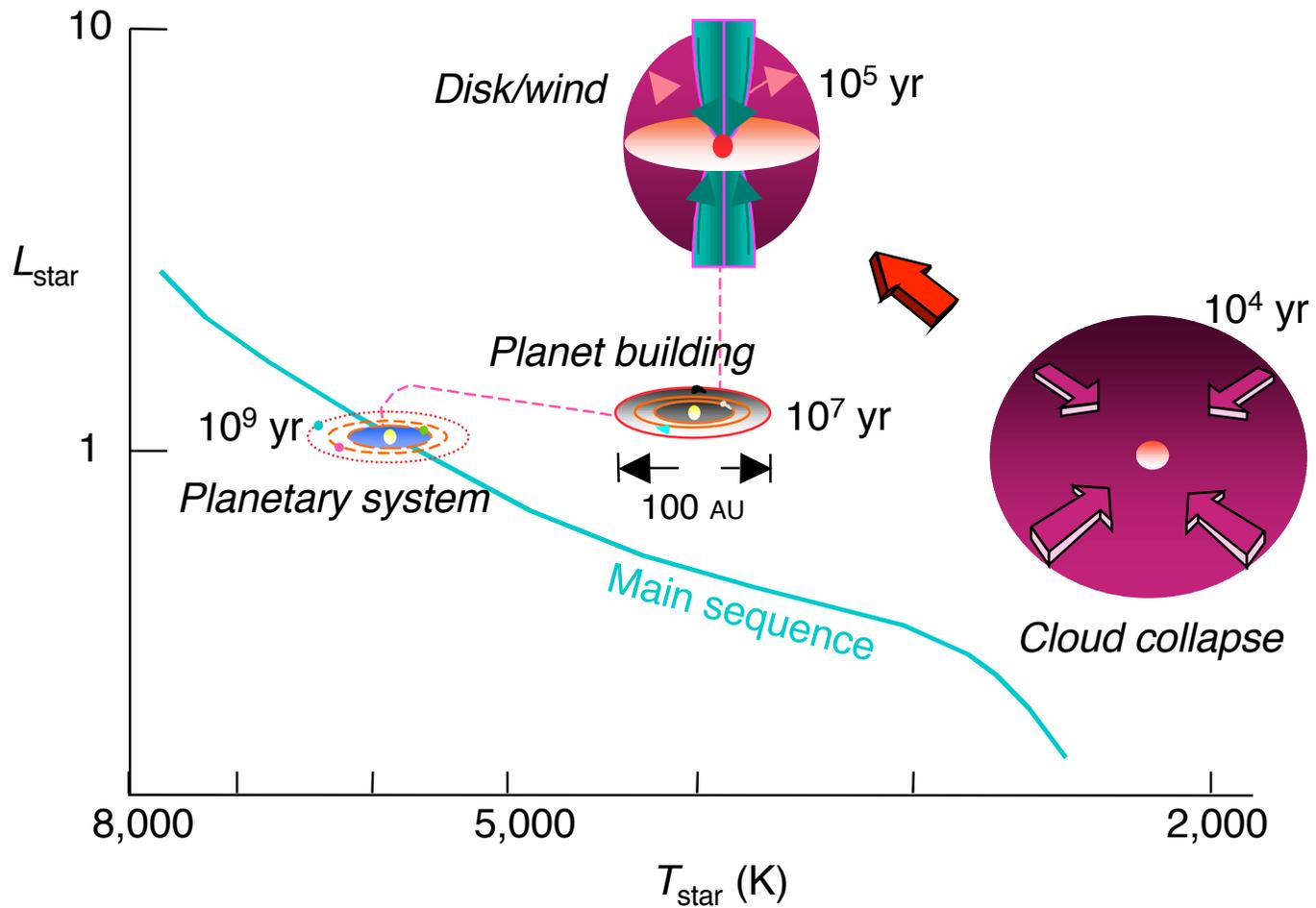


Ay 20 - Fall 2004
The Long-Lost Lecture 14:

**Planetary System Formation,
Extrasolar Planets,
Life in the Universe,
and SETI**

Pre-main Sequence Evolution



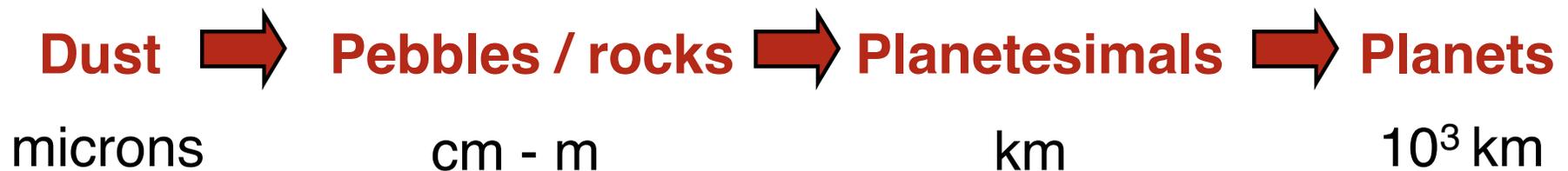
Formation of planetary systems

Protoplanetary disks contain dust - micron sized solid particles formed for example in the stellar winds of some stars.

Initially the dust is uniformly mixed with the gas in the disk, but over time it will settle under gravity toward the midplane of the gas disk.

Collisions between particles lead to growth:

- Initially because particles are `sticky` - dissipate energy of relative velocity on impact
- Eventually because bodies become large enough that their own gravity attracts other bodies



(From P. Armitage)

Planet Building

- Jovian planets began as aggregating bits of rock and ice that reached 15 Earth masses and began to capture large amounts of He & H
- Terrestrial planets have very little H & He because their low masses can't keep these gases from evaporating
- The comets are just remains of the icy planetesimals that Jupiter threw out far into the Solar system. They are fossils of the early Solar system

Formation of Planetesimals

3 Groups of Processes Operate:

- a) grains of solids grow larger; reaching diameters of centimeters to km. Larger ones are called *Planetesimals*.
- b) *Planetesimals* are said to be the bodies of the 2nd group of processes that eventually collect to form planets.
- c) 3rd set of processes clears away the remaining solar nebula.

Formation of Planetesimals

- 1) a particle grows by **condensation**—matter is added one atom at a time from surrounding gas.(formation of snowflake)
- 2) **accretion** is the sticking together of solid particles (building of a snow man). A planetesimal is reached once it becomes a km or so.
- 3) planetesimals flatten into a rotating disk plane that would have broken them into small clouds that would further help them concentrate to form planets.
- As they exceed 100 km in diameter they begin the protoplanet stage.

Growth of Protoplanets

- Protoplanets-massive enough objects destined to become planets.
- When planetesimals were moving in the same rotating orbit they “rubbed shoulders” with other planetesimals, and allowed them to fuse together rather than shatter if they had been headed straight on in the collision.
- Sticky coatings and electrostatic charges on the surfaces of the smaller planetesimals probably aided the formation.
- Larger planetesimals would grow fastest because of their large G field.

Growth of Protoplanets

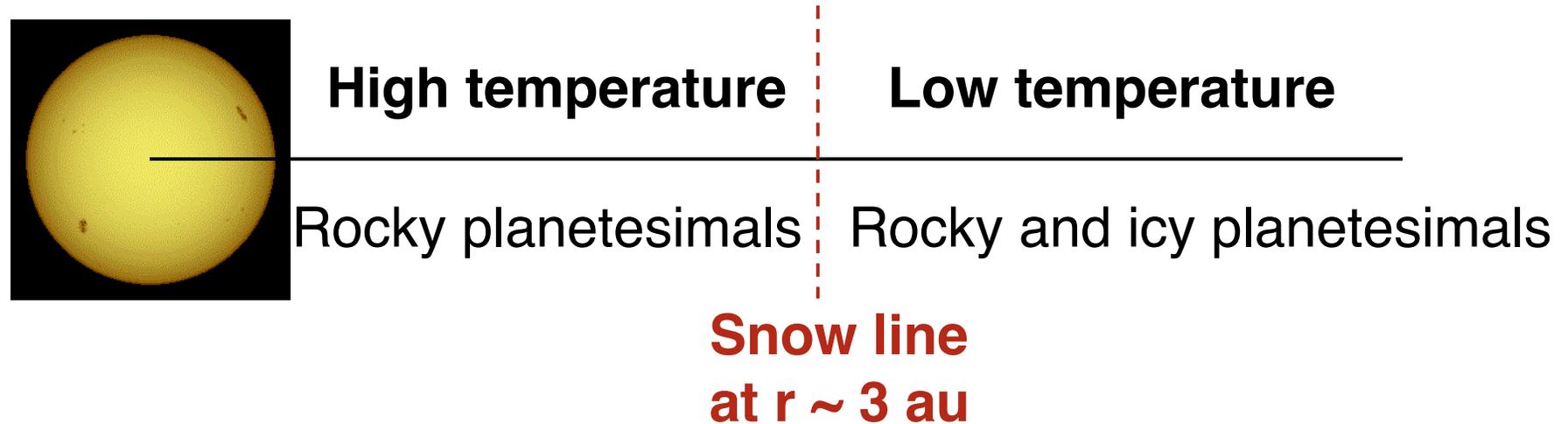
- Once planets formed, the heat of the short lived radioactive elements in their interiors would cause the planet to heat up and melt allowing the ...
- **Differentiation** to occur: Fe, Ni settled to the core, silicates floated to the surface
- **Outgassing** occurs—which is the formation of the planets atmosphere from the heating of the planet's interior. The earth's H and He were driven off by the heat
- This suggests that the Earth did not capture its atmosphere from the formation nebula, instead it created its atmosphere from the release of gases from the molten rock as the protoplanet grew

Clearing the Protosolar Nebula

Four effects cleared the nebula:

1. **Radiation pressure**-light streaming from the sun pushed against the particles of the solar nebula.
2. **The solar wind**—flow of ionized H helped push dust and gas out of the nebula.
3. **Sweeping of space debris by the planets**—the moons and planets are constantly getting bombarded by meteorites. **Heavy bombardment**—was a period when the craters were formed roughly 4 billion years ago.
4. **Ejection of material from the solar system by close encounters with planets**

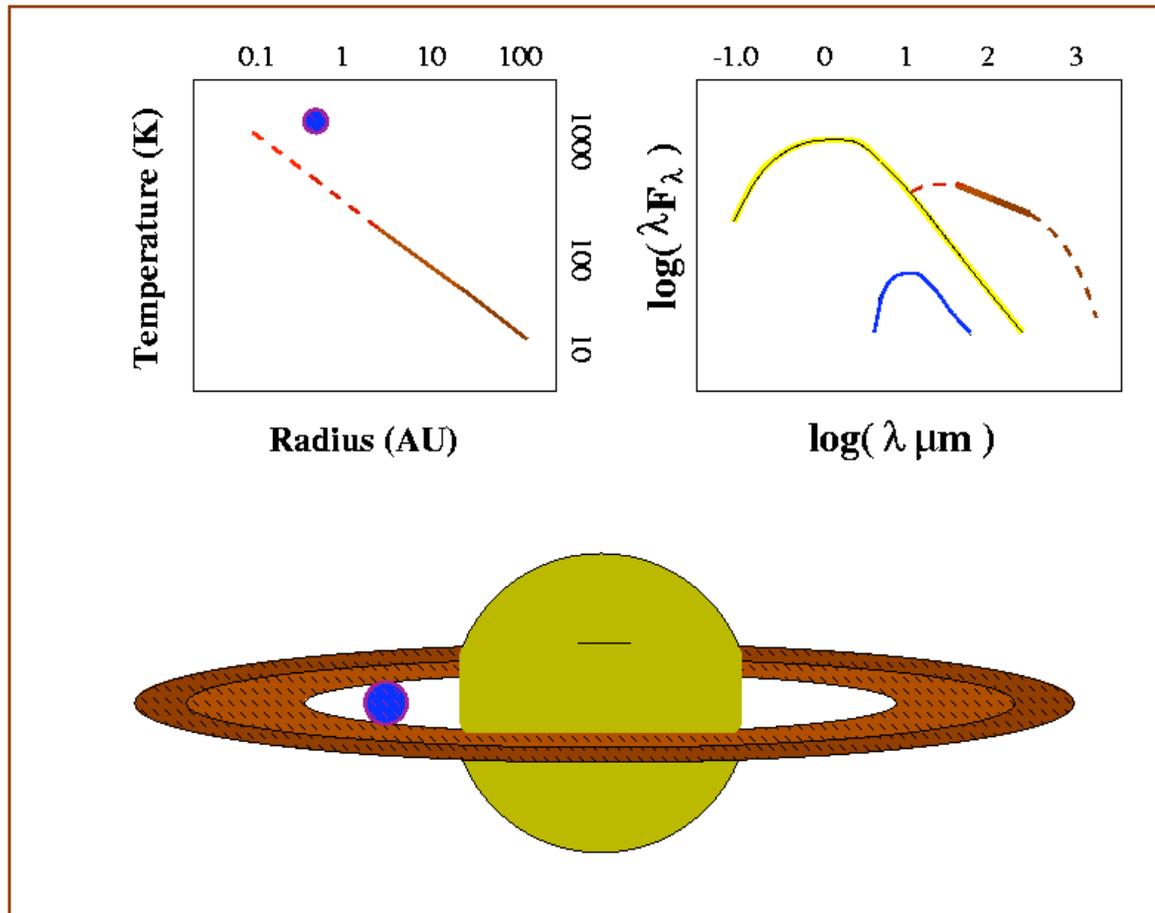
Traditionally, understood this as resulting from a temperature gradient in the protoplanetary disk:



