Planet-Star Interactions:

Impact of the Parent Star on Development and Detectability of Biosignatures

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Sagan Exoplanet Summer Workshop
Caltech, 29 July 2010

Topics: Planet-Star Interactions

1. Signs of life on Earth
2. HZ and habitability on Earth vs time
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4. M-star case
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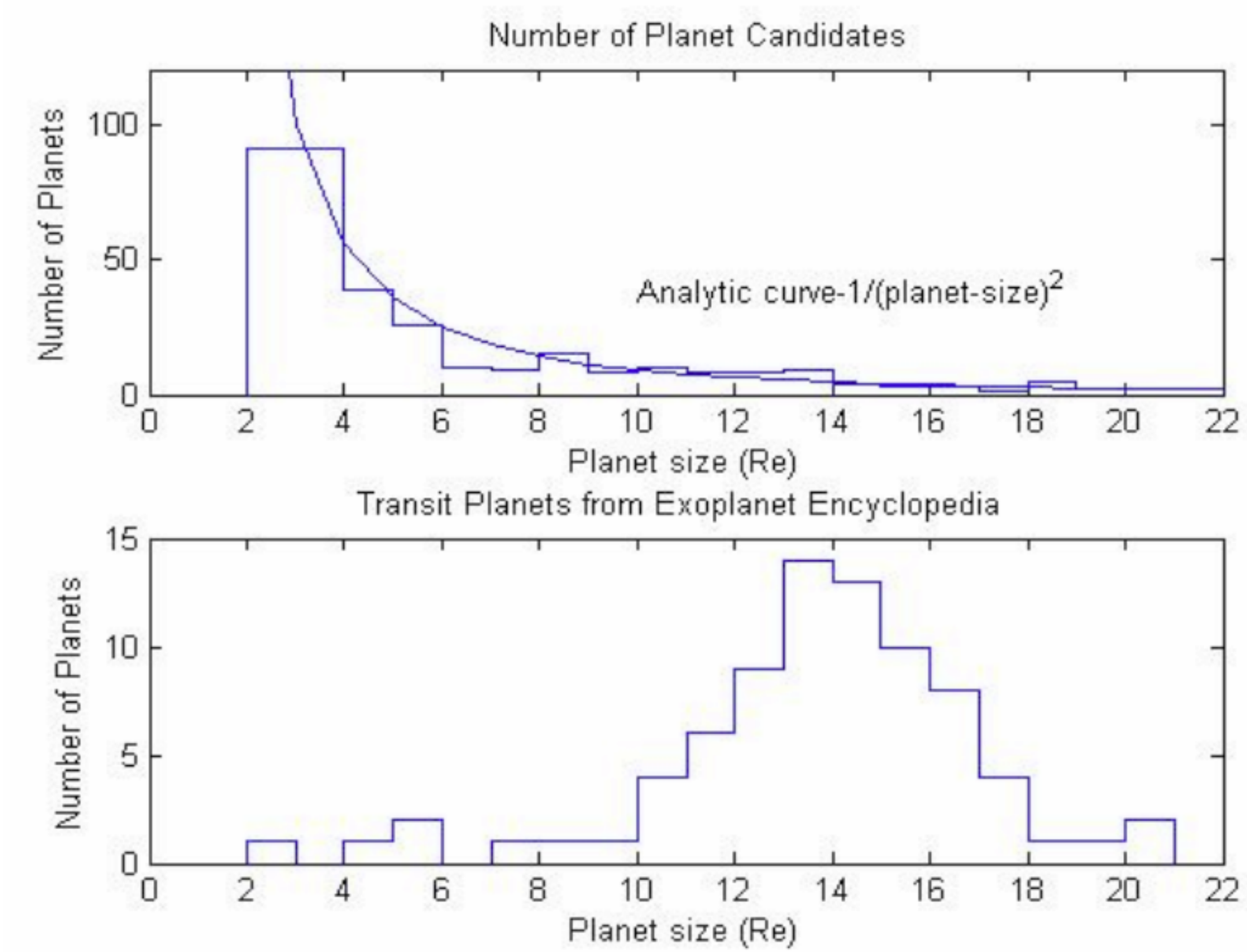
Signs of Life?

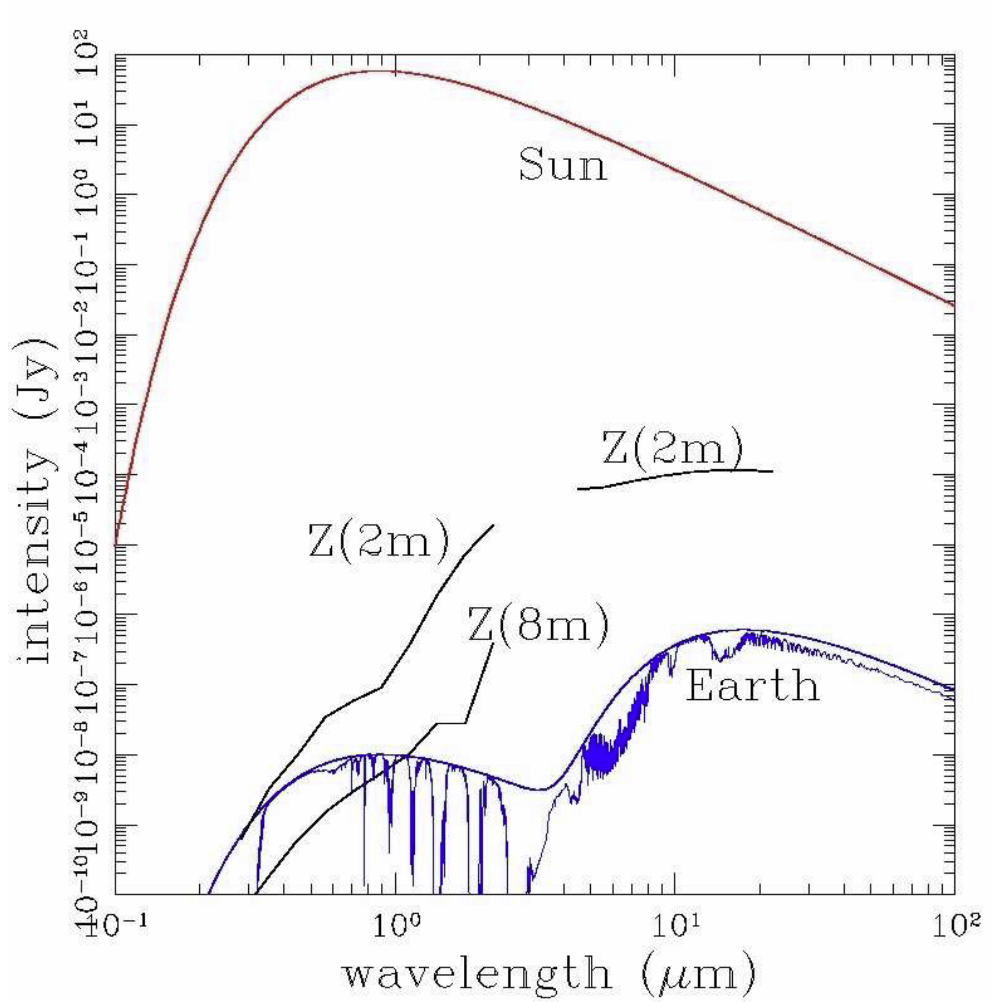
- We assume that we are looking for life similar to that on Earth.
- Life needs water, so we require a planet to have surface water.
- Cyanobacteria and plant life use CO_2, and produces O_2.
- Animal life uses O_2, and produces CO_2.
- Anaerobic bacteria produce CH_4.
- Large amounts of O_2 are a likely sign of life, especially if found in non-thermodynamical equilibrium with reducing species.
- All life needs protection from radiation, e.g., an atmosphere.
- Plants reflect red better than other colors.
- Life needs a planet surface on which to develop.
- These are our guiding principles.
- All of the above can be sensed using:
  - the **color and spectrum of reflected visible light**, and
  - the **spectrum of thermally-radiated infrared light**.

