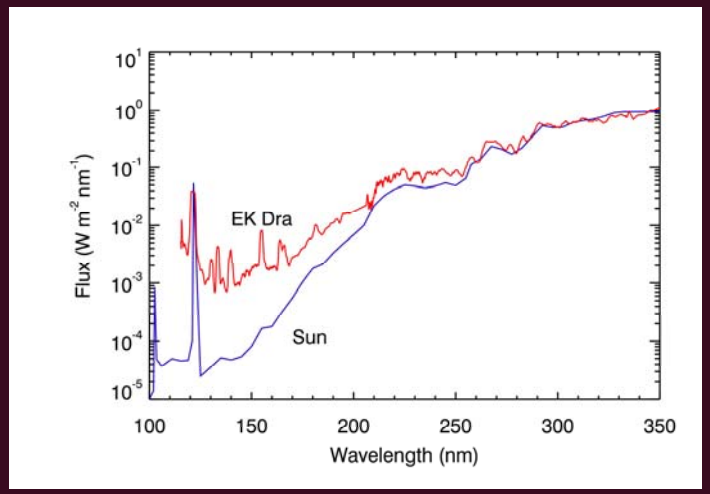
Our work

- We simulated atmospheres of planets without life located in the habitable zone of stars with 2 different levels of ultraviolet radiation.
- We calculated abiotic formation of O_2 and O_3 due to water photolysis using a photochemical model
- We obtained the reflected (visible) and emitted (MIR) spectra of the simulated planets using a radiative transfer model

Simulated atmospheres



- Low UV environment (present Sun, G2V, age 4.5 Gyr)
  - Standard case: 0.2 CO_2 bar atmosphere with volcanic outgassing (H_2, CH_4), surface pressure 1 bar, surface T = 278 K
  - No outgassing case: 0.2 CO_2 bar atmosphere with NO volcanic outgassing (H_2, CH_4), surface pressure 1 bar, surface T = 278K



- High UV environment (EK Dra, G1.5V, age 0.5 Gyr)
  - 0.02 bar CO_2: Surface pressure 1 bar
  - 0.2 bar CO_2: Surface pressure 1 bar
  - 2 bar CO_2: Surface pressure 2.9 bars (T=317K)

Photochemical model

↑

H_2 escape
Diffusion limit

Photolysis
H_2O, CH_4
→

Atmospheric
chemistry
↔

Hydrogen balance

$$\Phi_{volc}(H_2) + \Phi_{rain}(\text{Oxidized}) = \Phi_{esc}(H_2) + \Phi_{rain}(\text{Reduced})$$