- Surface density of planetesimals is larger beyond the snow line, in parts of the disk cool enough for ice to be present
- Higher surface density \rightarrow more rapid formation of planets
- In the outer Solar System, planets grew to $\sim 20 M_{\text{Earth}}$ while gas was still present, captured gas to form gas giants
- In inner Solar System, no gas was captured
- All circular orbits as formed from a circular disk

(From P. Armitage)

Blackbody Disk with Dynamically Cleared Gap



Distinction between planets and brown dwarfs

Two definitions have been proposed:

- 1) A brown dwarf is an object that does not burn hydrogen, but does burn deuterium. A planet is any object low enough in mass to burn neither.

Brown dwarf: $13 M_{\text{Jupiter}} < M < 0.08 M_{\text{sun}}$

Planet $M < 13 M_{\text{Jupiter}}$

- 2) A planet is a body that forms from a protoplanetary disk. A brown dwarf is an object that forms during the collapse or fragmentation of a molecular cloud.

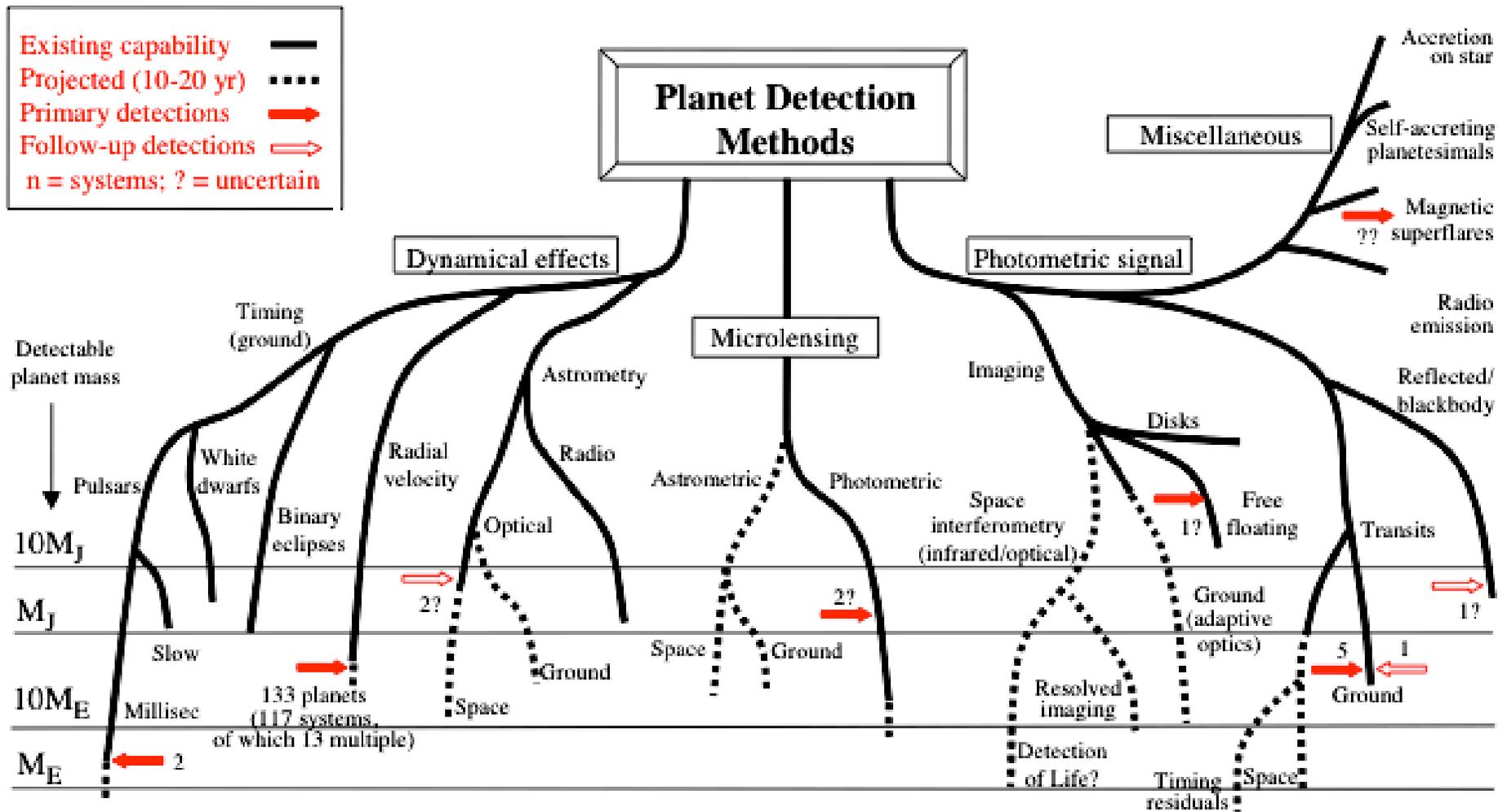
Restricts use of the term planet to the 'common sense' definition of a body orbiting a star

(From P. Armitage)

Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated November 2004)

[corrections or suggestions please to michael.perryman@esa.int]



If the planet reflected all the intercepted starlight, then the magnitude difference between the planet and the star would be:

$$m = -2.5 \log F + \text{constant}$$

$$m_p - m_* = -2.5 \log F_p + 2.5 \log F_*$$

$$m_p - m_* = -2.5 \log \left(\frac{F_p}{F_*} \right)$$

Find $\Delta m \sim 22$ magnitudes for Jupiter, 23 magnitudes for Earth.

Implied apparent magnitude is not too bad, e.g. for Earth orbiting a 5th magnitude G star (Solar type) would need to reach $V \sim 27$ mag.

But the real problem is the ***scattered light*** from the parent star. This requires extreme-contrast AO imaging, or a “nulling interferometer” (e.g., Keck Int.)

(From P. Armitage)

Direct Imaging Detection of Exo-Planets

- This is *extremely challenging* because:
 - Separation on sky is tiny (1 AU at 100 lt yrs subtends an angle = 0.03 arcsec)
 - Star is *much* brighter than the planet
 - In optical: 6×10^8 times as bright
 - In IR (10 μm): 3×10^5 as as bright
 - Warm dust (analogue of Zodiacal dust) around the star can be *much* brighter than the planet--i.e. the background from the dust can be very bright

TPF Strategy

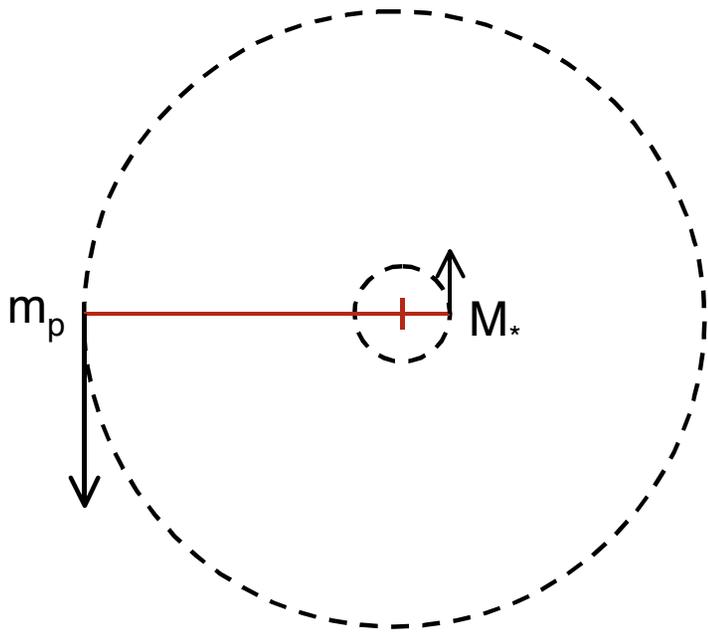
- First, must find nearby (within 150 lt yrs) terrestrial size planets in the habitable zone.
- Find the ones that have atmospheres and establish if they are, indeed, habitable
 - Determine the temperature at the surface
- Target the most promising planets for detailed spectroscopic observations to look for *biosignatures*, then....
- Argue for years over the results!

Indirect detection of extrasolar planets

Radial velocity method

Star - planet system is a special case of a spectroscopic binary where:

- Only observe the radial velocity of one component
- Very large ratio of masses between components



For circular orbits, as previously:

Ratio of velocities of
star and planet in orbit
around center of mass

$$\frac{v_*}{v_p} = \frac{m_p}{M_*}$$

Kepler's laws give:

$$v_p = \sqrt{\frac{G(M_* + m_p)}{a}} \approx \sqrt{\frac{GM_*}{a}}$$

...for star-planet separation a

(From P. Armitage)

Velocity of the **star** due to presence of orbiting planet is:

$$v_* = \frac{m_p}{M_*} \sqrt{\frac{GM_*}{a}}$$

How large is this velocity?

Jupiter: $m_p = 10^{-3} M_{\text{sun}}$, $a = 7.8 \times 10^{13} \text{ cm}$, $M_{\text{sun}} = 2 \times 10^{33} \text{ g}$

 $v_* \approx 1.3 \times 10^3 \text{ cm s}^{-1} = 13 \text{ m s}^{-1}$

Earth: $m_p = 3 \times 10^{-6} M_{\text{sun}}$, $a = 1.5 \times 10^{13} \text{ cm}$

 $v_* \approx 10 \text{ cm s}^{-1}$

Currently the best observations measure the stellar velocity to a precision of $\sim 3 \text{ m s}^{-1}$ (ultimate limit is not known, but is thought to be $\sim 1 \text{ m s}^{-1}$). **Can detect extrasolar `Jupiters`, but not Earths.**

(From P. Armitage)

Planet masses from radial velocity measurements:

$$v_{obs} = v_* \sin i = \frac{m_p}{M_*} \sqrt{\frac{GM_*}{a}} \sin i$$

$$m_p = v_{obs} \times M_* \times \sqrt{\frac{a}{GM_*}} \times \frac{1}{\sin i}$$

Inclination factor is unknown unless we see eclipses (transits)

Observed amplitude of stellar 'wobble' - measure this directly

Derive this from M_* and period P :

$$P = 2\pi \sqrt{\frac{a^3}{GM_*}}$$

Don't know stellar mass, but can get a good estimate from high signal to noise spectrum

(From P. Armitage)