Kepler: Many smaller planets than known before



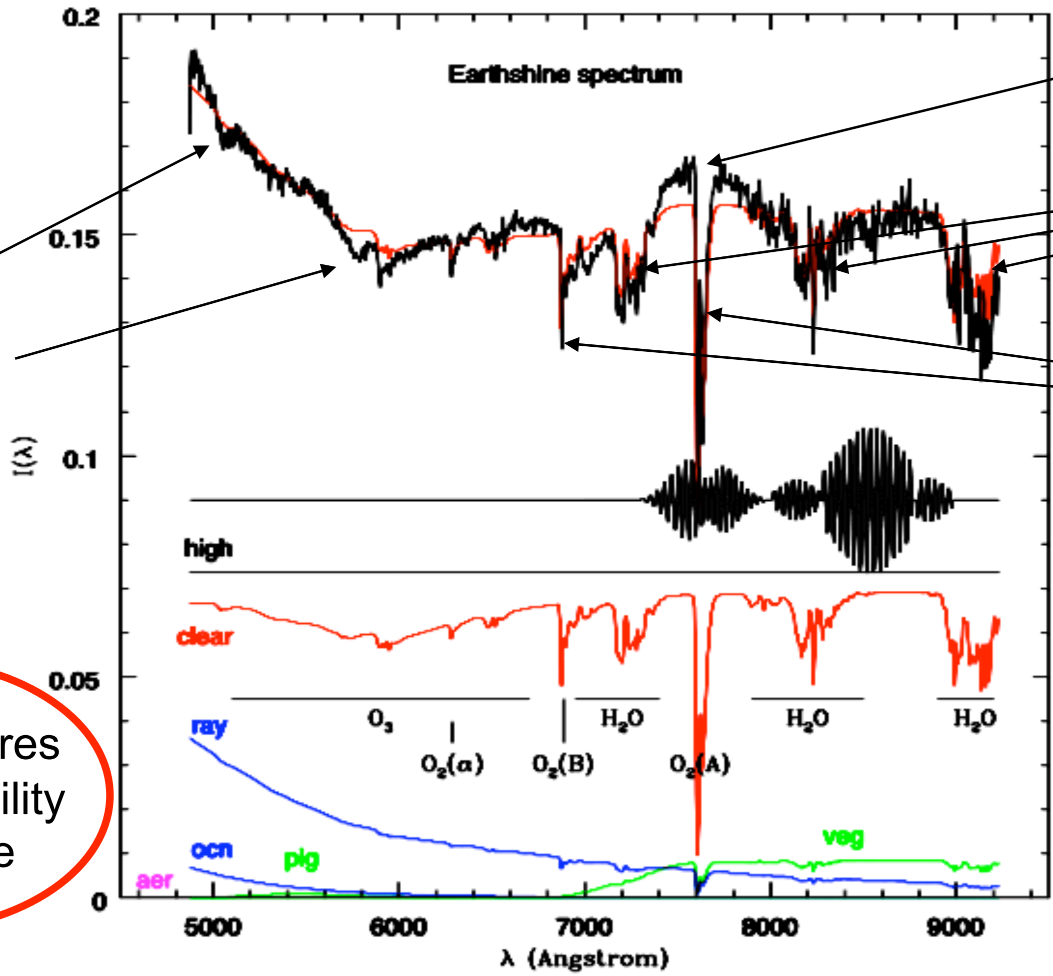
Ref.: Borucki et al., 2010

Earth Spectra

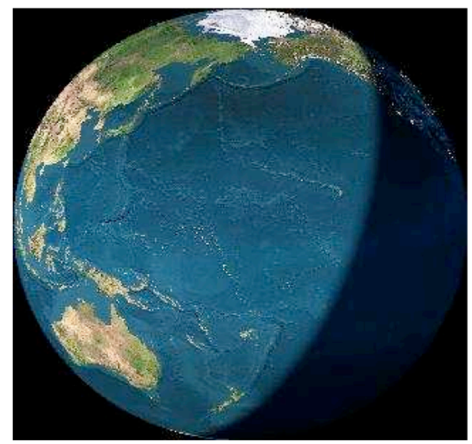


Ref.: J. Kasting & W. Traub, White Paper to Astro2010, 2009

Visible Earthshine Spectrum



Marked features show habitability & signs of life



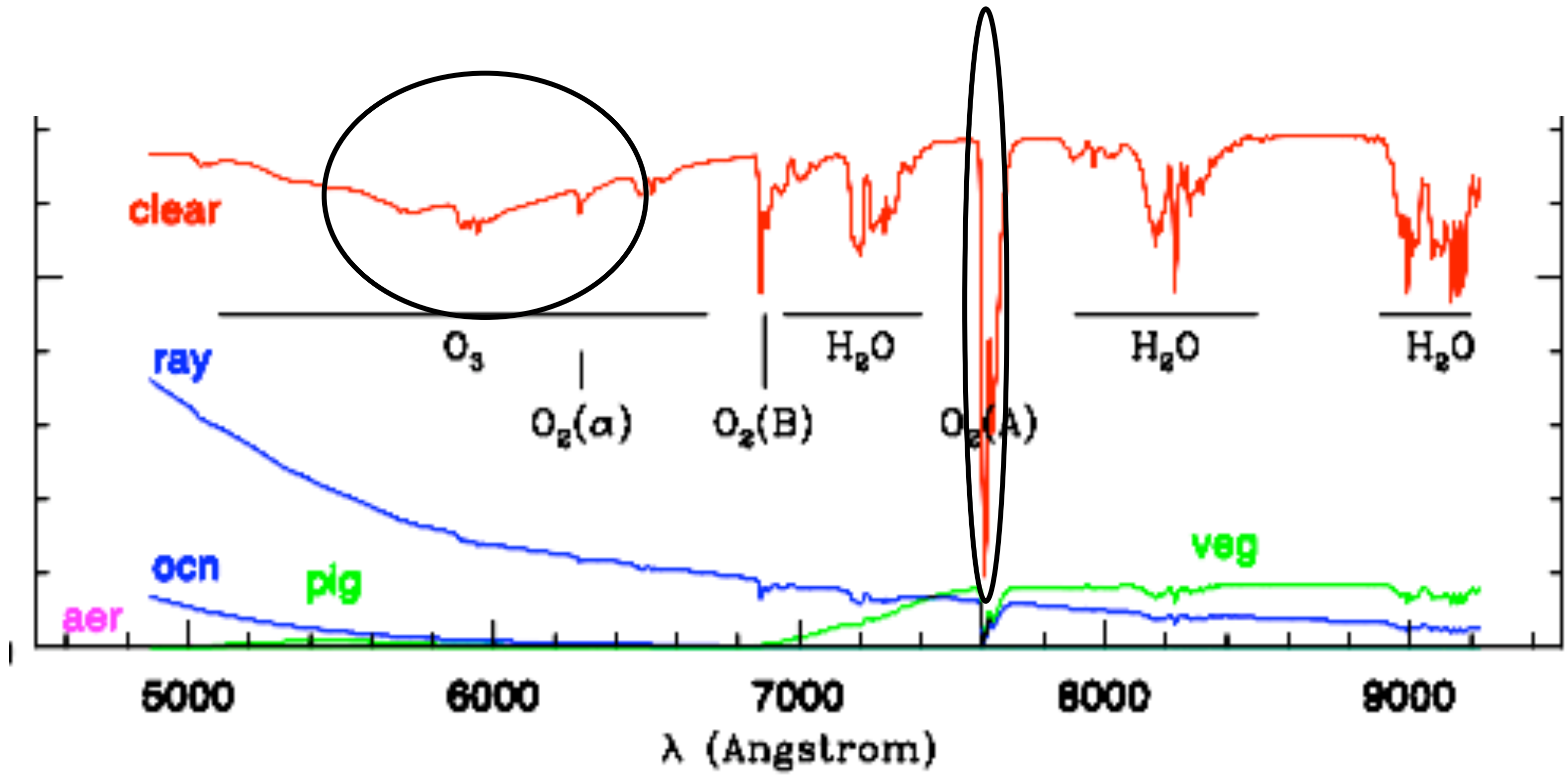
- Observed Earthshine, reflected from dark side of moon.

