

# Lecture 4 : Planets

## SUMMARY

We consider the different type of **planets** in the Solar System - telluric planets, gas giants and ice giants- and how they formed.

We then turn to **extra-solar planets** and how their study has transformed our understanding of planet formation and evolution.

We encounter **hot jupiters**, **super-Earths** and **ocean planets**.

We mention **habitability** and the search for extraterrestrial life.

## The old Solar system

The first extra-solar planet (i.e. planet orbiting a star other than the Sun) was discovered in 1995. The discovery and study of extra-solar planets (“exoplanets”) have profoundly transformed our understanding of our own planetary system. Prior to 1995, planetary systems were expected to share the overall architecture of the Solar System. Most of the features discovered in the properties of exoplanets were completely unexpected from the single example of the Solar System.

Planets form from the accumulation of solids in the disc of gas and dust surrounding a nascent star. Such discs are called *protoplanetary discs*. Particles of solid stick together into increasingly larger blocks, until planetary sizes are reached. What compounds will be able to coalesce into planets will depend on the temperature of the disc, which is mainly a function of the distance to the central star.

To estimate the temperature of the protoplanetary disc as a function of distance to the star, we consider *equilibrium temperature*, the temperature that a perfectly absorbing sphere orbiting at a distance  $a$  from the star would have at thermal equilibrium. Applying Stefan’s Law, the flux received by the absorber at the distance  $a$  will be:

$$area \cdot flux = \pi R^2 \cdot \sigma T_{star}^4 (R_{star}/a)^2$$

## Kepler’s Laws

The three laws of Kepler describe the orbits of planets around their host star.

*First law:* planetary orbits are *ellipses*, with the star at one focus.

*Second law:* the velocity of the planet is such that the planet-star line spans an *equal area* in an equal amount of time.

*Third law:* the square of the period ( $p$ ) is proportional to the cube of the orbital distance ( $a$ ) and to the mass of the star ( $M$ ). I.e.

$$p^2 = M a^3$$

where  $R_{star}$  and  $T_{star}$  are the radius and temperature of the star, and  $R$  the radius of the orbiting body. The flux re-emitted by the body is

$$4\pi R^2 \sigma T_{eq}^4$$

where  $T_{eq}$  is the equilibrium temperature.

This yields:

$$T_{eq}(a) = 2^{-1/2} T_{star} (R_{star} / a)^{1/2}$$

At the distance of the Earth, for instance, applying this relation gives a temperature of 279K (6° C). This is a fair approximation of the mean temperature of the Earth itself<sup>1</sup>.

The most abundant atoms in interstellar gas are hydrogen and helium, then carbon, oxygen and nitrogen, followed by various heavier elements, mainly metals. Planets form from the accumulation of solids. The composition of planet-forming aggregates (“planetesimals”) will strongly depend of the equilibrium temperature: in the colder part of the disc, the temperature will be low enough for water (H<sub>2</sub>O), methane (CH<sub>4</sub>) and ammonium (NH<sub>3</sub>) to condensate, and they will dominate the composition of planetesimals. At higher temperatures, only rocks and metallic compounds will condensate (the condensation temperature of rocks and metals in space is generally in the 1000-2000 K range).

This leads to the definition of an important locus in the protoplanetary disc: the **snow line**. It is the distance in the disc where the temperature gets low enough for water, methane and ammonia to condensate.

Therefore, inside the snow line, we expect

### The Sun’s planetary system

Our familiarity with the Solar System may obscure its global characteristics to us. Let us describe it as we would any other planetary system:

the Solar system is dominated by two **gas giant** planets, orbiting beyond the snow line at 5 AU and 9 AU.

It features two **ice giants** farther out, and four **telluric planets** within the snow line, and a ring of rubbles immediately inwards of the largest gas giant (the asteroid belt).

The planets have a large number of ice or rocks satellites.

Outside of the planet zone orbit numerous smaller ice bodies (the Trans-Neptunian objects, including Pluto), then a huge number of comets (the Kuiper belt and the Oort Cloud).