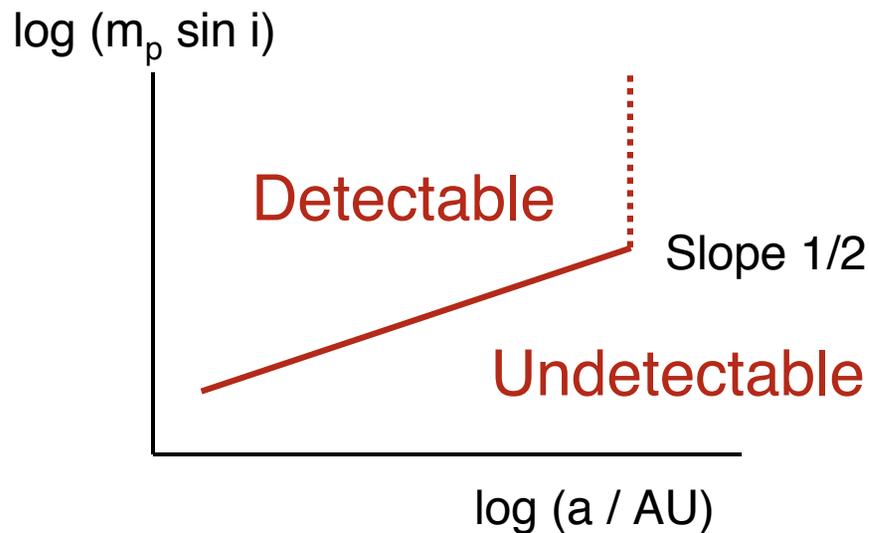
Radial velocity observables are:

- **Orbital period** (or semi-major axis)
- $m_p \sin(i)$ - i.e. a *lower* limit to the true planet mass
- **eccentricity of the orbit**

Selection effects:

$$v_* = \frac{m_p}{M_*} \sqrt{\frac{GM_*}{a}}$$

For fixed observational sensitivity, the minimum detectable planet mass scales as the square root of the orbital radius:



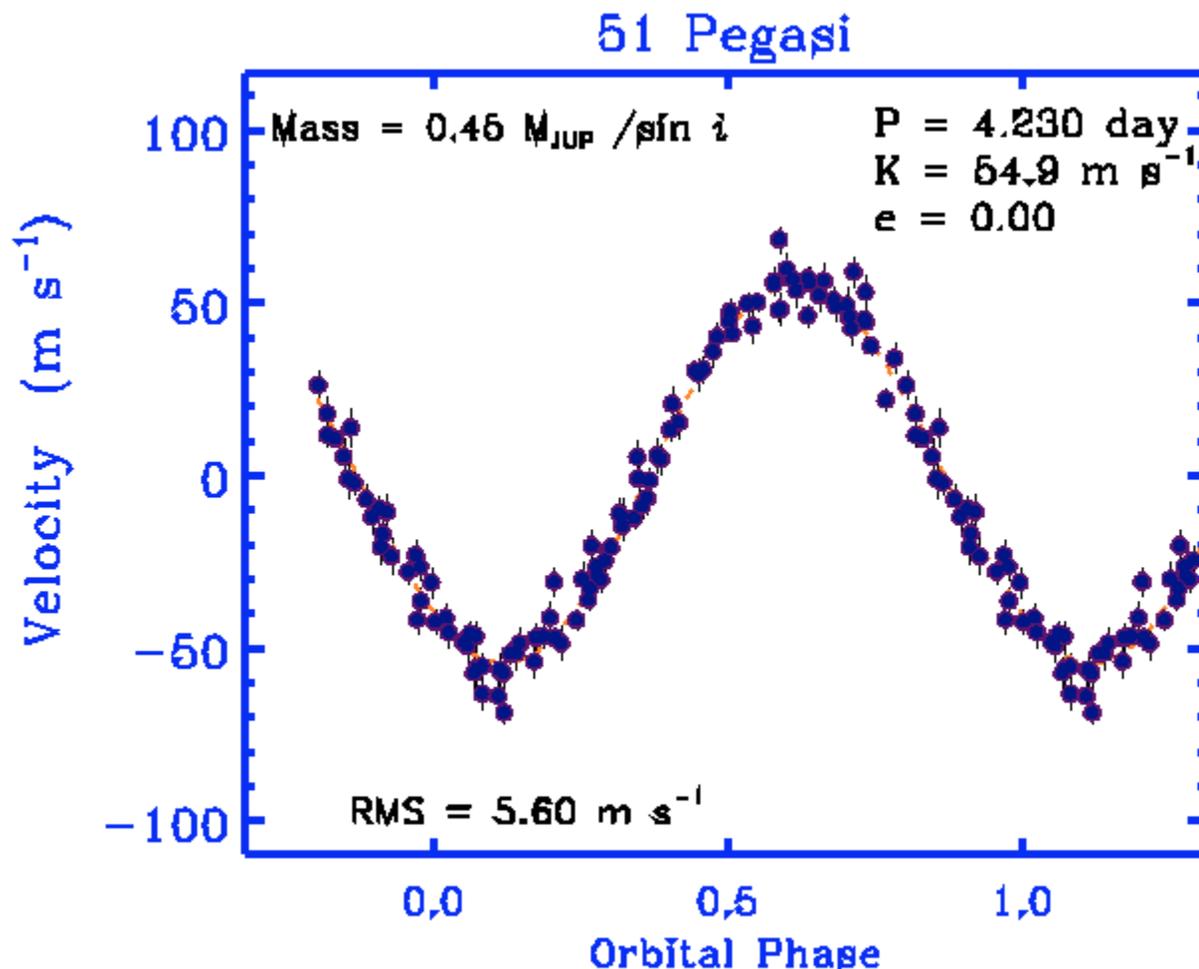
Also fail to detect very long period planets - won't (yet) have seen a complete orbit

Method favors detection of massive planets at small radii from the star...

(From P. Armitage)

Extrasolar planets

All but one known extrasolar planet around an ordinary star have been found by monitoring the stellar radial velocity



First planet found:
around the star
51 Peg by Mayor
and Queloz (1995)

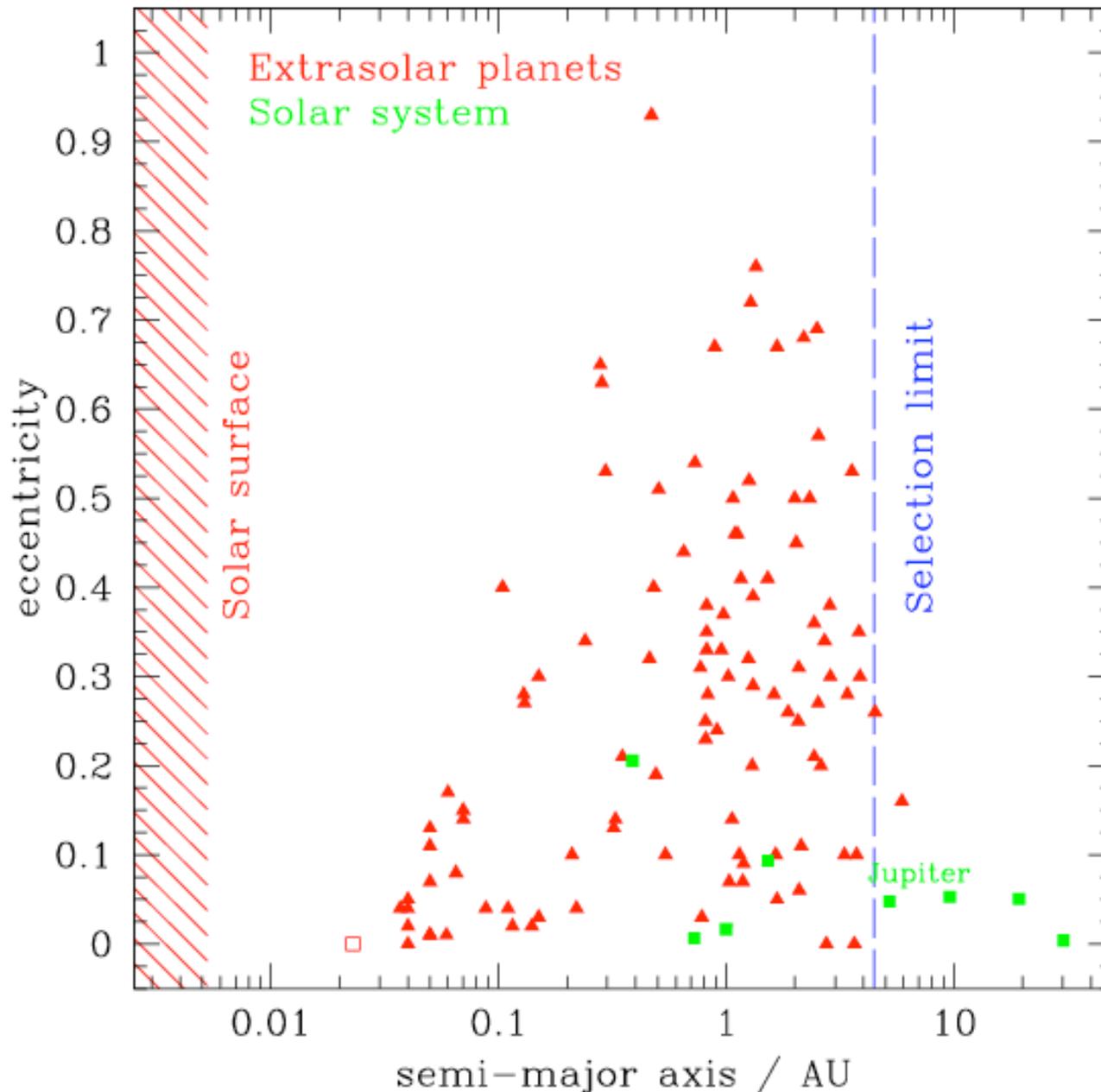
Sinusoidal curve:
circular orbit

Period: 4.2 **days**

A 'hot Jupiter'

(From P. Armitage)

Reported data October 2003



'Typical' planet may be at same orbital radius as Jupiter

High values of the orbital eccentricity are common

Hot Jupiters have circular orbits

(From P. Armitage)

