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New worlds outside the Solar System

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The discoveries of the first planets around a pulsar and around a star similar to our Sun have opened, after centuries of speculation, a new era in astronomy. The quest for other worlds has become reality. In this paper, the motivations for this search are presented. A comparative review is made of different techniques for their detection, with special attention paid to the planet parameters that can be derived from each method. The first discoveries and their astrophysical consequences are analysed. New questions and future projects beyond these first discoveries are reviewed, with special attention given to the search for life in extrasolar planetary systems. Finally, worldwide activities and the role of Europe are described.

1. Introduction

It is well known that there is an increasing gap between the ever more technical concepts introduced in science and their understanding by the general public. This is a great matter of concern for those who think about the evolution of society. There is, nevertheless, a remarkable exception to this pessimistic diagnosis: the search for 'other worlds'. It is part of a more general question of remarkable universality: 'Are we alone in the Universe?'

The search for other worlds is one of the oldest well-formulated scientific questions. It was raised for the first time in modern terms by Greek philosophers, such as Democritus and Epicurus. Since then, it has inspired many thinkers (Giordano Bruno, Fontenelle, Goethe, Kant, and so on), but the topic was pure speculation. There was one of the first practical attempts at a solution in the 17th century by Huygens (1698), who tried to see planets around other stars. He rapidly realized that this observation was far beyond the capabilities of his modest telescope. After that, for centuries, seeing such planets could only be a dream.

The techniques of the early 20th century enabled the detection of unseen companions to stars. However, the expected planet masses were too small to be reached by these methods – what were detected were faint stars. The Dutch astronomer, Peter Van der Kamp raised a slim hope in the 1950s. He thought he had detected a planet around Barnard's star (one of our closest stellar neighbours), but it proved to be a spurious artefact of the measurement technique.

A. Frail and D. Wolszcan detected the first planets around another star, a pulsar. It was a great encouragement for planet hunters, although the star itself (a neutron star) did not resemble our Sun at all. The great news exploded in October 1995, when the Swiss astronomers Michel Mayor and Didier Queloz claimed the detection of the first planet orbiting a star outside our own Solar System. They used a telescope at the Haute Provence Observatory (in the south of France). The planet orbited around the star 51 Pegasi, similar to the Sun. Understandably enough, there was some scepticism after decades of false alarms, but it took only a few months to confirm the discovery. We live therefore in a very special epoch, where progress in a twenty-three-century-old question 'Are we alone in the Universe?' has made a major step and the question can be investigated scientifically.

Many discoveries followed this first one. Since 1995, more and more extrasolar planets are being discovered each year. There are presently (February 2002) about 90 of them and the discovery rate is 1 to 2 planets per month. A frequently updated catalogue is maintained, together with other news and information, on the World Wide Web (see bibliography). In eight of the stars, more than one planet has been detected. In one case, one could measure the radius of the planet, which is Jupiter-sized. For this star, the observation is a definite proof that the object detected is indeed a planet.

After the initial discovery, it has become possible to go further, and astronomers are now willing to address several questions:

- How frequent are other planetary systems?
- Do they look like ours (number, masses, radii, reflectivity of the planets; radii, eccentricities, inclinations of their orbits, etc)?
- What type of environments do they have (atmospheres, Saturn-like rings, satellites, etc) and what are their properties?
- What are the other physical properties of the planets (duration of their day, climate, seasons, atmospheric circulation, presence of oceans, etc)?
- How do these features vary from star to star?

In addition to these purely astrophysical questions, there is a related question, which springs to the lips of every person: is there life elsewhere in the Universe? This question raises the problems of the different forms of life we can expect outside the Solar System, and of the definition of life. The conventional view is that life can develop on earth-like planets in the habitable zone of a planetary system (where the temperature favours the survival of water as a liquid, rather than as ice or steam). Astronomers would like to find such planets, and it would even be possible to search for spectroscopic signatures of life on these habitats.