Ref.: Woolf, Smith, Traub, & Jucks, ApJ 574, p.430, 2002

O2 and O3

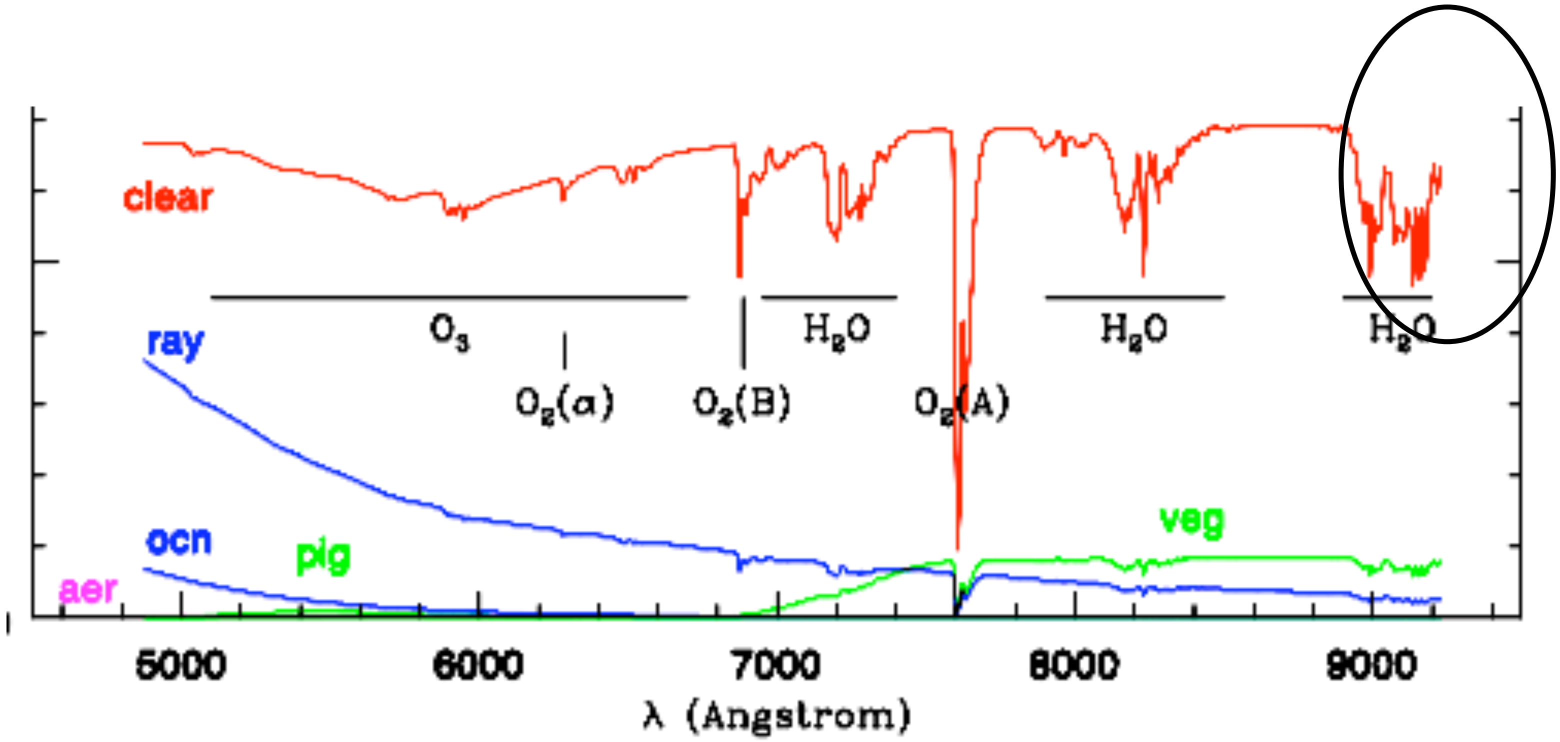
Assume O3 band at 580 nm.
Net SNR = 5.

Assume O2 band at 760 nm.
Net SNR = 5.



H2O

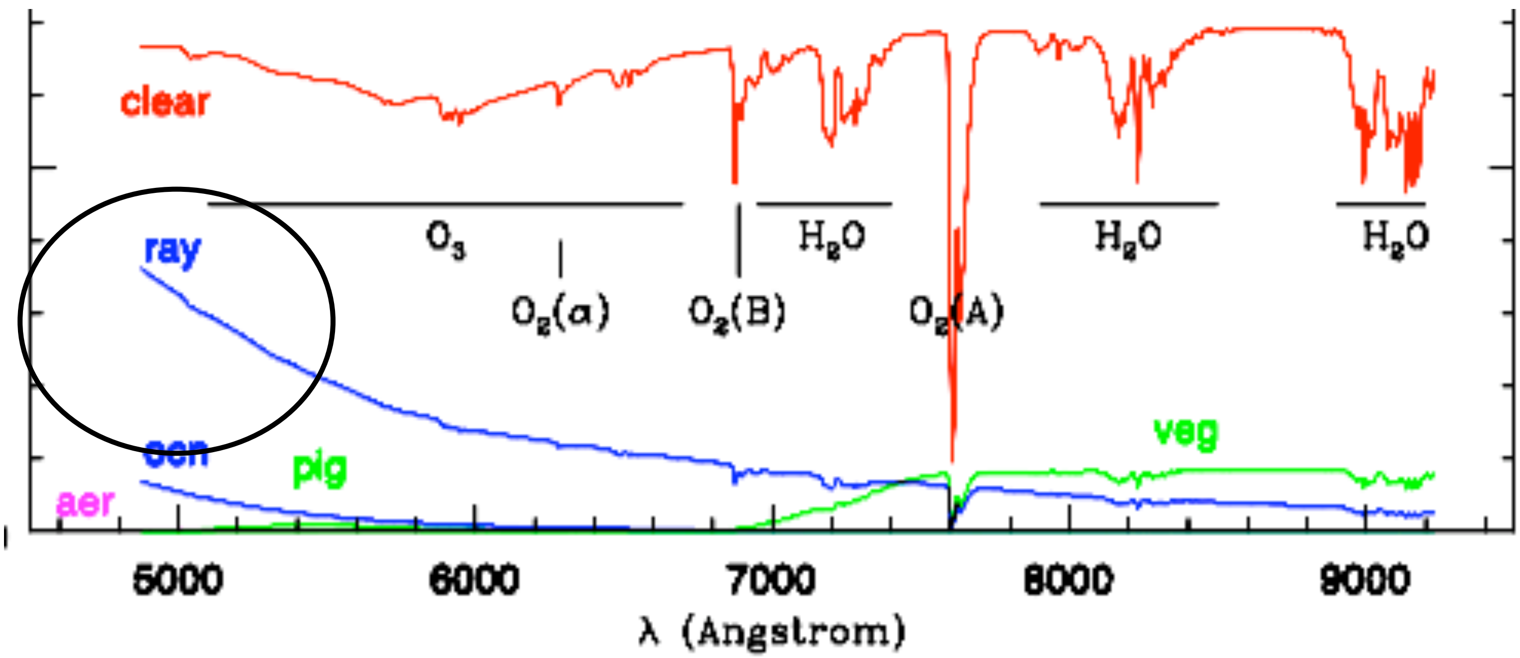
Assume water band at 940 nm.
Ignore other water bands (820, 720 nm).
Net SNR = 16 for detection of this feature.