Compare to distribution of binary stars

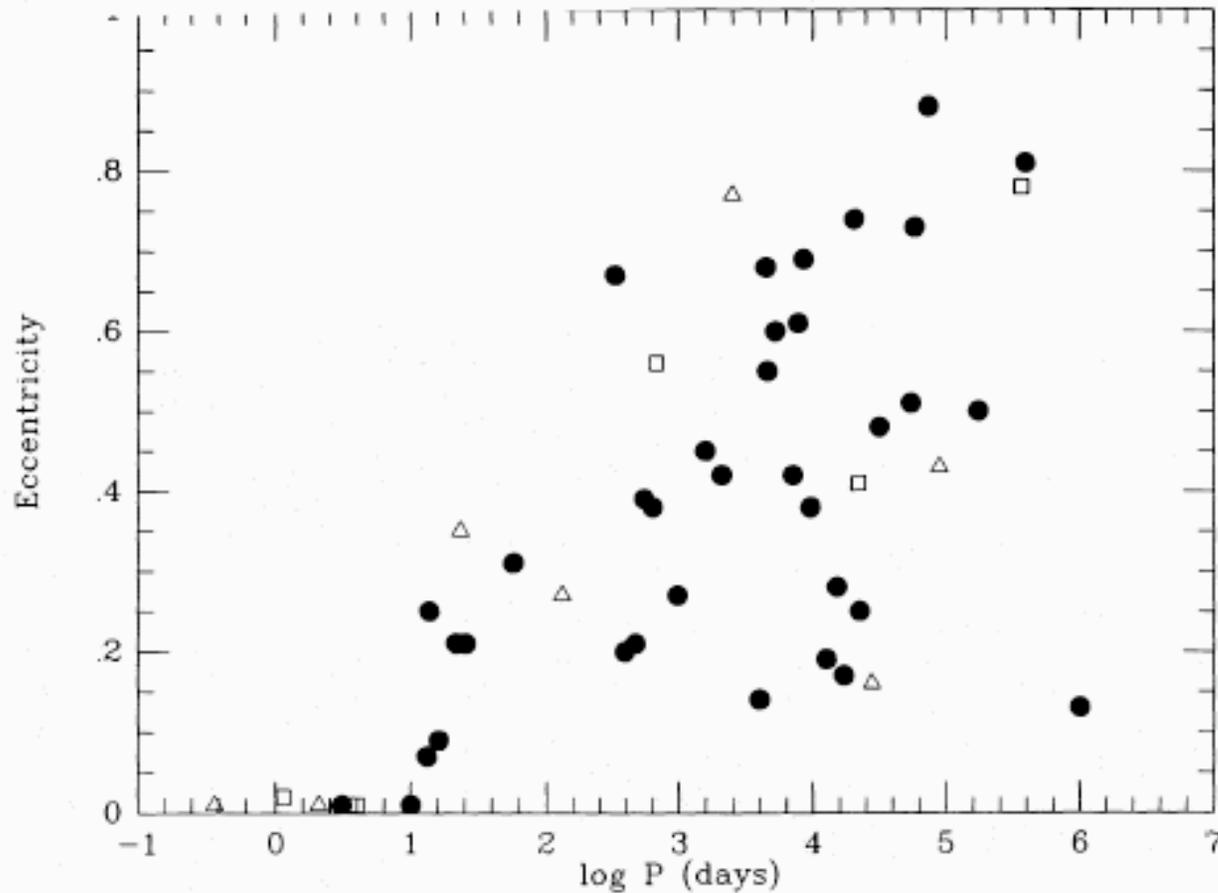
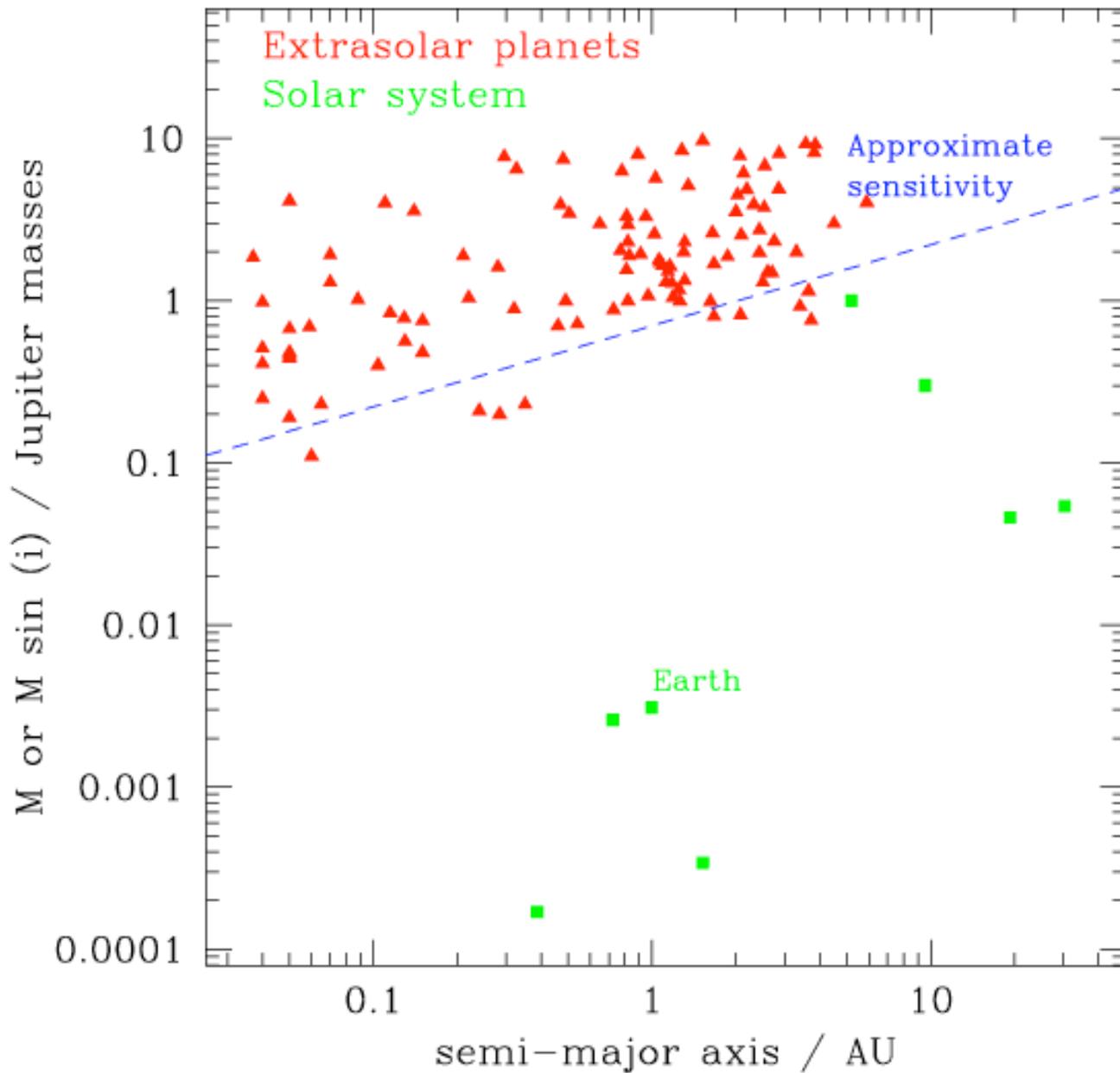


Fig. 5. Diagram eccentricity versus period for the complete nearby G-dwarf sample. Note the strong circularization effect due to tidal stresses for short periods binaries. The symbols are according to the multiplicity of the system: ● double, △ triple, □ quadruple

(From P. Armitage)

Reported data October 2003



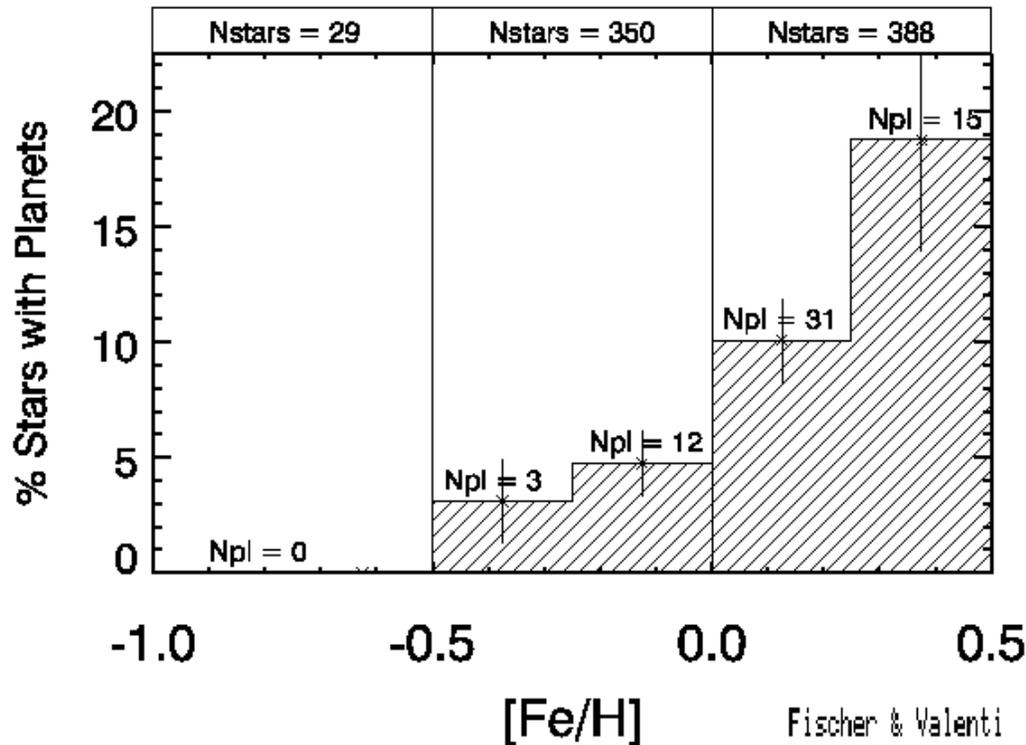
Sensitivity:

$$M_{\min} \propto \sqrt{a}$$

Mostly more massive than Jupiter

(From P. Armitage)

Metallicity distribution of host stars

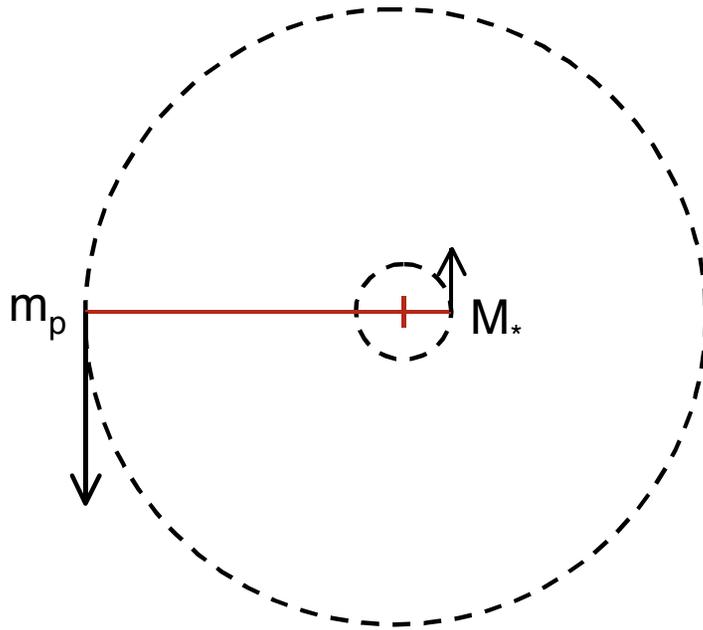


Consistent with theoretical ideas about massive planet formation:

- Higher fraction of heavy elements in the disk
- More planetesimals
- Faster planet formation / more likely to have planets

(From P. Armitage)

Astrometry



Conceptually identical to radial velocity method - look for motion of star *in the plane of the sky* due to orbiting planet. Star moves in a circle radius a_* , where:

$$a_* M_* = a m_p$$

(definition of center of mass)

Angular size of the circle on the sky: $\theta = \frac{a_*}{d}$

$$\theta = \frac{m_p}{M_*} \frac{a}{d}$$

Units: if the star-planet separation a is in astronomical units, and d is in parsecs, then angle θ is in arcseconds

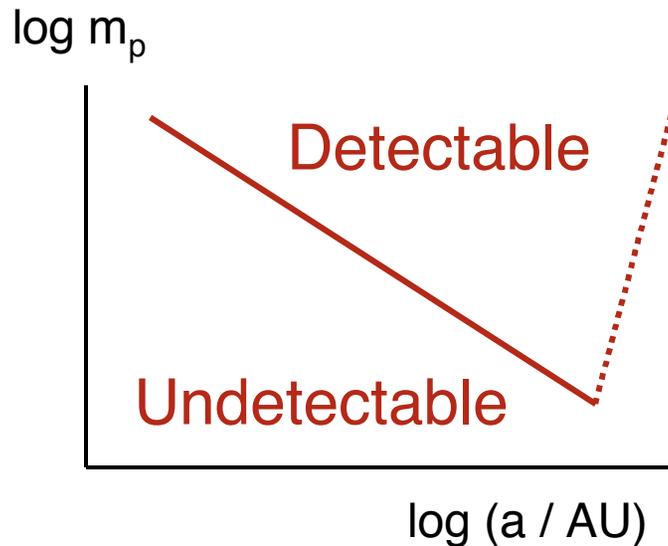
(From P. Armitage)

e.g. for Jupiter mass planets:

$$\theta \approx 0.5 \left(\frac{m_p}{m_{\text{Jupiter}}} \right) \left(\frac{a}{5 \text{ au}} \right) \left(\frac{d}{10 \text{ pc}} \right)^{-1} \text{ mas} \longleftarrow \text{units, milli-arcseconds}$$

Not achieved yet, but promising as fundamental limits do not preclude detection of even Earth-mass planets.