<sup>1</sup> the actual equilibrium temperature of the Earth is a bit lower because the Earth is not a perfect absorber (about a third of the incoming sunlight is reflected back towards space, mainly by clouds). The present mean temperature of the Earth is a bit higher than the equilibrium temperature because of the greenhouse effect.

planets made of rocks and metals, and outside the snow line, planets with a large fraction of frozen water, methane and ammonia.

Because these molecules are much more abundant in the disc than rocks and metals, much bigger planets can form beyond the snow line.

In the Solar System, the snow line is situated between Mars and Jupiter. The sublimation temperature of water in a vacuum is  $\sim 200\text{K}$ , which corresponds to  $a=2.6\text{ AU}$  using the expression above for equilibrium temperature.

Jupiter, Saturn, Uranus and Neptune are much bigger than the inner planets. Their moons are composed mostly of frozen water, methane and ammonium (“ices”).

Another threshold is reached when a planet becomes large enough that it is able to retain gaseous hydrogen and helium. These gases are light enough to escape from the Earth’s atmosphere for instance. A solid planet needs to be 10-15 Earth masses to retain hydrogen and helium. Since these two gases constitute the majority of the protoplanetary disc, planets above this threshold can grow to much larger masses. Jupiter, Saturn, Uranus and Neptune have large H/He envelopes. Jupiter ( $317 M_{\oplus}$ ) and Saturn ( $95 M_{\oplus}$ ) have vastly more H/He than heavier elements (“gas giants”), while in Uranus ( $14 M_{\oplus}$ ) and Neptune ( $17 M_{\oplus}$ ) the most abundant component is ice (“ice giants”). All four of the giant planets contain 10-15  $M_{\oplus}$  of elements heavier than helium, which is strong evidence for the standard formation model.

Altogether, the three type of planets found in the Solar System are accounted for by this scenario:

$\ll 15 M_{\text{Earth}}$  rock/metal planets within the snow line. **Telluric planets**

$\gg 15 M_{\text{Earth}}$  hydrogen/helium planets outside the snow line. **Gas giants**

$\leq 15 M_{\text{Earth}}$  ice planets outside the snow line. **Ice giants**

### The status of Pluto

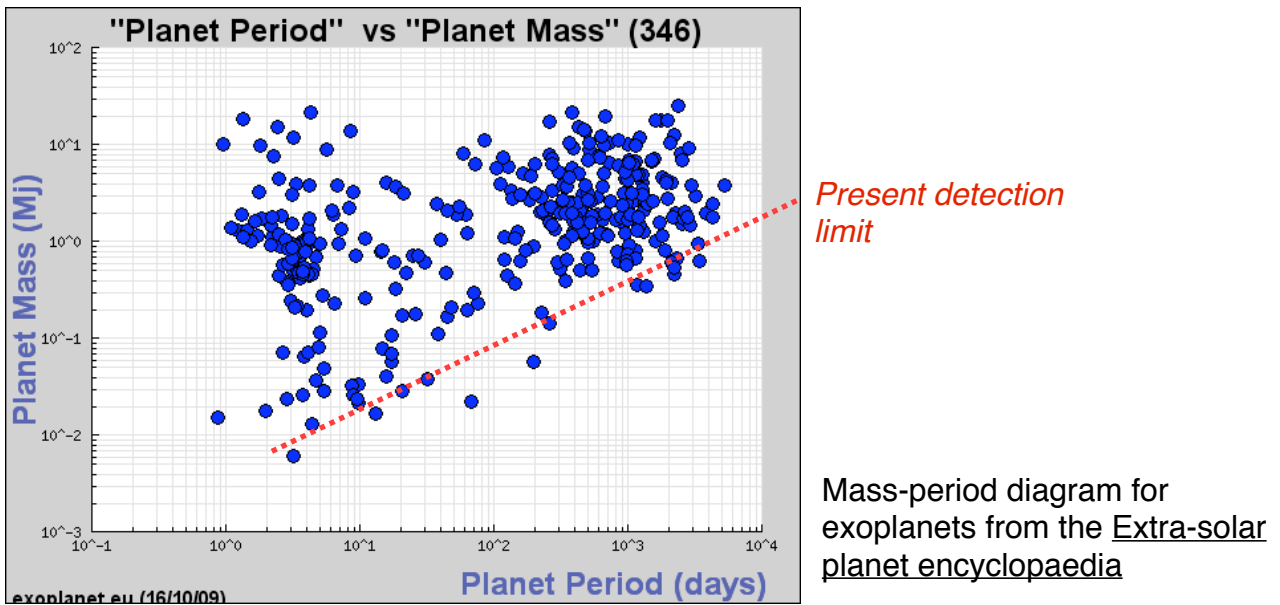
In 2006, at a widely publicised meeting of the International Astronomical Union, the definition of “planet” was revised. After a heated debate, it was decided that Pluto would no longer be considered a planet. As a result, there are now eight planets in the Solar System instead of nine.