Air Column

Assume Rayleigh scattering blue enhancement at 500 nm.

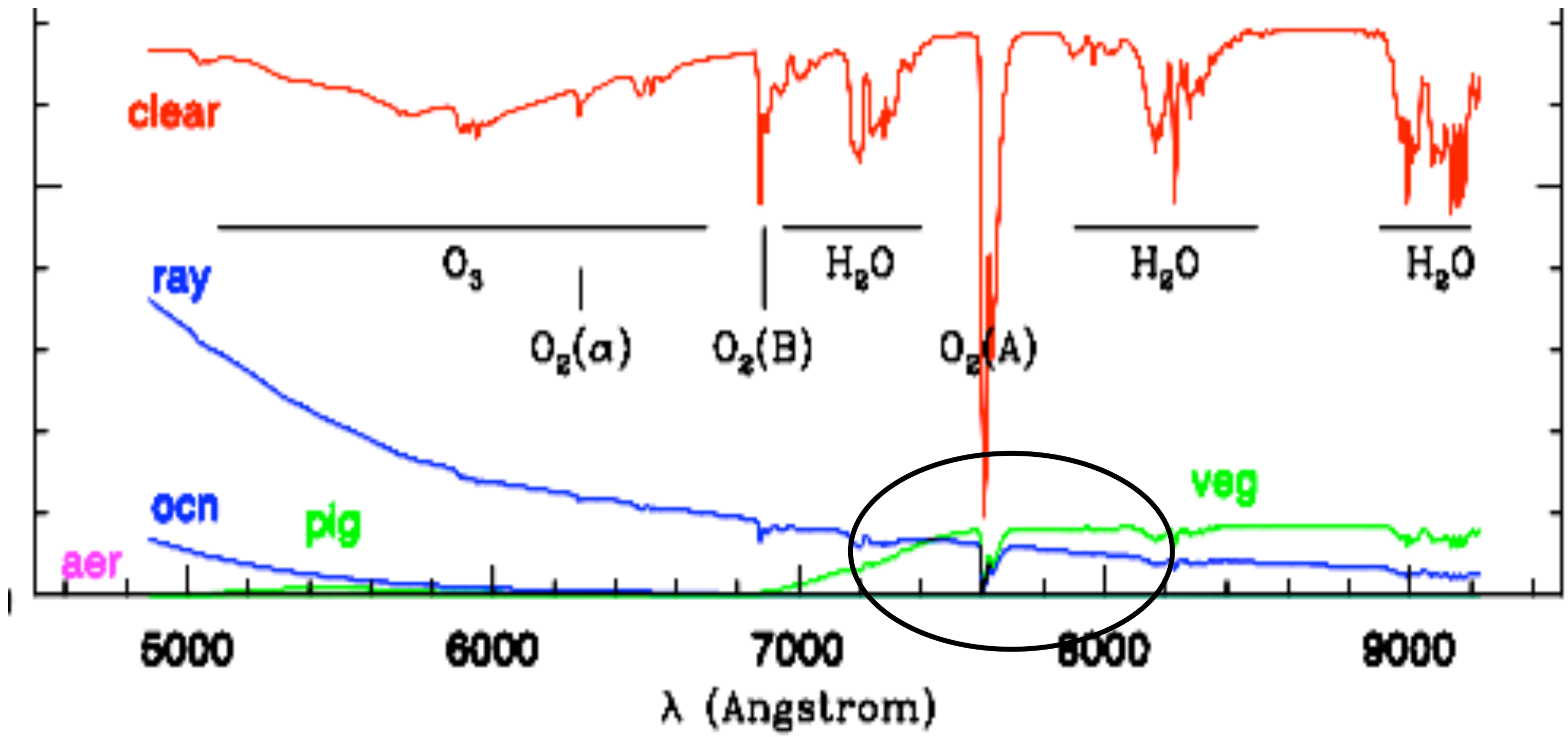
Net SNR = 4.



Land Plants ("Red Edge")

Assume red edge enhancement at 720 nm and longward.

Net SNR = 2.



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HZ boundaries

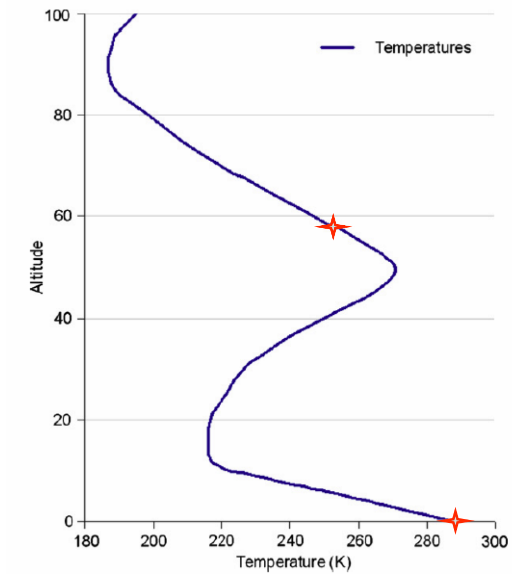
- HZ is defined as permitting liquid water on surface of planet.
- For today's Sun and Earth-albedo, HZ = (0.47, 0.88) AU.

- a(Venus) = 0.72 AU is inside HZ but is not hab.; why?
- a(Earth) = 1.00 AU is outside HZ but is hab.; why?
- a(Mars) = 1.52 AU is outside HZ, so why search for life there?

- Venus: runaway greenhouse, H2O lost, CO2 atm., heat trap.

- Earth: today have H2O &CO2 34K greenhouse, surface 288K.

- Mars: ancient CO2 greenhouse, liquid H2O.



Basic eqn. at optical depth unity:

$$T_{equil} = \left(\frac{1 - A_{Bond}}{4f}\right)^{1/4} \left(\frac{r_s}{a}\right)^{1/2} T_s$$

Other stars:

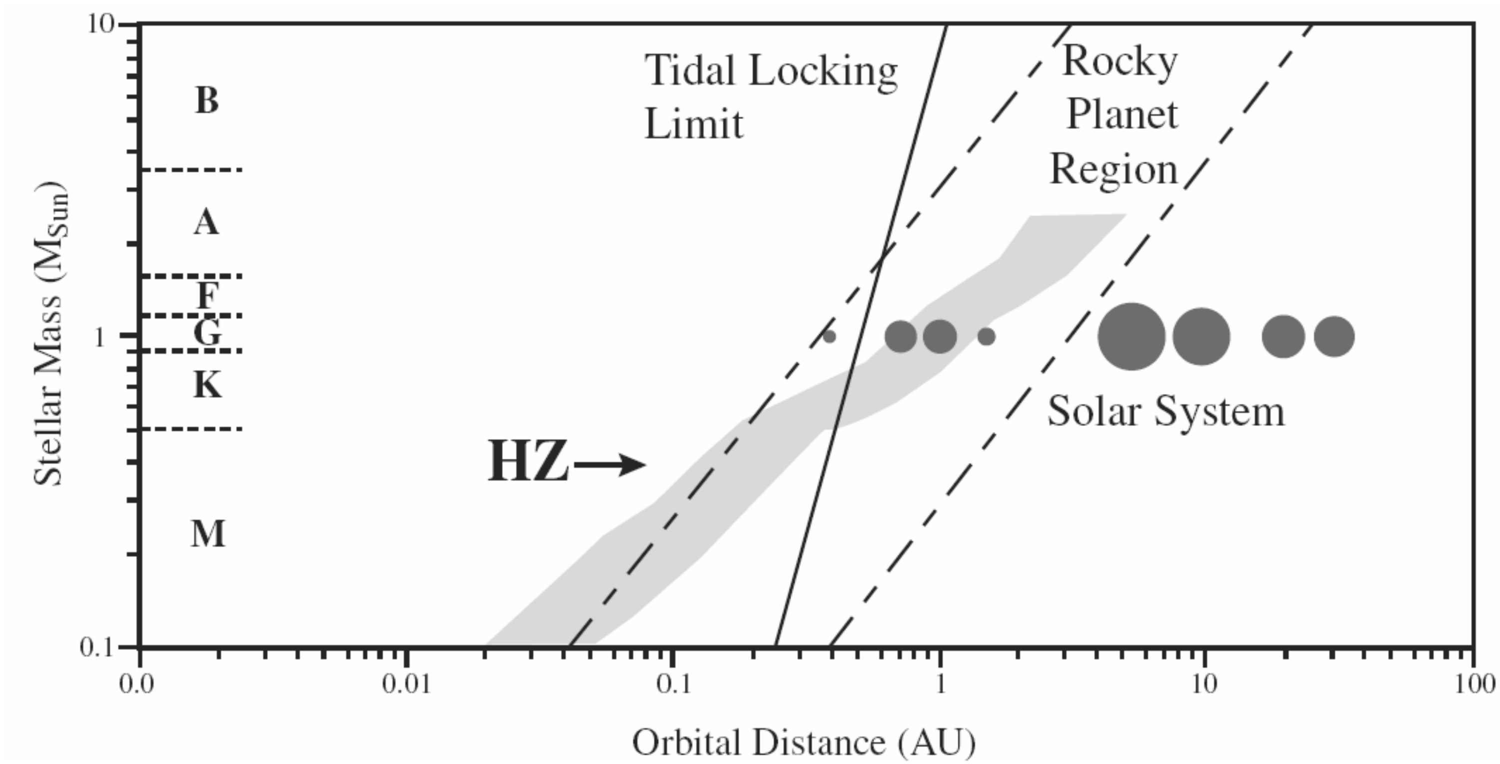
$$a(\text{HZ, E-like}) = (1AU)(L/L_{sun})^{1/2}$$

ALBEDO AND TEMPERATURE

Planet	a (AU)	p (visible geom. alb.)	A_{Bond} (Bond alb.)	$T^{(a)}_{equil}$ (K)	$T^{(b)}_{eff}$ (K)
Mercury	0.387	0.138	0.119	433	433
Venus	0.723	0.84	0.75	231	231
Earth	1.000	0.367	0.306	254	254
Moon	1.000	0.113	0.123	269	269
Mars	1.524	0.15	0.25	210	210
Jupiter	5.203	0.52	0.343	110	124.4
Saturn	9.543	0.47	0.342	81	95.0
Uranus	19.19	0.51	0.290	58	59.1
Neptune	30.07	0.41	0.31	46	59.3

Ref: Traub & Oppenheimer, Chapter in "Exoplanets", S. Seager, Ed.

HZ of other stars



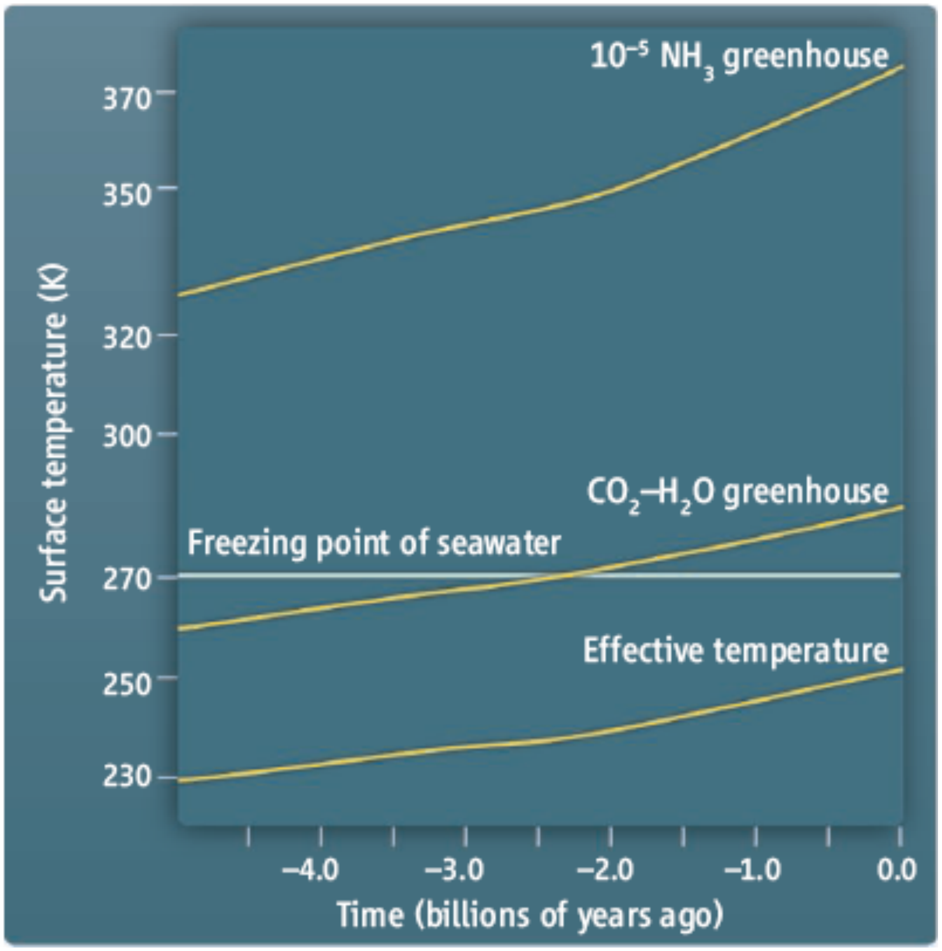
Other stars:

$$a(\text{HZ, E-like}) = (1AU)(L/L_{sun})^{1/2}$$

$L \sim M^{3.5}$ so $a(HZ) \sim M^{1.75}$ (shaded area)

Ref.: 2006 Astrobiology Primer, L. Mix, Ed., Astrobiology 6, 735-813, 2006.