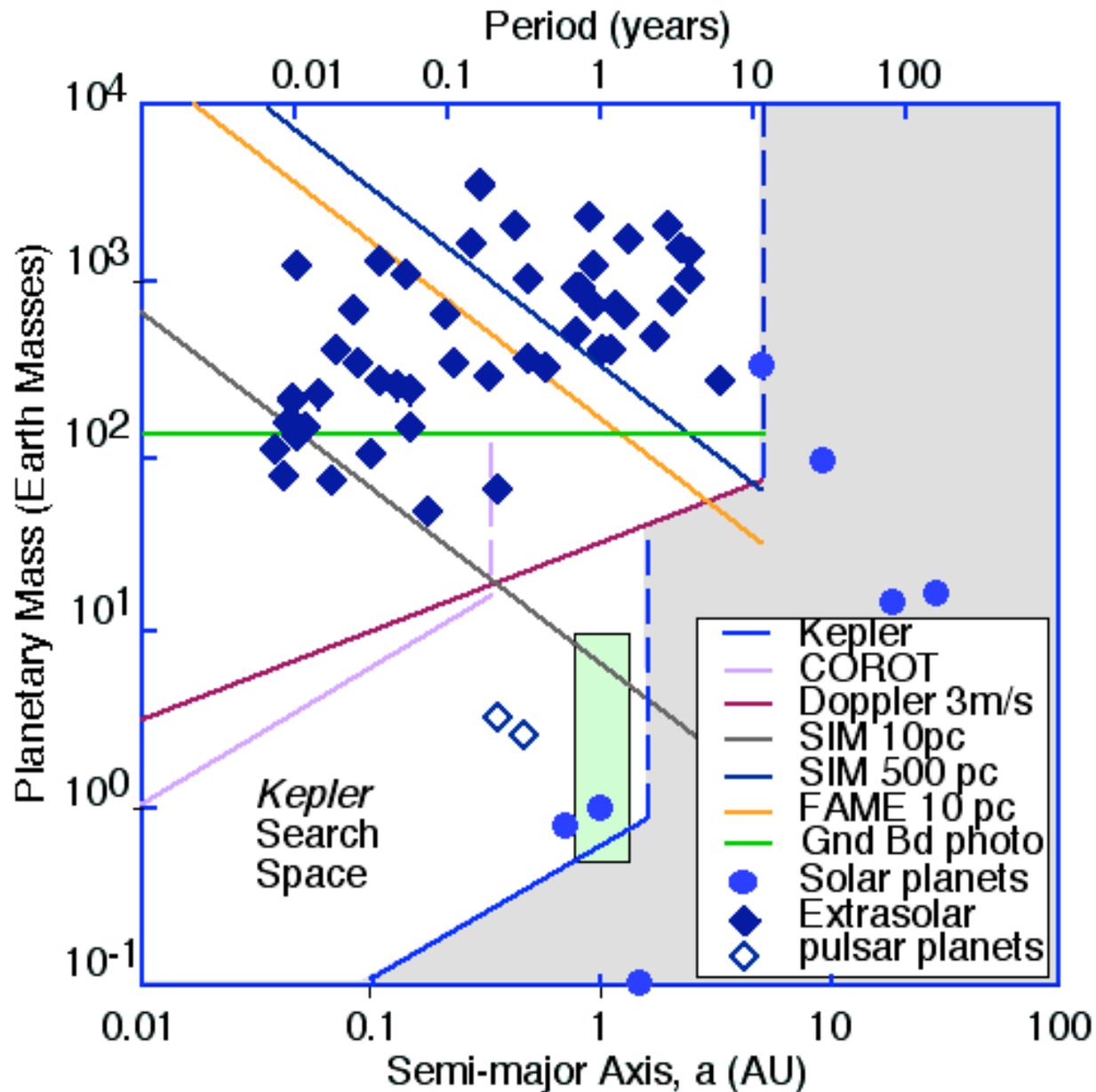
Sensitivity is complementary to radial velocity searches:



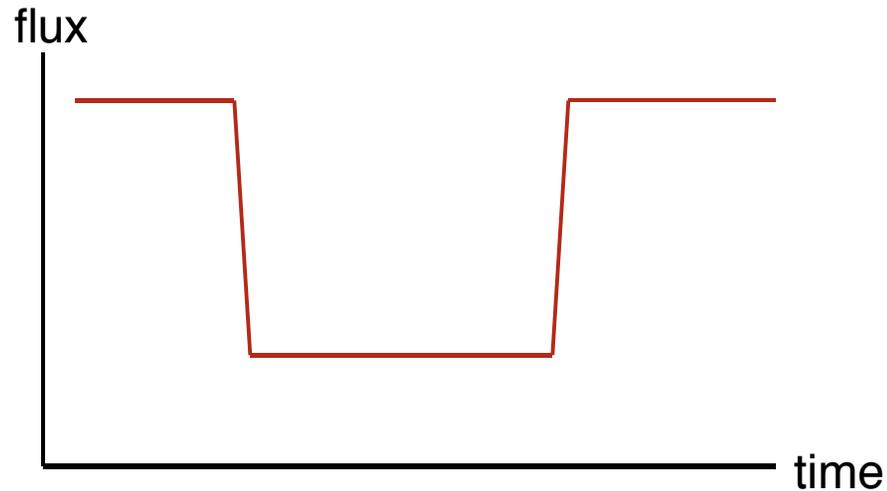
Easiest to find massive planets at large orbital radius, as long as the period isn't much longer than the duration of the search

(From P. Armitage)

Astrometric Search Parameter Space



Schematic transit lightcurve:



Fraction of starlight absorbed (transit *depth*):

$$f = \left(\frac{R_p}{R_*} \right)^2$$

Giant planets all have very similar radii $\sim 0.1 R_{\text{sun}}$

Signal for Jupiter is $\sim 1\%$ drop in stellar flux during transit

For Earth, radius is $\sim 0.01 R_{\text{sun}}$

Signal for Earth is drop in flux by 1 part in 10^4

Photometry accurate to $\sim 0.1\%$ is possible (very difficult) from the ground, accuracy at 10^{-5} level thought achievable in space.

(From P. Armitage)

Transit photometry

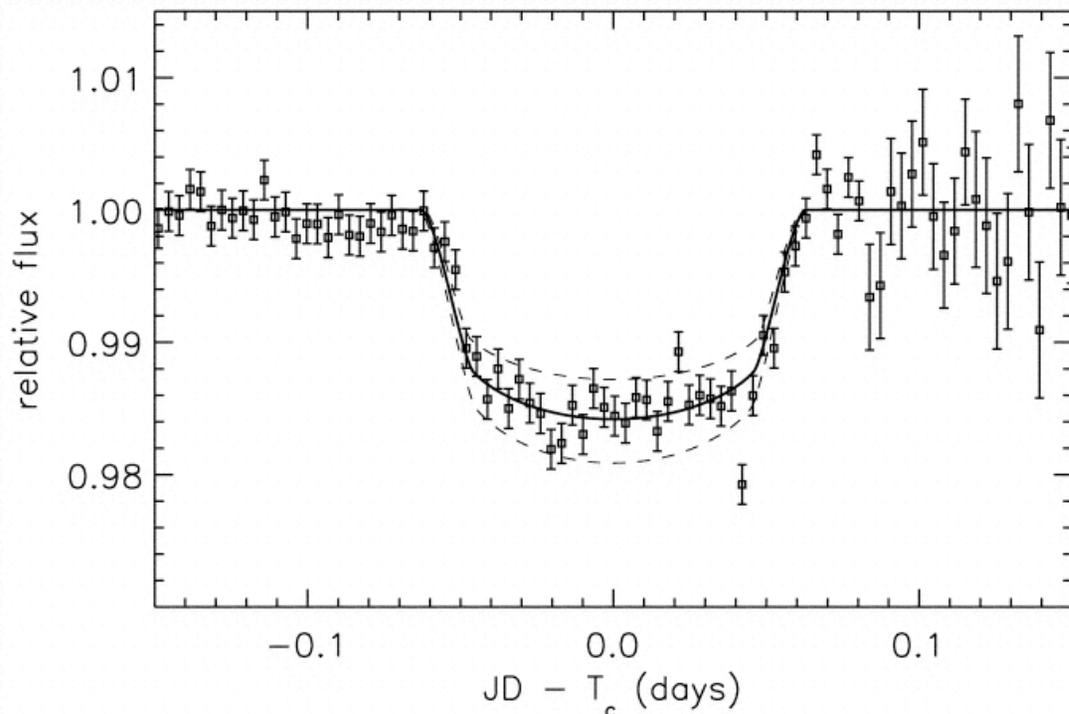
- When planet passes in front of star, luminosity of star decreases by ratio of areas (r_p^2/r_s^2)
 - For Earth-size planet passing in front of Sun-size star, lum'y decreases by 1 part in 10^4
 - This should be detectable by Kepler!
- Smaller orbits --> higher probability of transit and have shorter orbital periods
 - To be sure of terrestrial sized planets, must see at least three transits; four is better

Probability of transits: $P \approx \frac{R_*}{a} \approx \frac{7 \times 10^{10} \text{ cm}}{6 \times 10^{11} \text{ cm}} \sim 10\%$



$a = 0.04 \text{ au}$ for a hot Jupiter

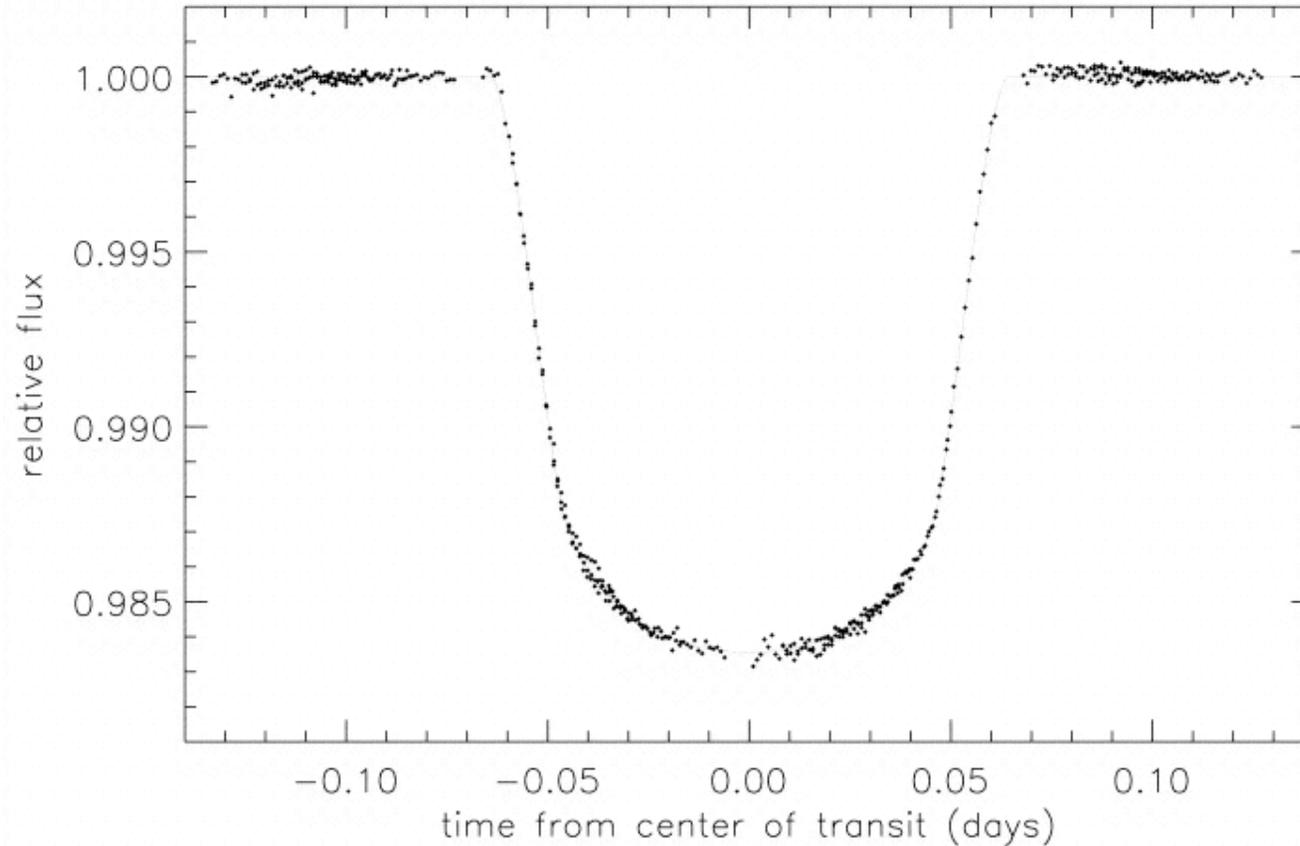
10 - 20 such planets known - approximately one likely to have orbital inclination favorable for detecting a transit...



Observation from the ground

(From P. Armitage)

HST light curve



Determines:

- Planetary radius
- Constrains presence of moons / dense rings
- Atmospheric composition (level of clouds)

(From P. Armitage)

Kepler

NASA has approved a Discovery class mission to search for transits by terrestrial planets:

- monitor 10^5 stars for 4 years
- 0.95 m telescope
- designed for a photometric precision of 10^{-5}
- planned launch in Fall 2007

Built by Ball aerospace

If all stars (in some mass range) have on average 2 planets with $R = R_{\text{earth}}$ orbiting between 0.5 au and 1.5 au, ~50 will be detected. Likely to provide first clue as to how common habitable planets are.