The main cause of this revision was the discovery in the past decade of several “Pluto’s extended family”, bodies of comparable size on eccentric orbits beyond Neptune. It seemed unavoidable either that these bodies would be admitted into the circle of bona fide planets, or that Pluto would join them as another kind of object (the third solution was to consider the definition of planets a “cultural” item, and freeze the list at nine). The second solution was chosen: the new category of “dwarf planets” was created for Pluto-like objects.

The new definition reflects our changing view of the Solar System. The eight planets are on stable orbits, and have cleared their surrounding “rubble” or captured them as satellites. These are the kind of planets that we would detect around other stars. Beyond the planets lies a huge number of smaller bodies on eccentric and perturbed orbits, dwarf planets and comets, that have no individual influence on the dynamics of the system. Most of these objects stay on the outskirts of the Solar System, while a few, like Pluto and the Halley Comet, occasionally venture inside the zone of the “real” planets.

## Extra-solar planets

Hundreds of exoplanets have now been discovered. The figure below shows how their masses and periods are distributed (remember that through Kepler's third law, the period is directly related to the orbital distance),



Two features of extra-solar planets have shaken previous ideas about planetary systems:

1- the abundant presence of planets on **very close orbits** ( $P < 10$  days). Many planets are found at 0.1 AU from the star or nearer, much closer than Mercury is to the Sun.

2- the clear dominance of **eccentric orbits** over circular orbits. Circular orbits are rare among exoplanets, and systems as orderly as the Solar System seem very uncommon.

Two mechanisms could explain the presence of close-in exoplanets. The first is **planet migration**. During its formation process, a growing planet induces tidal waves in the protoplanetary disc, and these can interact with the planet to make it spiral inwards towards the star. The second is **planet-planet scattering**. If planet formation is very efficient, a planetary system can end up

**The Doppler method**

Most extra-solar planets are detected with the *radial velocity method*, or Doppler method. The planet is not detected directly, but the reflex motion of the star is measured via slight changes in the wavelength of the atomic lines in its spectrum, due to the Doppler effect. If the planet moves along its orbit with a velocity  $V_p$ , the star will move in the opposite direction with a velocity  $V_s = M_p/M_s V_p$ . The radial component of this motion causes a small but detectable Doppler shift in the wavelengths of the star's light.

after the planet formation stage with too many planets to be stable over the longer term. Planets interact catastrophically, and can fling each other towards the star and on wider orbits by exchanging angular momentum.

Why couldn't gas giant planets form at 0.1 AU to their parent stars? First, the condensation of ices is thought to be necessary to reach the critical core mass required to accrete hydrogen. Second, the amount of mass in the central part of the disc is likely to be insufficient to form heavy planets. In the Solar Systems, all planets combined contain about 100 Earth masses of elements heavier than Helium. The widest planetary orbit, that of Neptune, is  $\sim 10$  AU. Assuming a constant density of matter in the protoplanetary disc, this corresponds to  $(0.1/10)^2 100 M_{\oplus} = 0.01 M_{\oplus}$  of heavy elements within 0.1 AU. Even accounting for a higher disc density close to the star, this is clearly not sufficient.

## The planet zoo

Searches for extra-solar planets have added many items to the catalogue of planetary types, in addition to the three types found in the Solar System (gas giants, ice giants, telluric).

The “*hot jupiters*” are close-in gas giants, similar in mass and size to Jupiter, but with equilibrium temperatures exceeding 1000K and periods shorter than 10 days.

There is a class of “super-heavy” gas giants, in the 4-20  $M_{\text{Jup}}$  range, whose status between large planets and small stars is uncertain.