Early Earth & Early Faint Sun Paradox



- Early Earth had liquid water
- Early Sun was L ~ 70%, so oceans freeze

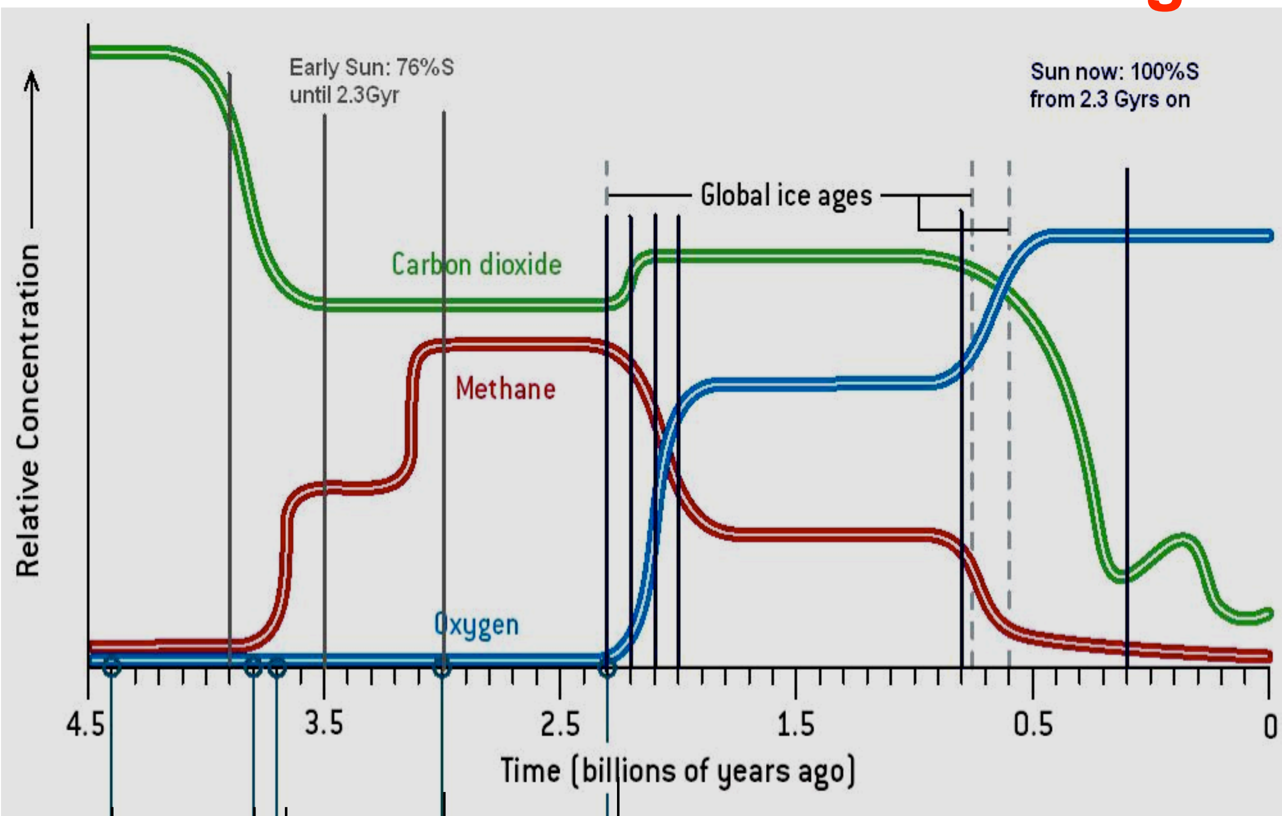
- Need greenhouse to solve paradox

- CO2 and H2O not sufficient greenhouse
- NH3 and CH4 newly popular
- Also both could help with start of life

- Key may be CH4 fractal haze
- Thin in optical, thick in UV
- UV shield protects NH3 photolysis

Refs.:
Chyba, Science 328, 1238, 2010
Kasting, Nature, 464, 687, 2010

Earth Over Geologic Time



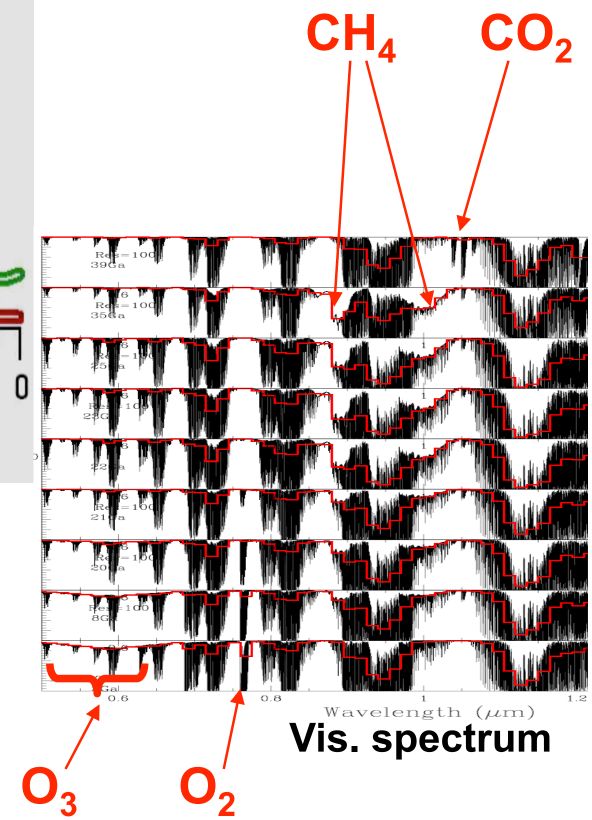
Oxygen appears in atmosphere

Oxygen-producing bacteria start

Methanogens start

First life consumes CO_2

High CO_2 compensates for faint Sun



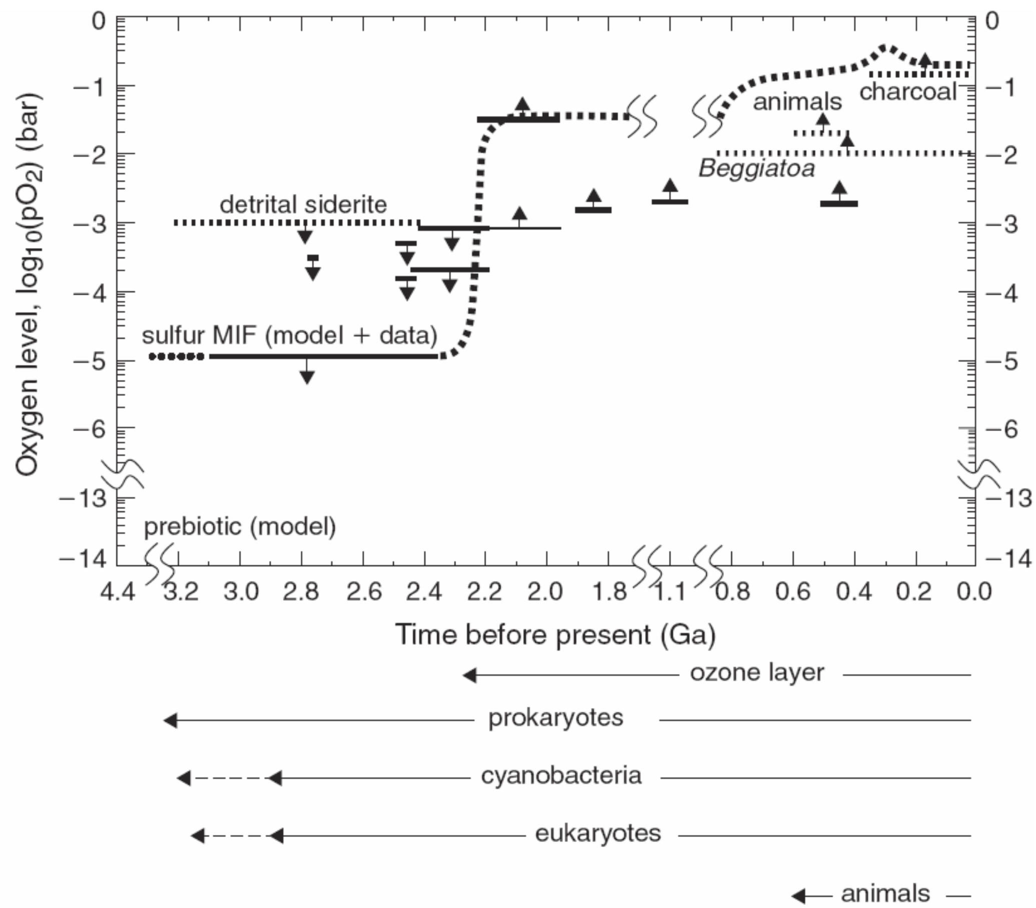
Refs:

Kasting, Scientific American, July, 80, 2004

Kaltenegger & Traub, ApJ, 658, 598, 2007

Holland, Phil Trans Soc London, 361, 903, 2006

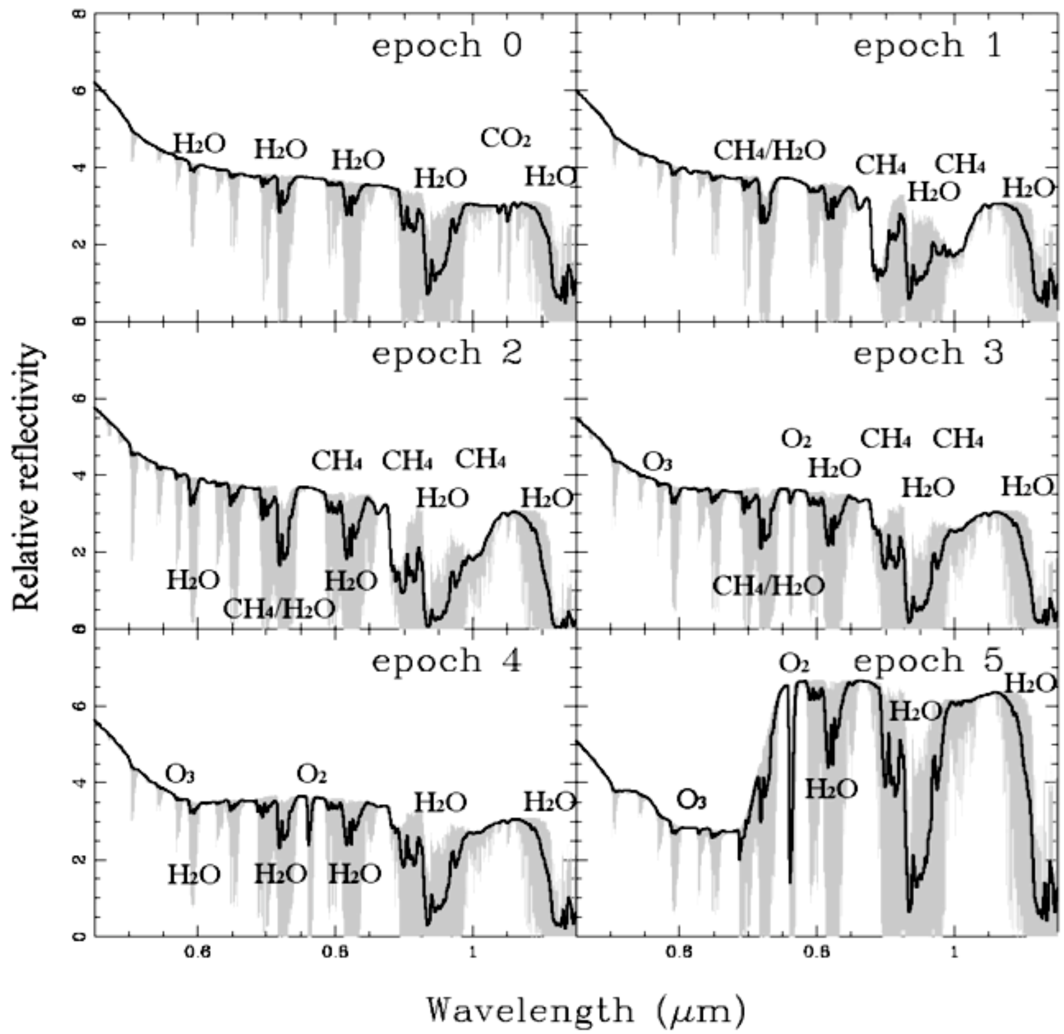
Oxygen vs Earth history



- "great oxygenation event ~ 2.2 Ga
- 2nd increase ~ 0.8 Ga

Ref.: 2006 Astrobiology Primer, L. Mix, Ed., Astrobiology 6, 735-813, 2006.

Earth's Spectrum Changes with Age



Early Earth:
- Weak CO_2
- Growing CH_4

Evolving Earth:
- Weakening CH_4
- CO_2 gone
- O_3 starting

Recent Earth:
- O_3 constant
- Vegetation strong (if cloudless sky)
- O_2 growing & strong

Ref.: Kaltenegger & Traub, ApJ 658, 598, 2007

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Venus & Mars

- Venus: best guess is runaway greenhouse from H_2O and CO_2,
  H_2 escaping to space,
  Surface too hot to hold water,
  CO_2 stays in atmosphere,
  keeps surface hot.

- Mars: best guess is some combination of CO_2 and H_2O greenhouse,
  barely warm enough for H_2O liquid,
  short time,
  cold and dry since that time.

- No special influence of Sun in either case.

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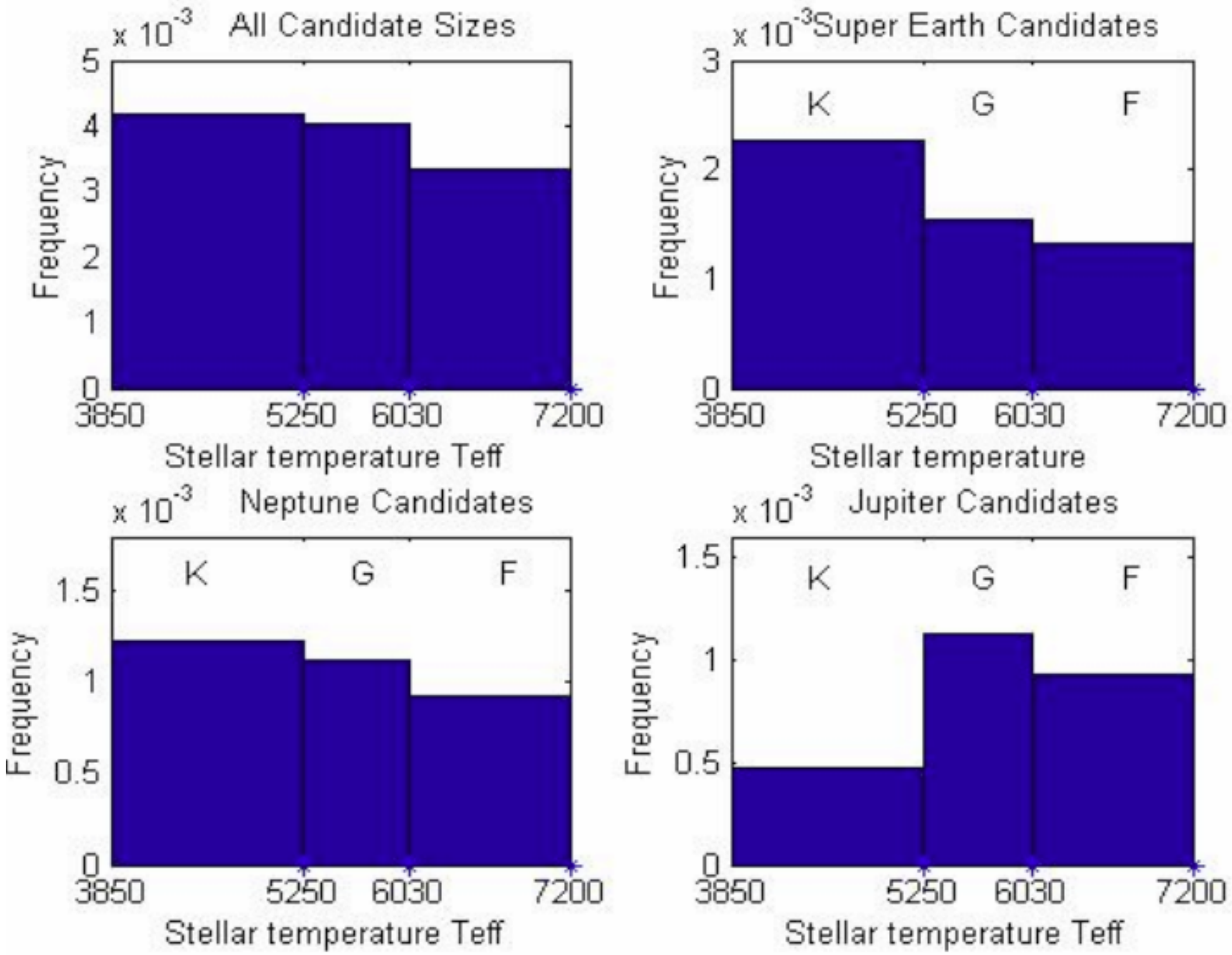
Kepler: Small Stars Prefer Small Planets