Possible that gravitational lensing (even less direct method, discussed next semester) will find Earth-mass planets first.

(From P. Armitage)

Properties of extrasolar planets

Two aspects of the orbital properties of extrasolar planets differ from those of Solar System planets and are unexpected based on simple theory of planet formation:

Existence of hot Jupiters

Expected giant planets to form outside the snow line where there was a larger density of rock / ice to allow rapid planet formation.

Frequently non-circular orbits

Expected close to circular orbits since planets form out of disks that have circular orbits.

(From P. Armitage)

Migration

Most popular explanation for the existence of hot Jupiters is **orbital migration**:

- Giant planets **form** at large radii within the protoplanetary disk (several au)
- Lose energy and angular momentum
- **Migrate** to present orbits closer to the star

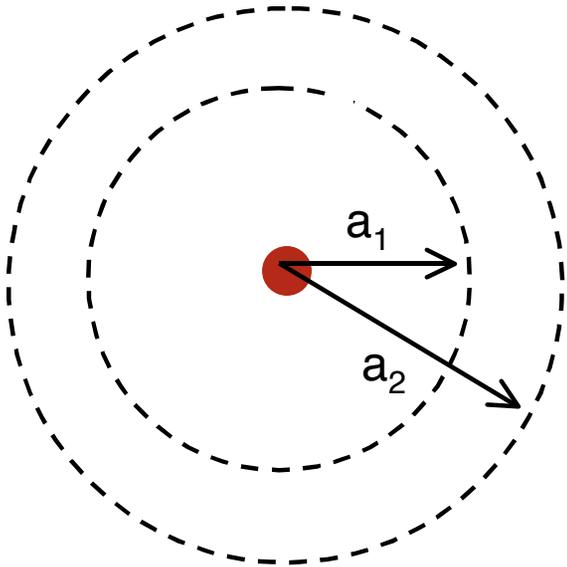
Suggested mechanisms for orbital migration:

Gravitational scattering of other planets or planetesimals in an initially unstable planetary system

Gravitational interactions of a single planet with the protoplanetary disk soon after planet formation

(From P. Armitage)

How might gravitational scattering work in practice



Form two or more planets in orbits that are too close to be stable over long time scales.

How close is too close? Define quantity Δ :

$$\Delta = 2.4 \left(\frac{m_1}{M_*} + \frac{m_2}{M_*} \right)^{1/3}$$

If: $a_2 > a_1(1 + \Delta)$...the system will be stable

Otherwise, the system will often be unstable. Note: for two Jupiter mass planets $\Delta = 0.3$, so planets have to be close together for instability.

No known results for 3 or more planets...

(From P. Armitage)

When instability occurs:

- Planets evolve until orbits cross
- Close encounters lead to:
 - (i) Migration of some planets to larger radii, or ejection from whole system
 - (ii) Survivors move to closer orbits to conserve energy and angular momentum
 - (iii) Develop significantly eccentric orbits

As a consequence of the interactions, system becomes more stable, eventually reaches a state that can survive for Gyr until observed epoch...

(From P. Armitage)

Planet - disk interactions

Planet embedded within the protoplanetary disk exerts a gravitational force on the gas: forms a spiral wave pattern in the gas

Interaction with gas inside location of planet:

- angular momentum is transferred to planet
- gas is decelerated - tends to `fall' to smaller radii

Interaction with gas outside orbit of planet:

- planet loses angular momentum
- gas gains angular momentum, moves to larger radii

(From P. Armitage)

How does this lead to orbital migration?

For a massive enough planet, interaction is strong enough to open a **gap** in the protoplanetary disk.

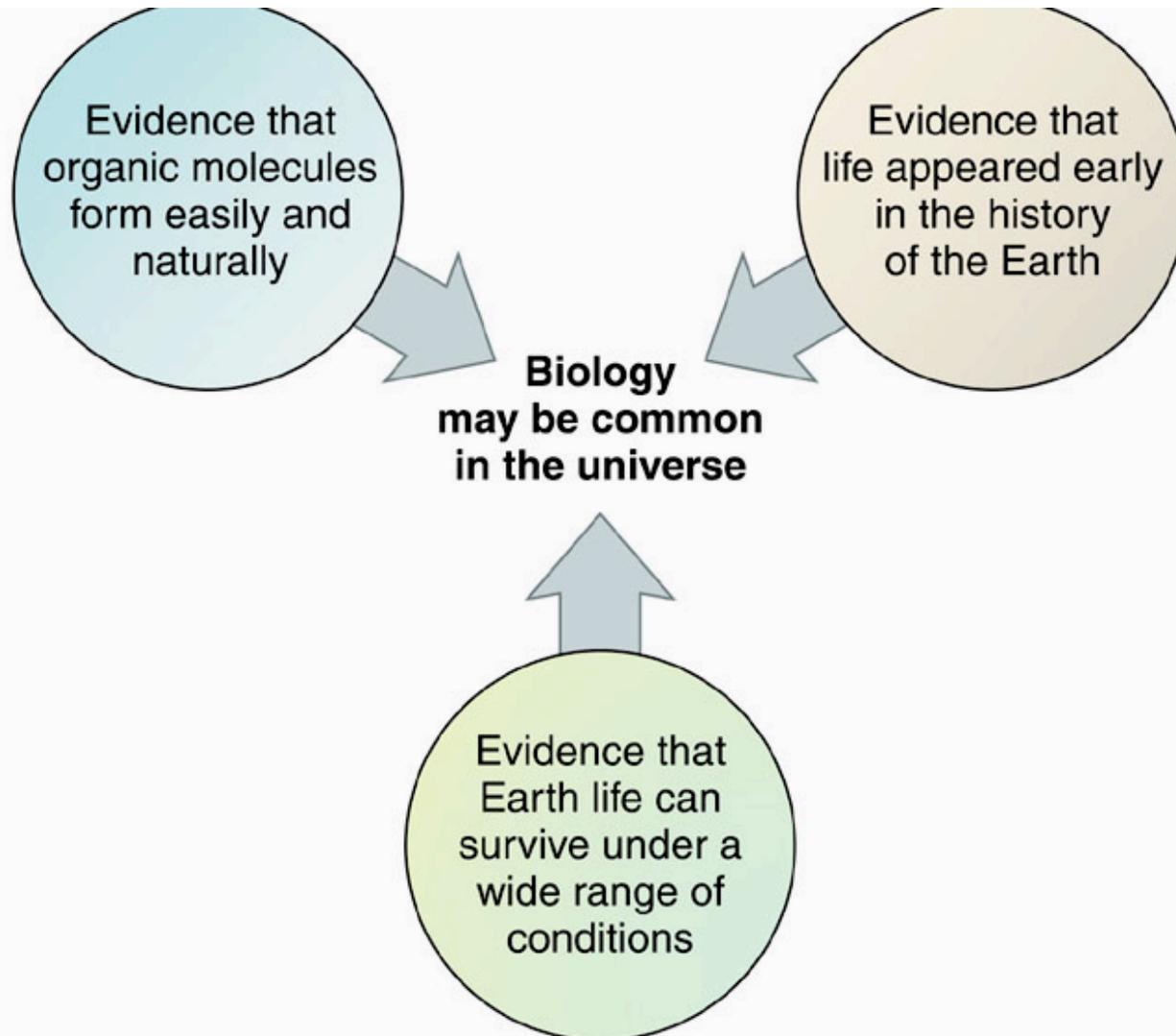
Once gap has been formed, planet acts as a dam in the disk, gas can only flow inward onto the star by first pushing the planet to smaller orbital radii.

Gravitational forces transfer the planet's angular momentum to the disk material at larger radii.

Ultimately, planet may end up being swallowed by the star, or may stop migrating when the disk is dispersed and survive at very small orbital radius as a hot Jupiter.

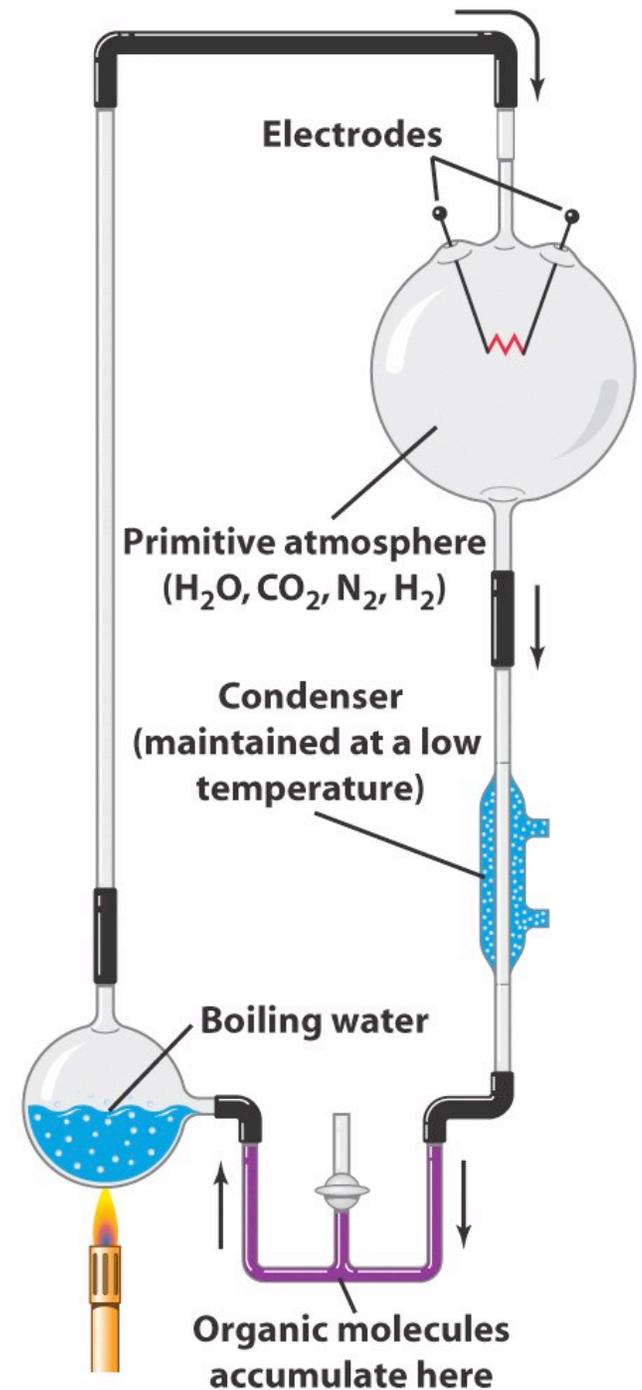
(From P. Armitage)

Astrobiology (or Bioastronomy): Life in the Universe (and other strange places?)



- Organic molecules are common in the ISM (life in interstellar clouds?)
- Another likely source for organic molecules is chemical reactions in the Earth's primitive atmosphere
- Similar processes may occur on other worlds

Miller-Urey-type experiment



Life in Extreme Environments

(On the Earth and
elsewhere)

We have to watch for
our anthropocentric,
earth-centric, carbon-
centric, water-centric,
... prejudices

Life in the Solar System

The best candidates:

- **Mars:** probably dead now, but maybe not; good evidence for a wet Mars in the past
- Jovian and Saturnian moons, in particular **Europa** (ocean!) and **Titan**, possibly others
- Elsewhere?
- What is needed:
 - Heat: solar, tidal
 - Water(?), organics
 - Radiation (mutations)

Evidence for Water on Ancient Mars



Viking Lander (1976)

- We have searched for life on Mars.
- Viking scooped up soil and ran tests
 - looked for products of respiration or metabolism of living organisms
 - results were positive, **but** could have been caused by chemical reactions
 - no organic molecules were found
 - results inconsistent with life
- This is not the final word.
 - Viking only sampled soil on surface
 - took readings at only two locations
 - life could be elsewhere or underground

**Both of the NASA rovers that reached Mars
in 2004 landed at locations that may once
have been covered in water**

- The unsuccessful *Beagle 2* mission to Mars was to carry out a different set of biological experiments on samples taken from the interiors of rocks
- These experiments may be attempted again on a future mission

Meteorites from Mars have been scrutinized for life-forms



- An ancient Martian rock that came to Earth as a meteorite shows circumstantial evidence that microorganisms once existed on Mars
- Subsequent studies indicate possible contamination by terrestrial bacteria
- It could be also inorganic forms
- Inconclusive!