There are planets whose orbit is so *eccentric* that the amount of irradiation received at periastron and apoastron varies by a factor 1000.

*Hot neptunes* are  $\sim 15-25 M_{\oplus}$  planets on close orbits. As in the Solar System, there seems to be a gap between Saturn-mass and Neptune-mass planets.

*super-Earths* are  $5-10 M_{\oplus}$  rock/ice

### Transiting planets

Some exoplanets happen to cross the disc of their star, as seen from Earth. This event is called a *transit*. It can be detected even on a remote star by a small decrement in the total luminosity during a few hours every orbit.

Transiting exoplanets play a key role in the field. Because the dip in luminosity during the transit is proportional to the size of the planet projected on the disc of the star, a transit measures a planet's size. That is how we can distinguish gas giants, ice giants and telluric exoplanets.

Transiting planets also provide another opportunity: the atmospheric spectrum of the planet can be measured as the planet passes behind the star on the other side of the orbit (the “occultation”). That is how astrophysicists have now been able to measure some broad features of the atmospheric spectrum of several extra-solar gas giant planets.

planets, without equivalent in the Solar System.

The sensitivity of planet searches is not sufficient at present to reach the domain of Earth-mass planets<sup>2</sup>.

## Planetary atmospheres

The planets that can be studied in most details with present techniques are the ones closest to their host star. They are gas giant planets, with atmospheric temperatures in the 1000-2500 K range.

Although they are comparable to Jupiter in mass and size, these “hot jupiters” have a very different atmospheric physics. The two key differences with Jupiter are

- (1) the “hot jupiters” are tidally locked to their star (rotation synchronous with the orbit), so that they rotate much more slowly than Jupiter
- (2) they receive more heat from the star than from their interior (for Jupiter the opposite is true) and are much hotter

The result is that the atmospheric dynamics will be dominated by the redistribution of the heat from the day side to the night side. According to present models, powerful jet streams will do this. Heating from above also means that convection will be suppressed, another key difference with Jupiter.

To know whether the jet streams can balance the temperature on the day side and night side, we need to compare the *wind speed* with the *cooling timescale* of the atmosphere. If the latter is longer, the winds can carry the heat from day side to night side and the day-night temperature contrast will be low. Otherwise, the day-night temperature contrast will be high. Some models and observations indicate that there could be two kinds of hot jupiters. The first kind are hot enough to have TiO (titanium oxide) vapours in their upper atmosphere. TiO is a very efficient absorber of visible light and blocks the star light before it can reach the lower atmosphere were the cooling timescale is longer. In those planets, the day-night heat redistribution would be inefficient, and the day-night temperature contrast high. In the second kind of hot jupiters, TiO remains condensed in grains, and the heat redistribution would be efficient, leading to a low day-night contrast.

---

<sup>2</sup> although exoplanets lighter than Earth have been detected around pulsars, using a completely different method. Since pulsars are the remnant of a supernova explosion, these planets are thought to have condensed from the debris of the explosion.

## **Tilted planets**

In the summer of 2009, a series of new measurements have revealed another stunning feature of exoplanets: the orbits of many hot Jupiters is not at all aligned with the rotation of their host stars. They follow very tilted orbits, rather like Pluto and the comets in the Solar System, bodies that are thought to have been scattered by larger planets. Some exoplanets even rotate in the direction opposite to the spin of their parent star.

Tilted orbits are difficult to imagine in a disc+migration scenario. The best explanation seems to be planet-planet scattering. Therefore, even large gas giants may often suffer from catastrophic encounters in planetary systems.

## **The new solar system**

According to the study of extra-solar planets, as well as new discoveries about asteroids, comets and Pluto twins, planetary systems seem much more eventful places than was previously thought. Catastrophic encounters between planets may be the norm rather than the exception.