Degassing
H_2, CH_4
↑

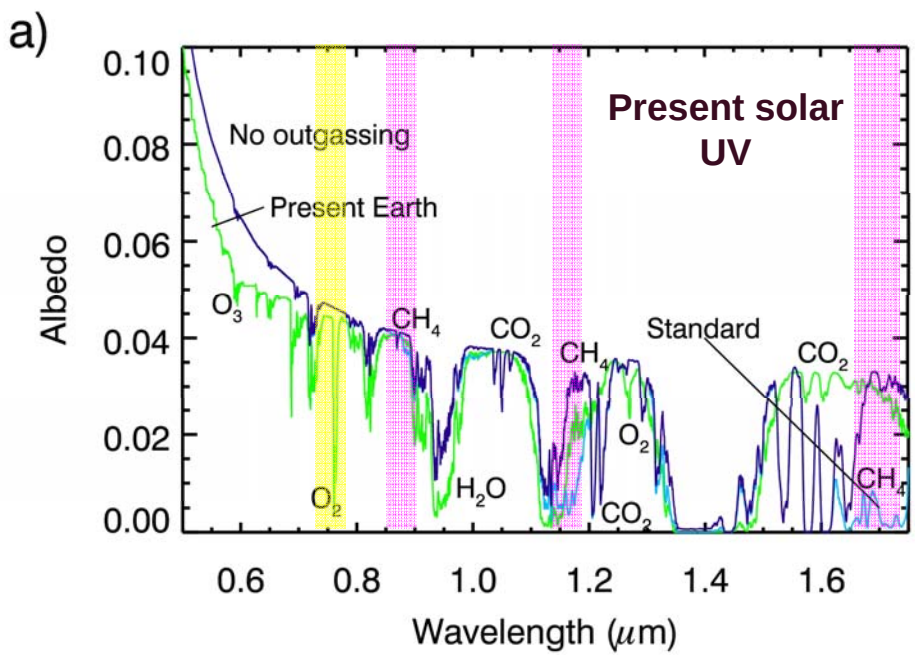
Rainout
H_2O_2, H_2S
↓

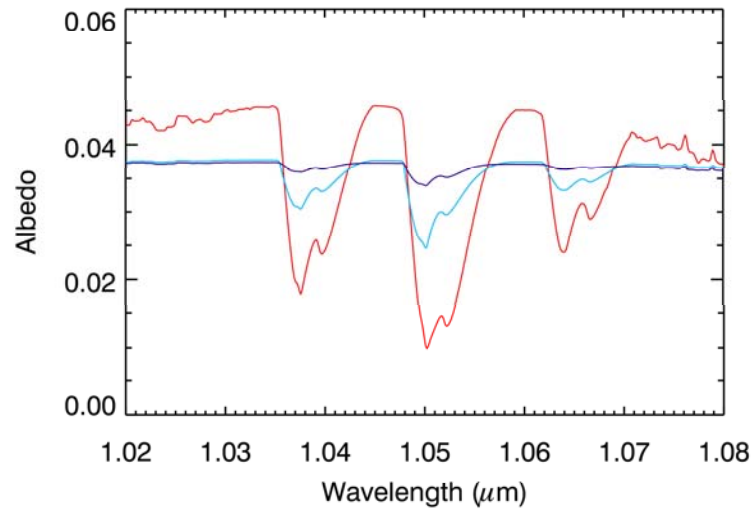
Deposition in the sea
↓

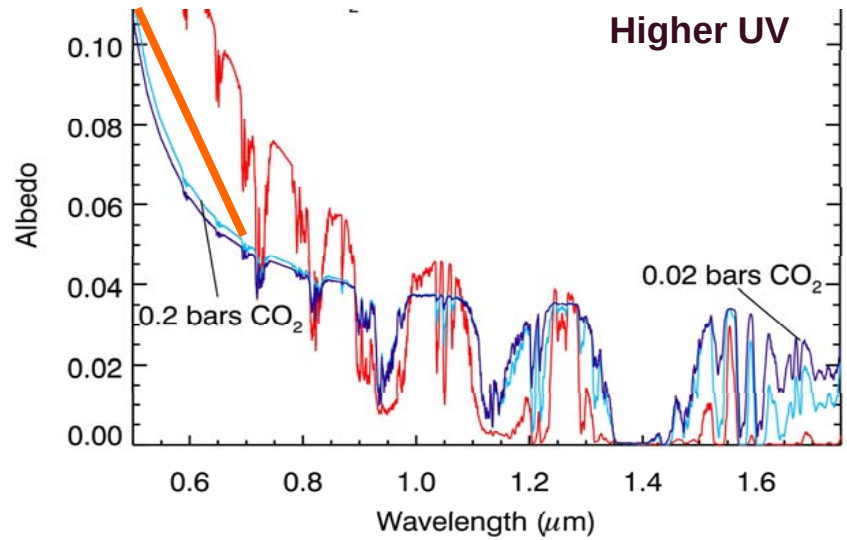
Results

Case (bars CO_2)	O_3 (cm^{-2})	O_2 (cm^{-2})	H_2 (mixing ratio)	CH_4 (mixing ratio)
Present Earth	8.61×10^{18}	4.65×10^{24}	5.5×10^{-7}	1.6×10^{-6}
0.2 Low UV (standard)	1.87×10^{14}	1.24×10^{19}	1.25×10^{-3}	1.38×10^{-4}
0.2 Low UV, no outgassing	7.51×10^{15}	4.94×10^{19}	4.85×10^{-6}	9.4×10^{-12}
0.02 High UV	3.53×10^{14}	6.62×10^{18}	8.29×10^{-4}	1.66×10^{-5}
0.2 High UV	6.70×10^{14}	3.63×10^{19}	1.09×10^{-3}	4.07×10^{-5}
2 High UV	5.13×10^{14}	4.24×10^{19}	1.17×10^{-3}	8.75×10^{-5}