Possible Life on Jovian Moons

- Beneath its icy surface, Europa may have an ocean of liquid water.
 - Tidal heating keeps it warm
 - Possibly with volcanic vents on the ocean floor
 - Conditions may be similar to how Earth life arose
 - Could be more than just microbial life?
- Ganymede & Callisto may also have subsurface oceans, but tidal heating is weaker.
- Sulphuric life on Io?

Possible Life on Saturnian Moons

- Titan has a thick atmosphere of organic haze, produced by the effect of sunlight on methane: chemistry similar to the pre-life Earth?
- It may have oceans of methane and ethane
 - water is frozen
 - perhaps life can exist in liquids other than water
- Pockets of liquid water may exist deep underground

Questions to address in the search for life outside the Solar System

- What makes a planet habitable and how can that be studied remotely?
- What are the diverse effects of biota on spectra of planetary atmospheres?
- What false positives might be expected?
- What are likely evolutionary histories of atmospheres?
- Especially...what are robust indicators of life?

What Makes the Earth Habitable?

- Provides an environment with:
 - Reliable source of useable energy
 - Sun--no substantial short term variability
 - Release of internal heat--e.g. vents on ocean floor
 - Liquid water
 - Abundant and relatively benign solvent in which biochemical reactions can take place
 - Transport mechanism for nutrients in/waste out
 - Liquid over a range of T suited to organic chemistry...273K - 647 K (0 - 374 C)

What Makes the Earth Habitable?

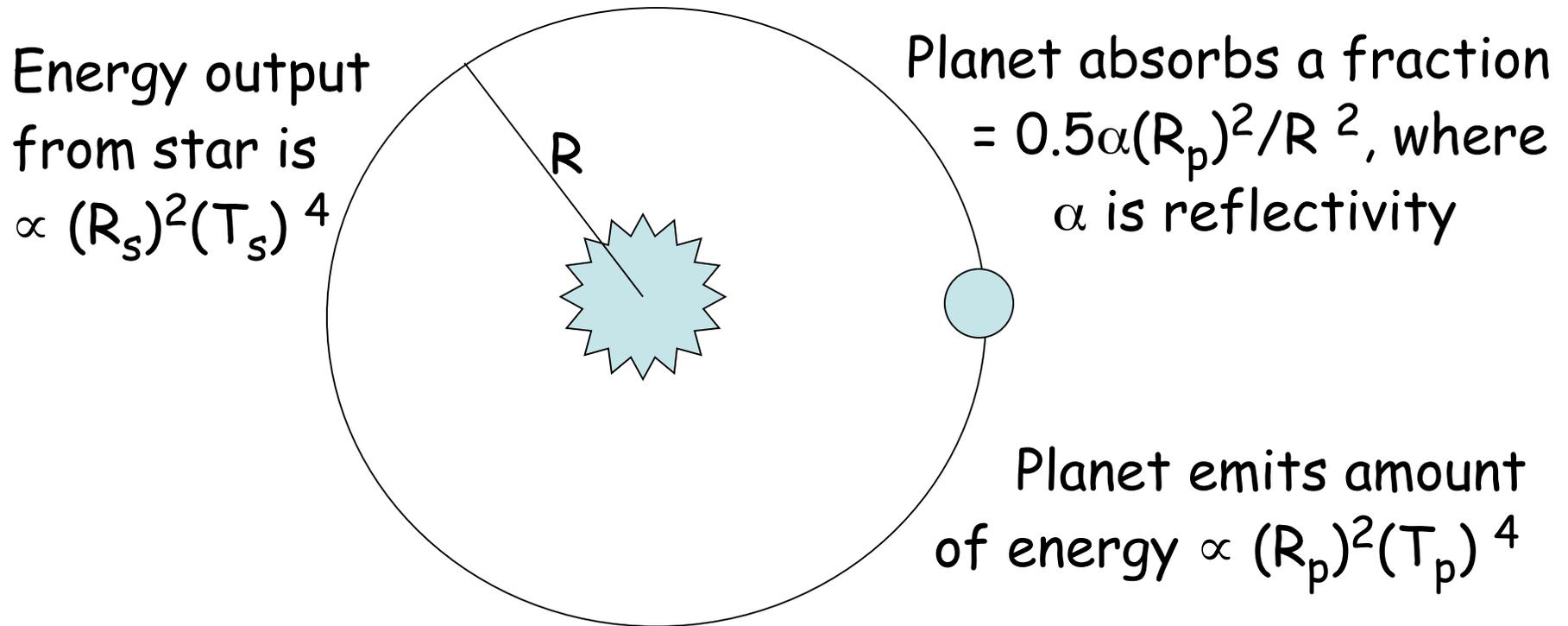
- Suitable abundance of ‘free’ Carbon
 - Fundamental to life as we know it
 - Greatest tendency to form bewildering variety of stable and complex molecules...chains, sheets, rings
 - Abundant--4th in Solar System (after H, He, O)
 - Availability depends critically on geologic activity
- Protection from outside hostile influences
 - Cosmic rays...by magnetic field
 - Ultraviolet...by Ozone layer (more recent)
 - Impacts...by Jupiter (but not all!)
- Provides for reasonably long term stability
 - Earth’s tilt (precession/nutation) moderated by damping effects of Lunar tides

What should we look for?

- Solid surface --> Planets
- Liquid water can exist
- Conducive to carbon chemistry
- Star: stability, lifetime, temperature, luminosity
- Planet size

Note that each and every one of these reflects our own existential biases!

Conditions for Liquid Surface Water



Effective temperature of a planet found by balancing energy absorbed from its star with the energy radiated by the planet. This temp not necessarily = temp of surface!

Conditions for Liquid Surface Water

So $T_p \approx (R_s/R)^{1/2} \alpha^{1/4} T_s$ [plus modifications due to greenhouse effect]

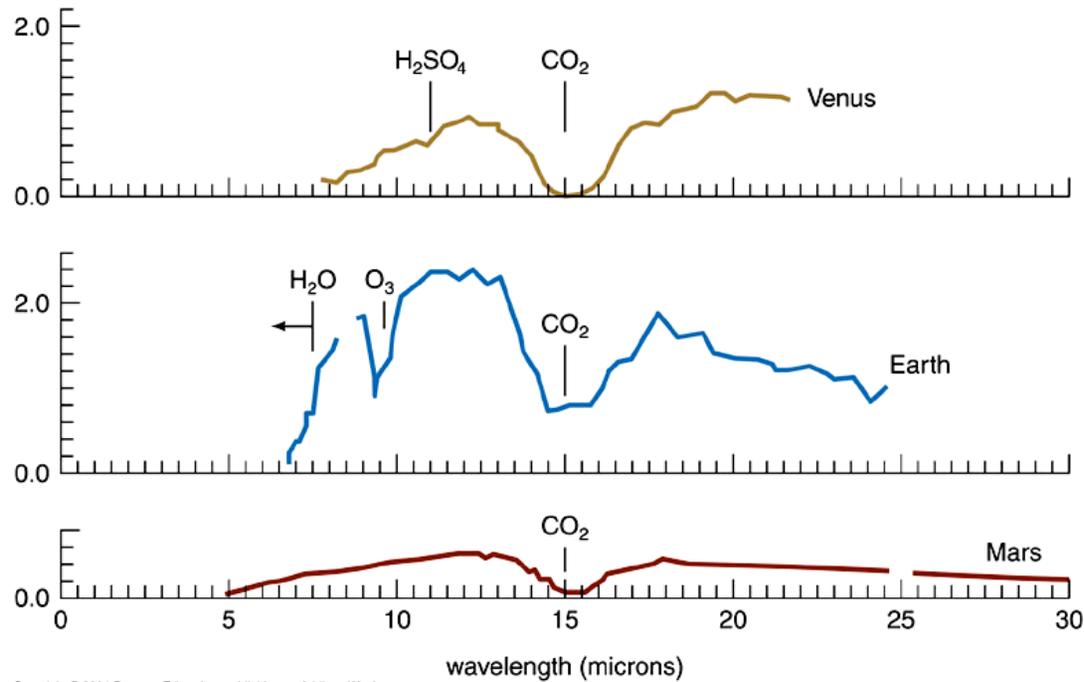
For liquid water to be present on the surface, we need $270 < T_p < 400$. And this defines the 'habitable zone' around a star.

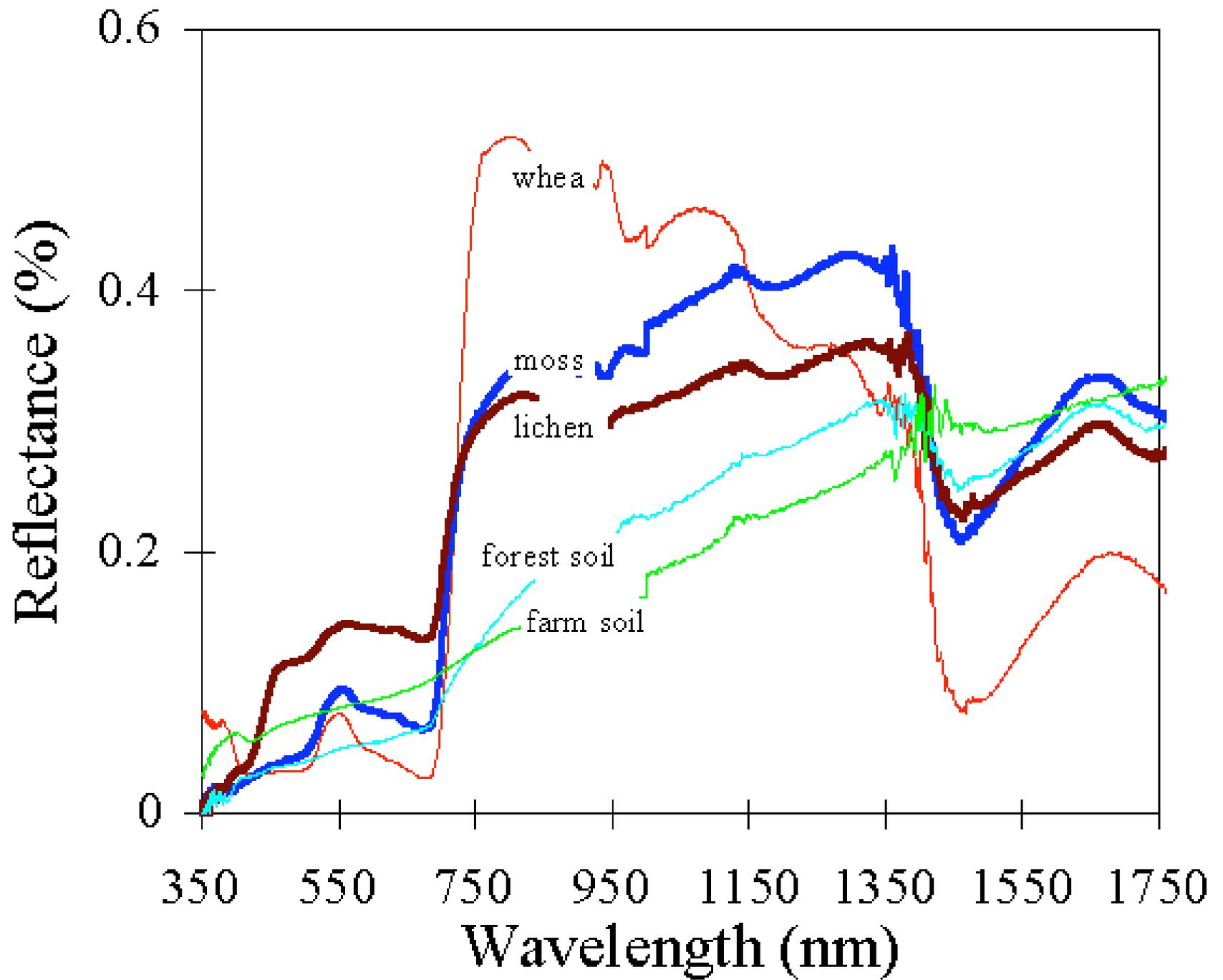
For Earth we have $(R_s/R) \approx 100$, $\alpha \approx 0.4$, and $T_s \approx 5800\text{K}$, so that $T_p \approx 300\text{K}$. (Actually, the effective Temp is about 260K give or take. Difference has to do with day-night effect and other details.)