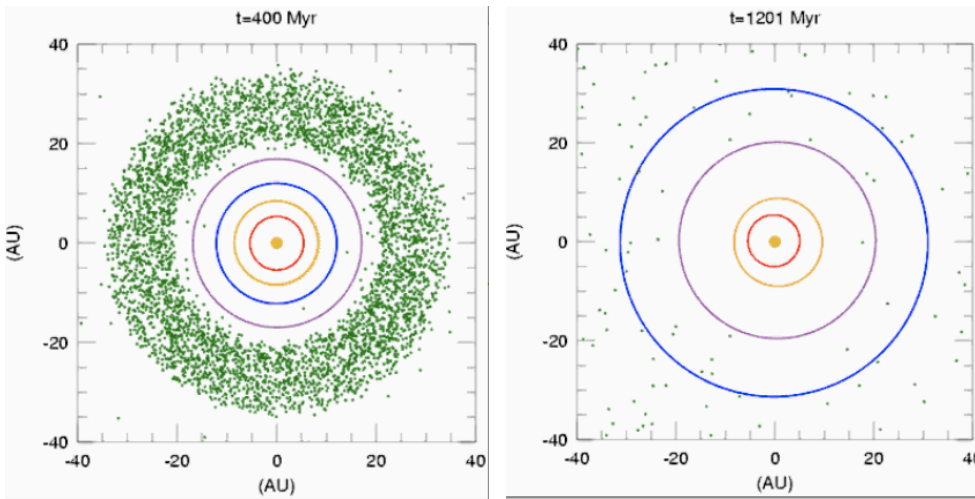
It is likely that the Solar system was formed with planets more closely packed than at present. Jupiter and Saturn were close to their present position, but Neptune and Uranus could have been much closer in, and with their respective positions exchanged.

Late in the formation process, catastrophic collisions were still common. Earth bears clear scars of this: the Moon is thought to have resulted from the impact of a Mars-size planet on the proto-Earth. The large north-south asymmetry of Mars may also be a scar from this period. The asteroid belt is a testimony of a planet that simply failed to form because the perturbation - mainly from Jupiter - were too strong.

Then, after ~700 millions relatively quiet years, Jupiter and Saturn edged close to a resonance (with Saturn exactly twice the period of Jupiter) that sent the whole Solar System grasping for balance. Uranus and Neptune exchanged their relative positions, and both were thrown out on much wider orbits. Countless Pluto-size bodies and smaller comets were scattered towards the outer regions of the Solar Systems, or flung inwards. On the inner planets, this event corresponded to a rain

of impactors called the **late heavy bombardment**, recorded by a surge of cratering on the Moon for instance.

In the Solar System, the orbit of Jupiter remained stable. Had Saturn been a bit heavier, this would not have been the case. The eccentric orbits of some extra-solar gas giant planets may be due to such interactions with other planets.



The outer system before and after the Jupiter-Saturn resonance, according to a simulation. The green dots are minor planets and comets, the four circles show the orbit of Jupiter (red), Saturn (yellow), Uranus (violet), and Neptune (blue). Note that Uranus and Neptune have swapped rank.

### Telluric exoplanets

One of the objectives of the study of exoplanets is to place our Earth in a cosmic context. How common are Earth-like planets? What kind of surface and atmosphere do they have?

No Earth-like exoplanet has been detected yet, because it is much easier to detect larger planets. However, we are closing in on Earth-like planets from several directions at once. Planets a few times the mass of the Earth ( $3-5 M_{\oplus}$ ) have been found by the radial velocity method on close orbits, and by the microlensing method on very wide orbits. The Kepler space mission launched in 2009, has the capacity to detect Earth-size planets with the transit method.