Visible and NIR spectra of high CO_2 planets

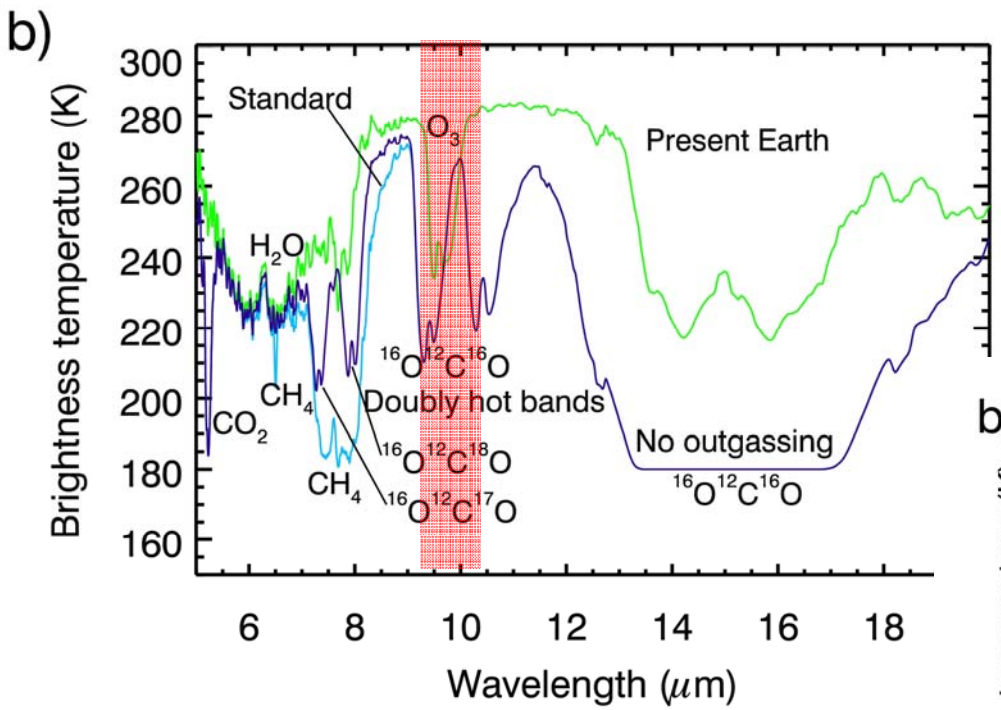




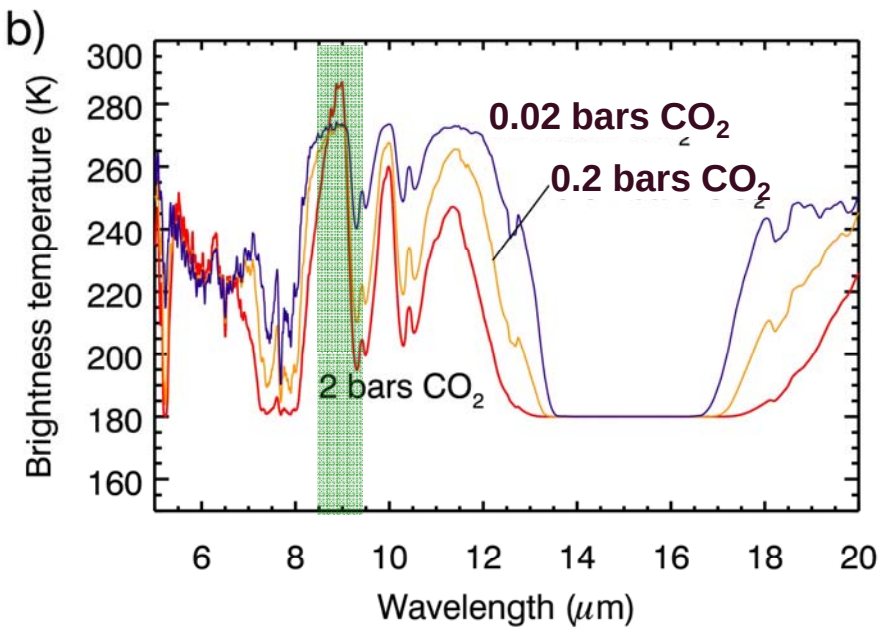


- No signature of O_2 at 0.76 μ m (A-band)
- Methane signature at various wavelengths
- Slope between 0.5 – 0.7 μm due to strong Rayleigh from CO_2