Ref.: Borucki et al., 2010

M-star HZ

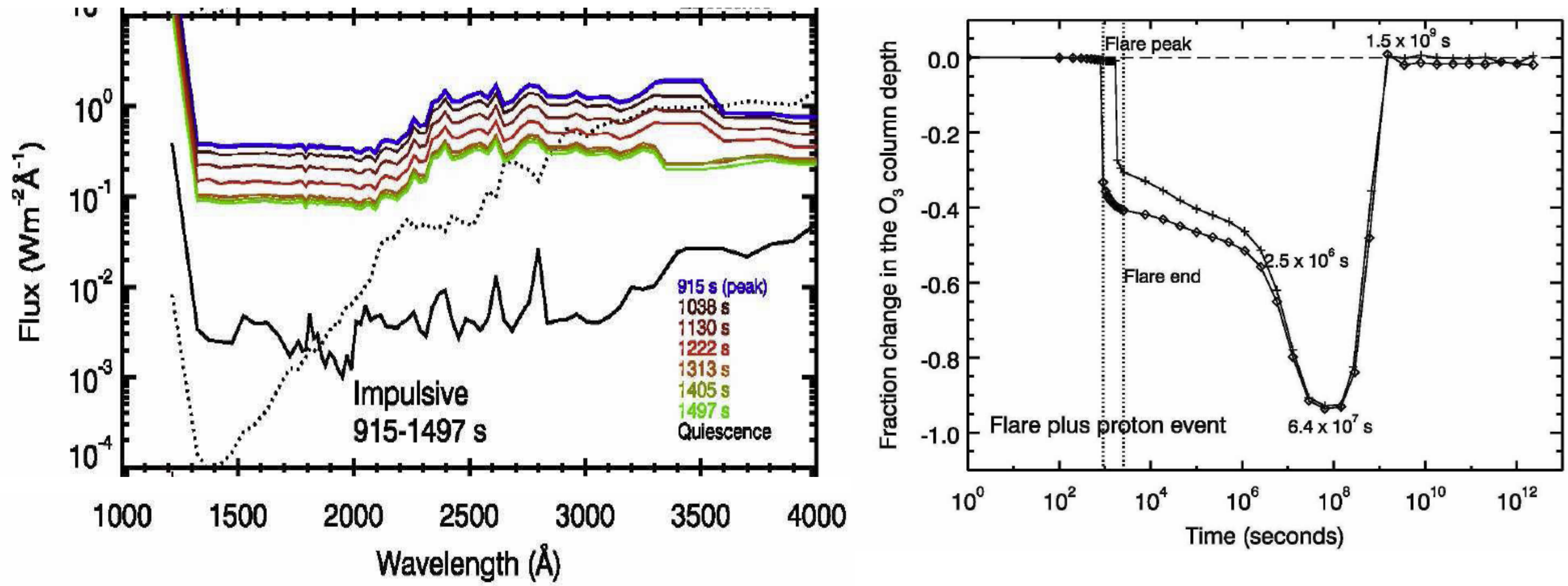
The Physical Characteristics of Each Subclass of M Stars are Listed Here, Along with Derived Values Related to an Earth-size Planet in the HZ

SpTy Dwarf	T (K)	R (R_{sun})	Mass (M_{sun})	$L/100$ (L_{sun})	M_V (mag)	a(HZ) (AU)	P(HZ) (hr)	ΔT(HZ) (hr)	$\Delta I/I$ (%)
M0	3800	0.62	0.60	7.2	9.34	0.268	1571	5.37	0.022
M1	3600	0.49	0.49	3.5	9.65	0.190	1039	3.96	0.035
M2	3400	0.44	0.44	2.3	10.12	0.152	786	3.36	0.043
M3	3250	0.39	0.36	1.5	11.15	0.123	633	2.96	0.055
M4	3100	0.26[a]	0.20	0.55	12.13	0.075	401	2.06	0.124
M5	2800	0.20	0.14	0.22	16.0	0.047	238	1.50	0.209
M6	2600	0.15	0.10	0.09	16.6	0.030	147	1.07	0.372
M7	2500	0.12	~0.09	0.05	18.8	0.022	98	0.78	0.582
M8	2400	0.11	~0.08	0.03	19.8	0.019	81	0.69	0.69
M9	2300	0.08	~0.075	0.015	17.4	0.013	46	0.43	1.31

- typical M-star HZ is at 0.1 AU
- typical orbital period is about a month
- so M stars are a potential place to find habitable planets

Ref.: Kaltenegger & Traub, ApJ 698, 519, 2009

M-star large flare at HZ



- large UV flare observed on M star
- solar analogy implies an associated proton event.
- planet in HZ would have received large UV & proton fluxes
- combination destroys ~90% of O3 column for ~10 years
- however authors conclude that UV "would not present a direct hazard for life"

Ref.: Segura et al., astroph, 2010

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Other possible effects of star on planet

- thermal evaporation and photo-evaporation are relatively slow processes
  (e.g., Earth, hot Jupiters)

- particle erosion of atmosphere could be fast if magnetic field is weak
  (e.g., Mars)

- climate responds to solar activity in ways that are not fully understood
  (e.g., Maunder minimum caused Europe to freeze)

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Is complex life rare?

Many reasons are cited:

- lack of water during planet formation
- lack of Jupiter to protect Earth from worse bombardment
- lack of greenhouse effect to keep Earth from freezing under weak Sun
- lack of exactly the metals needed for present life
- lack of mechanism for cells to become started
- complexity of DNA suggests it will never happen again
- complexity of photosynthesis suggests it too will never happen again
- extinctions on Earth have been frequent, so not likely we would make it next time
- lack of plate tectonics to keep CO2 low and temperature comfortable (Gaia)
- wrong part of Galaxy
- lack of a Moon to stabilize spin and generate tides
- lack of rapid rotation hence stimulating weather patterns
- lack of comets to deliver life molecules from space
- etc.

Refs.:
P. Ward & D. Brownlee, *Rare Earth*, 2004
P. Ward, *Life as We Do Not Know It*, 2005
P. Ward, *Out of Thin Air*, 2006

Or is our understanding yet too rare?

However the extremely early appearance of signs of life on Earth, very soon after it cooled,

and the ubiquity of life in all niches on the planet,

and the manifest re-invention of life elements (eyes, wings, etc.) in separate instances,

and the observed ability of life forms to adapt to temperature, pressure, radiation, etc.,

all suggest that life will happen under many other circumstances,

and that it probably has done so on planets around nearby stars.

We may know if NASA will be given the charge
to search for planets around nearby stars,
and to search for signs of life on those planets,
when Astro2010 becomes public at 8am on Friday 13 August 2010.

Ref.: J. Kasting, *How to Find a Habitable Planet*, 2010

Thank you!