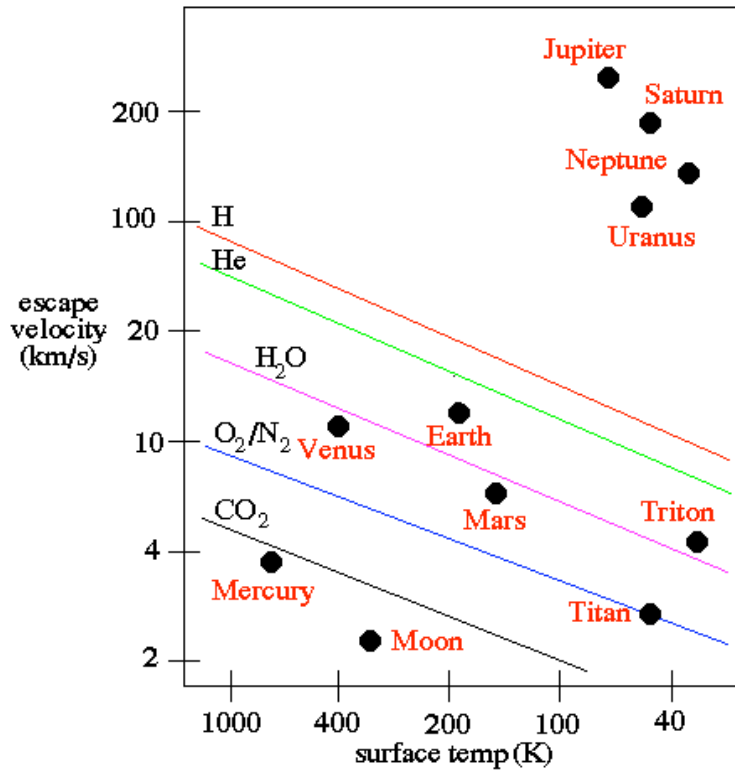
Using models and extrapolating from heavier planets, astrophysicists have started speculating about the possible nature of Earth-mass exoplanets. Because planetary migration is thought to be very common, an Earth size planet orbiting near 1 AU will not necessarily be composed mostly of refractory elements (rock and metals), like the inner planets in the Solar System. It could be a planet predominantly composed of ice brought inwards from beyond the snow line. The warmer temperature would then melt the ice, opening the possibility of *ocean planets*: Earth-mass planets mostly made of water.

Another parameter that could be very different on Earth analogs is orbital eccentricity. As mentioned earlier, orbits as circular as those of the Solar System seem rare among exoplanets. An Earth-like planet on an eccentric orbit would be submitted to large variations in the amount of star light that it receives along its year. This would lead to much more extreme seasonal variations than on Earth.

## **Habitability**

Another, more remote, objective of the study of exoplanets is to understand how common are the conditions that allowed the apparition of life on Earth. The presence of liquid water is generally thought to be the one key element for the kind of life that we know. Hence the definition of the concept of *habitable zone* for exoplanets: the habitable zone around a star is the region where the temperature on an Earth-like planet would be between the freezing and the boiling point of water. If a planet orbits in the habitable zone, any body of water on its surface could remain liquid, whereas outside the habitable zone, it would either freeze to permanent ice (as on Mars) or boil away in the atmosphere (as on Venus).

The habitable zone around the Sun ranges from near the orbit of Venus to near the orbit of Mars (interestingly, Venus and Mars could potentially harbour liquid water if their atmospheres were subjected to a different amount of greenhouse effect. Venus has too much greenhouse effect, all its water has been evaporated into steam then lost to space. Mars has too little, it has lost most of its atmosphere to space because its mass is not sufficient to cling to it.)



Escape velocity as a function of surface temperature for Solar-System planets. The lines show the level below which the named chemical compounds can escape to space (log scales).

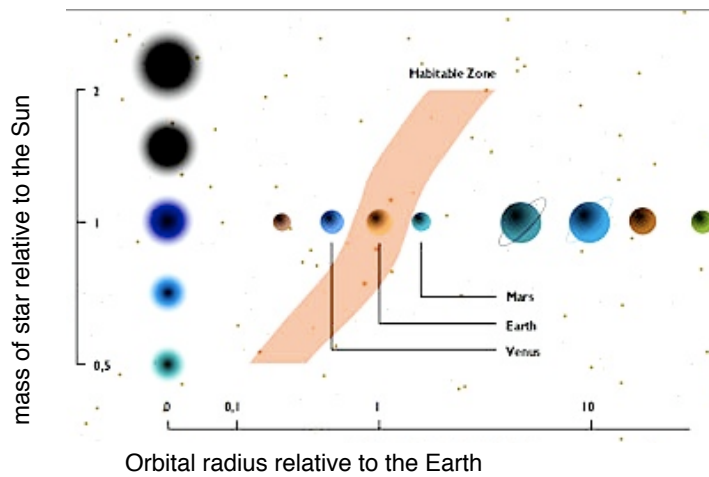
Because the mass-luminosity relation for stars is very steep, the position of the habitable zone changes drastically for stars of different masses. For red dwarf stars ( $<0.5 M_{\odot}$ ) the habitable zone gets quite close, to orbital periods of only a few weeks.