- Strong CO_2 absorption in triplet of bands centered in 1.05 μ m

Mid IR spectra of high CO_2 planets



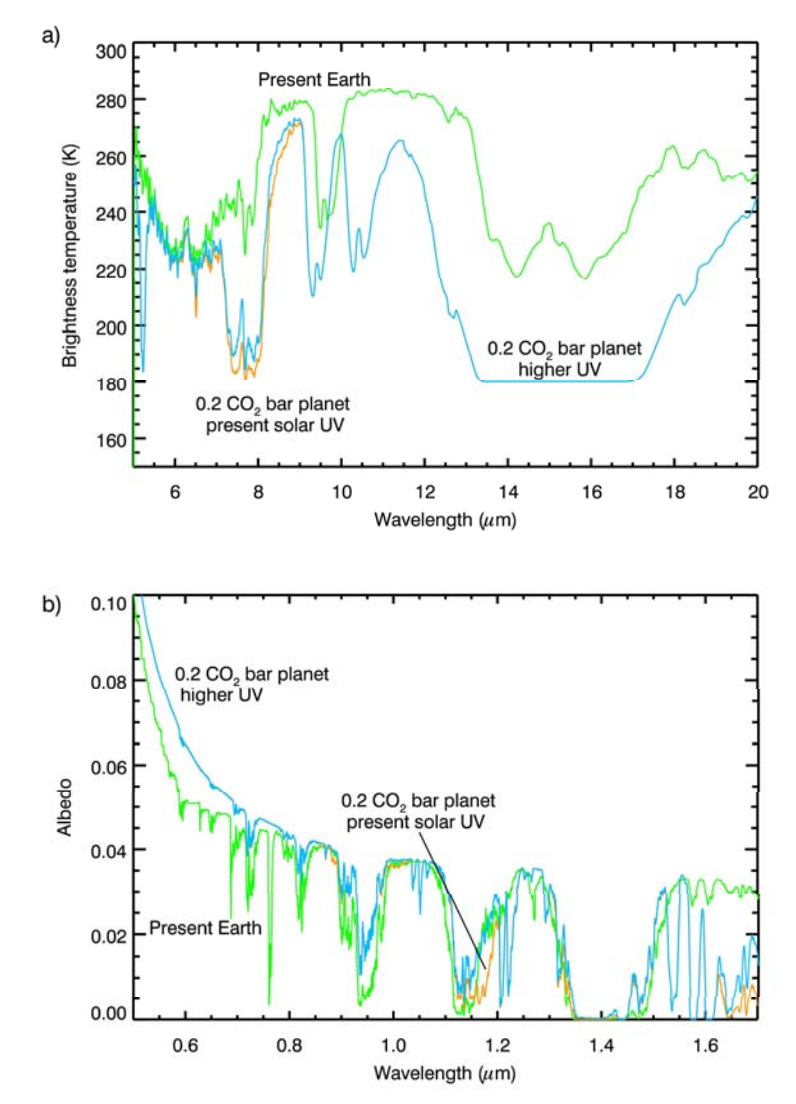
- Surface temperature is not sampled by the spectra
- For the 2 bar CO_2 case the sampled temperature at the 9 μm window is 30 K cooler than the surface T