Biosignature: A Working Definition

- A feature (e.g. spectroscopic) whose presence or abundance indicates a biological origin.
 - Created during acquisition of energy or chemical ingredients for biosynthesis (e.g. O_2 , CH_4)
 - Products of biosynthesis of information-rich molecules (e.g. complex organics)
 - Chemical disequilibria that cannot be explained by abiotic processes (e.g. O_2 on geologically active planet that puts out reduced* gases)
 - Or...an electromagnetic signal generated by an advanced (and alien) technology (SETI)
- * “Reduced” means likes to join up with O_2

Possible Spectroscopic Signatures of Earth-Like Life



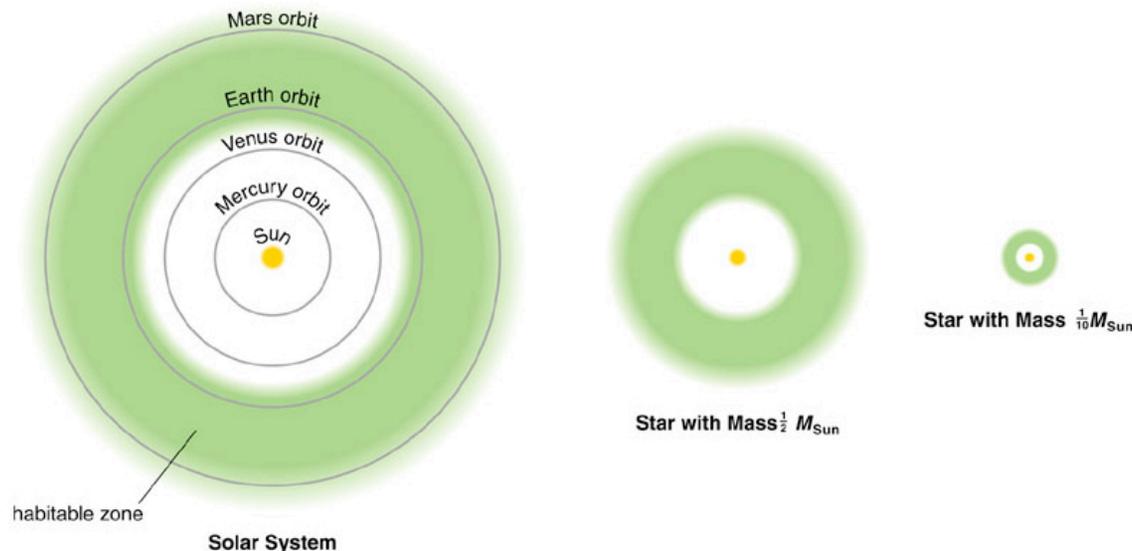


Stellar Types Suitable for Life

- Main sequence stars
 - Luminosity relatively stable for longest time
- Not too massive
 - Lifetime depends on $(1/M^{3.5})$
 - UV flux is much higher for higher mass stars
- Not too small
 - Stellar flares
 - Tidal locking --> atmospheric condensation
- So, less massive than A stars, more massive than M stars: F, G and K stars are primary targets

Which Stars make Good Suns?

- Which stars are most likely to have planets harboring life?
 - they must be old enough so that life could arise in a few $\times 10^8$ years
 - this rules out the massive O & B main sequence stars
 - they must allow for stable planetary orbits
 - this rules out binary and multiple star systems
 - they must have relatively large **habitable zones**
 - region where large terrestrial planets could have surface temperature that allow water to exist as a liquid



Earth-like Planets: Rare or Common?

- Most scientists expect Earth-like planets to be common.
 - billions of stars in our Galaxy have at least medium-size habitable zones
 - theory of planet formation indicates terrestrial planets form easily in them
- Some scientists have proposed a “rare Earth hypothesis.”
- Life on Earth resulted from a series of lucky coincidences:
 - terrestrial planets may only form around stars with high abundances of heavy elements
 - the presence of Jupiter deflects comets and asteroids from impacting Earth
 - yet Jupiter did not migrate in towards the Sun
 - Earth has plate tectonics which allows the CO₂ cycle to stabilize climate
 - our Moon, result of a chance impact, keeps tilt of Earth’s axis stable
- There is debate about how unique these “coincidences” truly are.
 - we will not know the answer until we have more data on other planets in the Galaxy

**The Search for
Extraterrestrial
Intelligence
(SETI)
... or Artifacts
(SETA)
... or ... ?**

History of SETI

- 1959: Cocconi & Morrison—using μ -waves for interstellar comm.
- 1960: Frank Drake, Project Ozma
 - 2 stars/at 1420 MHz
- 1960's: dominated by Russians
- Early 70's: NASA Ames + Barney Oliver
 - Project Cyclops
 - Plus independent observing programs...
Planetary Society/META; UC/SERENDIP;
Ohio State, etc. etc.

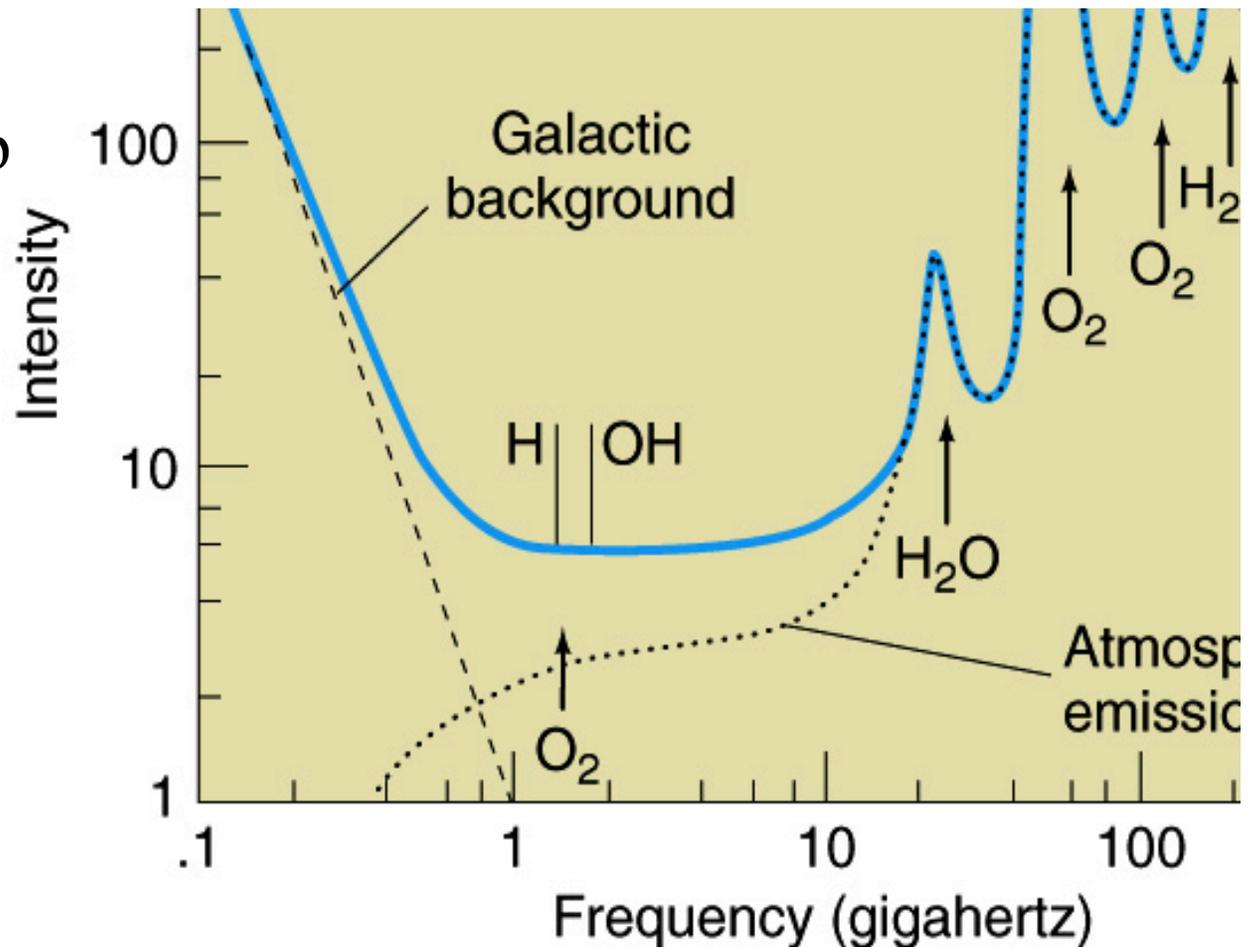
SETI in Radio

Where would we search for a signal (at what wavelength)?

The water hole:

between the spin-flip line of H I at 21 cm, and the OH line at 19 cm.

A pure earthcentric bias?



History...continued

- Late 70's --> late 80's: Ames & JPL
 - Complementary approaches
 - Ames: Targeted search - JPL: All sky survey
- 1988: NASA adopts strategy and begins development
- 1992: Congress terminates
- Private funding sought, obtained for Project Phoenix
 - Targeted search using existing large radio telescopes

Project Phoenix

- **Targets about 1000 stars**
 - **Nearest 100: all systems out to 25 lt yrs**
 - **Best and Brightest: 140 out to 65 lt yrs**
 - **Very close to Solar type stars**
 - **About 1/2 are old and single**
 - **G Dwarf Sample: 650 out to 200 lt yrs**
 - **Pretty close to Solar type stars**
 - **About 1/2 are old and single**
- **Looking in: $1000 < f < 3000$ MHz**
 - **1 Hz resolution --> ~ 2 Billion channels/star**

One Way It's Done: SETI@home
(you can help find the aliens!)

The Drake Equation

$$N = R_* f_p n_e f_l f_i f_c L, \quad \text{where}$$

- N = # civilizations in MW with e/m
- = R_* Rate of formation of suitable stars
- = f_p fraction with planets
- = # of solar systems that are habitable
- = f_l fraction of these on which life arises
- = f_i fraction on which intelligent life arises
- = f_c fraction that develop tech'y for e/m
- L = length of time that they do this

How Many Civilizations Exist in the Galaxy with Whom We could make Contact?

- We can not calculate the actual number since the values of the terms are unknown.
- The term we can best estimate is N_{HP}
 - including single stars whose mass $<$ few M_{\odot} AND...
 - assuming 1 habitable planet per star, $N_{\text{HP}} \approx 100$ billion
 - unless the “rare Earth” ideas are true
- Life arose rapidly on Earth, but it is our only example.
 - f_{life} could be close to 1 or close to 0
- Life flourished on Earth for 4 billion yrs before civilization arose.
 - value of f_{civ} depends on whether this was typical, fast, or slow
- We have been capable of interstellar communication for 50 years out of the 10 billion-year age of the Galaxy.
 - f_{now} depends on whether civilizations survive longer than this or not

Another Way: Send Them a Postcard?

Pioneer plaque

Voyager plaque

... Or a Record?

(Do *you* have a way of playing old LP's?)

But the flip side is: should we be looking for extraterrestrial artifacts in the Solar System? Where? What? How?

The Fermi Paradox: Where are They?

- With our current technology it is plausible that...
 - Within a few centuries, we could colonize the nearby stars
 - Within a few million years, we could have outposts throughout the Galaxy
- If, like us, most civilizations take 5 Gyr to arise...
 - The Galaxy is 12 Gyr old, 5 Gyr older than Earth
 - If there are other civilizations, the first could have arisen as early as 5 - 7 Gyr ago
 - There should be many civilizations which are millions or billions of years ahead of us
 - They have had plenty of time to colonize the Galaxy
- So...where is everybody? Why haven't they visited us?
 - This is **Fermi's paradox**, who first asked the question in 1950

Possible Solutions to Fermi's Paradox

- We are alone.
 - civilizations are extremely rare and we are the first one to arise
 - then we are unique, the first part of the Universe to attain self-awareness
- Civilizations are common, but no one has colonized the Galaxy.
 - perhaps interstellar travel is even harder or costlier than we imagine
 - perhaps most civilizations have no desire to travel or colonize
 - perhaps most civilizations have destroyed themselves before they could
 - we will never explore the stars, because it is impossible or we will destroy ourselves
- There *is* a Galactic civilization.
 - it has deliberately concealed itself from us
 - we are the Galaxy's rookies, who may be on the verge of a great adventure
- We may know which solution is correct within the near future!!