Using the relation:

$$T_{\text{eq}}(a) = 2^{-1/2} T_{\text{star}} (R_{\text{star}} / a)^{1/2}$$

we find that around the Sun, the equilibrium temperature is equal to  $0^{\circ}\text{C}$  for  $a=1.46\text{ AU}$  and to  $100^{\circ}\text{C}$  for  $a=0.74\text{ AU}$ . This defines a band around the position of Earth, from near the orbit of Mars (1.76 AU) to Venus (0.73 AU).

The mass-luminosity relation for star is approximately  $L/L_{\odot} \sim (M/M_{\odot})^{3.5}$ . The luminosity of a  $0.5 M_{\odot}$  star will be  $\sim 0.09 L_{\odot}$ . The inner edge of the habitable zone around such a planet will be at  $\sim 0.21\text{ AU}$ . Using Kepler's third law, this corresponds orbital 0.14 years, which is seven weeks.



### The origin of life (on Earth)

Not so long ago, the search for extra-terrestrial life was often perceived as the preserve of eccentric scientists and lunatics. This has somewhat changed in recent years. The main cause of this shift, apart from the discovery of exoplanets, has resulted from the study of life on Earth.

It used to be thought that the apparition of life microbial life on a planet was an extremely unlikely event, and that, once life had appeared, the “progress” of life towards more complex creatures and ultimately towards sentient and intelligent beings was somewhat natural. Advances in biology have largely turned this paradigm on its head.

One one hand, it has been found that microbial life is present in the earliest rocks were it could be found. Life seems to have appeared very early on Earth, without any delay suggesting an unlikely event. Also, research in molecular biology has started bridging the gap between life and inanimate organic chemistry, building credible scenarios for intermediate stages. It no longer seems so highly unlikely that, given the right conditions, life could emerge reliably in a few million years on any planets with bodies of liquid water on the surface.

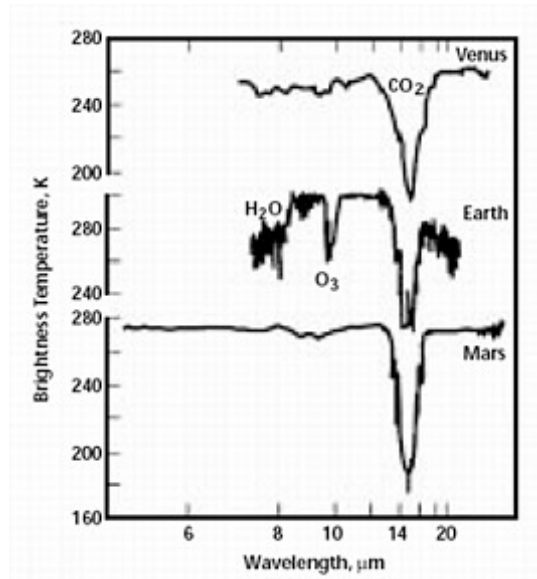
On the other hand, the inevitability of the emergence of intelligent life from single-celled precursor seems much less solid. A better understanding of the “tree of life” and the position of mankind in it has lead to the impression that the apparition of humans on Earth was more accidental than necessary. Even such a simple step as multi-celled organisms has taken 2 billion years to appear on Earth, which hardly suggests inevitability.

As a result, when astrophysicists speak about the search for extra-terrestrial life, what is generally meant is the search for bacteria-type life on exoplanets with liquid water. True, the

search for extra-terrestrial intelligence (“SETI”) is still going on, but it has become a reduced priority.

### Search for life on exoplanets

The current strategy to search for life on exoplanets is to try to detect the effect of life on the composition of a planet’s atmosphere. Even a crude spectrum of the Earth’s atmosphere from space shows obvious differences with Venus and Mars, due to the presence of water and free oxygen. This kind of atmospheric features could be detected in Earth-like exoplanets by sufficiently large space telescopes in space. This is one of the objectives of astrophysics in the next generation.



Low-resolution infrared spectra of Venus, Earth and Mars