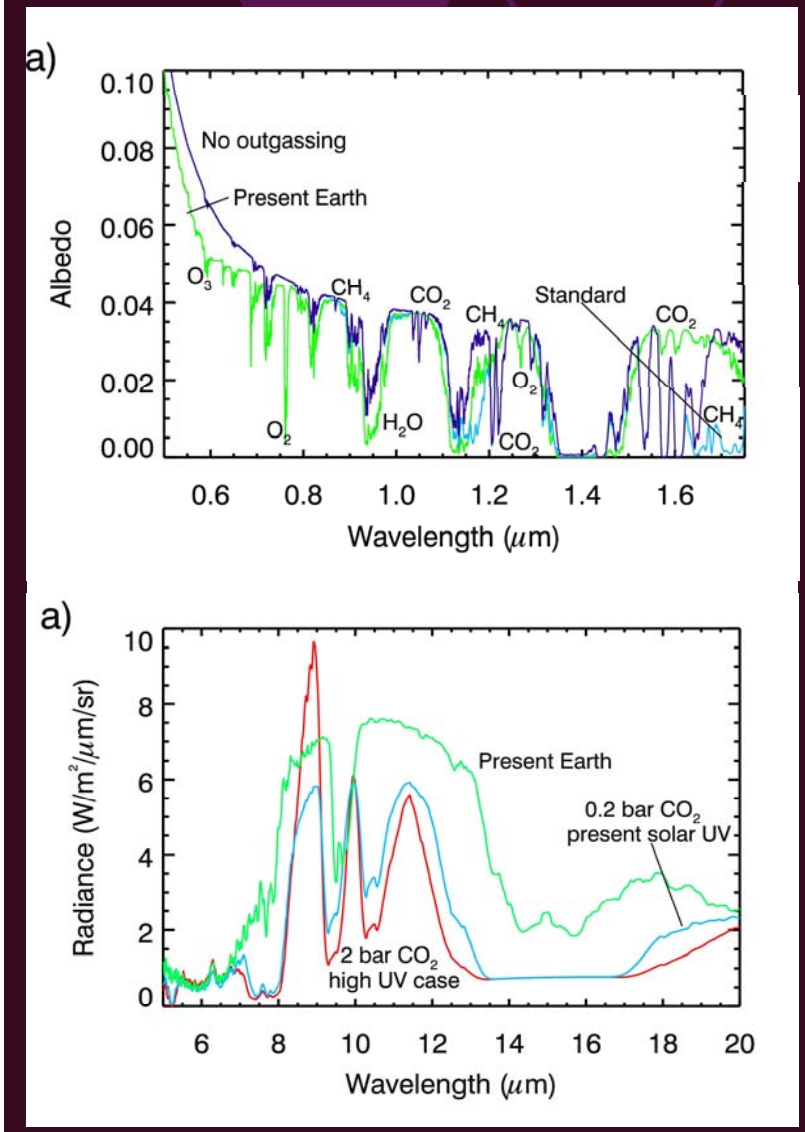
- O_3 band hidden by CO_2 doubly hot bands (noted by Selsis et al, 2002)
- Methane and water absorption
- Oxygen isotopes within CO_2

Results and Conclusions

- EK Draconis is an upper limit of UV radiation emitted by an early Sun-like star.
- O_3 and O_2 production are not severely affected by this parameter
- CH_4 is more abundant on high-CO_2/low-UV environments



Results and Conclusions

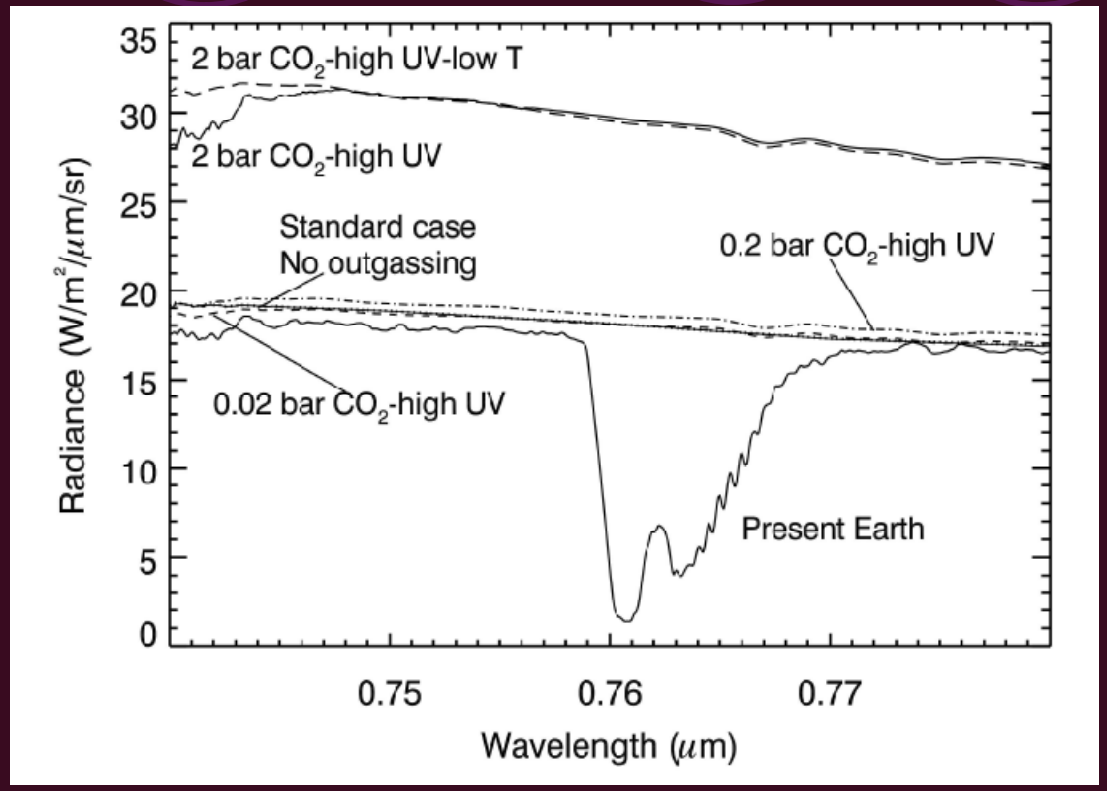


CO_2-dominated habitable atmospheres exhibit a wealth of spectral features:

- Multiple CO_2 absorption bands throughout the visible-NIR range accessible to an optical coronograph (0.5-1.7μm)
- The CO_2 band in the visible-NIR near 1.62 μm, produces a potentially detectable feature
- For atmospheres with high CO_2 abundances (0.2-2bars of CO_2), the 1.05 μm bands provide strong absorption features, and are better features for potential quantification of large amounts of atmospheric CO_2 provided R~50.

- MIR interferometer (5-25 μm) provide differing sensitivity to a large range of CO_2 abundances.
- The CO_2 15 μm feature provides the strongest absorption for CO_2 and is the most detectable feature in a terrestrial planet atmospheres
- Isotopes of CO_2, produce strong features that may provide clues to the O isotopic composition of a CO_2-dominated terrestrial planet.

Conclusion



For planets with water located in the habitable zone an abiotic “false positive” signal with strong O_2 or O_3 absorption is unlikely, and does not pose a significant hazard for habitable planets observed with TPF or Darwin.

Wake up I already finished!

…don't miss the paper:

Abiotic Formation of O_2 and O_3 in High-CO_2 Terrestrial Atmospheres

by A. Segura, V. S. Meadows, J. F. Kasting, D. Crisp, and M. Cohen

Cooming soon at Astronomy and Astrophysics

Already available at arXiv:0707.1557