2. How to detect and characterise extrasolar planets

Astronomers make use of several methods of detection and observation to search for extrasolar planets. They can be detected either by direct or indirect methods. Each detection method is characterized by some observables, which are related to the intrinsic physical parameters of the planet. These parameters are intrinsic ones, such as the mass, radius, and temperature, characteristics that depend on their orbit, such as the distance from their parent star, orbital period, and brightness, and their distance from our Earth. The potential success of a given method depends naturally on its instrumental limitations. Let us explain in more detail some of the main approaches.

2.1. Direct imaging

The most natural gesture to detect a planet is trying to 'see' it.

There may be free-floating planets, i.e. planets that are isolated in interstellar space, without parent stars. There is no problem of confusion due to the parent star. However, if there is no star near free-floating planets then there is no light to reflect and they are not warmed by its radiation. Only their intrinsic thermal emission can be detected and it is very faint.

For the normal case of a planet in orbit around a star, one could see either its reflected illumination by the parent star or its intrinsic infrared emission caused by its heating by the star. However, one then faces a severe problem: the light or infrared radiation coming from the planet is extremely faint and, at the same time, the planet is extremely close to its star, so that it is very difficult to separate them. The light emitted by the star radiates in every direction and the planet receives only a tiny fraction. The amount that the planet receives is proportional to its surface area and decreases with increasing star-to-planet distance.

Part of the illumination received by the planet is reflected with a certain reflection factor, called the *albedo*. The non-reflected part is absorbed and heats the planet. The heated planet then emits thermal emission by infrared radiation, again proportional to the planet's surface area. In both cases, the net result is an extremely small planet-to-star brightness ratio. Take, as an example, a planet like Jupiter, that is of the size of Jupiter and at a distance from its sun of 5 Astronomical Units (or AU, i.e. the Sun–Earth distance), like Jupiter. The expected amount of light reflected from its surface is one thousand millionth of the amount of light

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from its sun, and the thermal emission is one millionth. The closeness of the planet to its sun compounds the problem. The planet is seen by the observer at an angle very close to the star, measured in fractions of a second of arc (i.e. thousandths of a degree). Therefore, the planet – in addition to being very faint – is embedded in the light halo of the star caused by diffraction of starlight by the telescope.

To circumvent this difficulty, two types of countermeasures are possible. The first aims to reduce the size of the stellar halo so that the planet is outside the halo. The second tries to turn the starlight off (without turning off the planet!)

The shrinking of the star diffraction halo makes use of a law of optics: the larger the telescope, the narrower the stellar halo. This would require the use of telescopes whose diameters would be many tens of metres for the infrared wavelengths at which it is sometimes desirable to work. Single dish telescopes this big do not exist, but astronomers have multiple dish telescopes, called *interferometers*, that reach such dimensions. It helps to have the telescope in the clarity of space, rather than on the Earth's surface, below the blurring effects of the atmosphere.

The (quasi-) suppression of the starlight can be made in various ways by devices called coronagraphs. The simplest is a physical obstruction in the image at the telescope focus, which blocks the starlight. A more complicated technique is to construct an optical device to make the light from the star interfere negatively with itself but not produce the same effect in the region around itself.

Of course, the most efficient solution is to combine all these approaches: shrink the stellar halo thanks to (very) large telescope apertures, suppress the starlight with a coronagraph and operate the telescope in space. These approaches have led to proposals for future space projects, stimulating several instrumental developments. However, observations are currently limited to telescopes based on the ground, where there is an additional source of degradation of images: atmospheric turbulence. One can, in that case, increase the sharpness of images by adaptive optics, a technique that counteracts the deformation of images by the atmosphere by compensating deformations, in real time, of the telescope mirror.

Despite the difficulties presented by direct detection, astronomers put much effort into this technique because it is the only way to access several properties of the planet. As an example, careful study of any changes of the brightness of the planet at different wavelengths can reveal its diurnal rotation period, its seasonal variation, the relative amount of water at the surface (oceans) etc.

2.2. Dynamical perturbation of the star by the planet

Instead of seeing the planet directly, one can search for its effects on the parent star. The first of these effects is the gravitational perturbation of the star's position

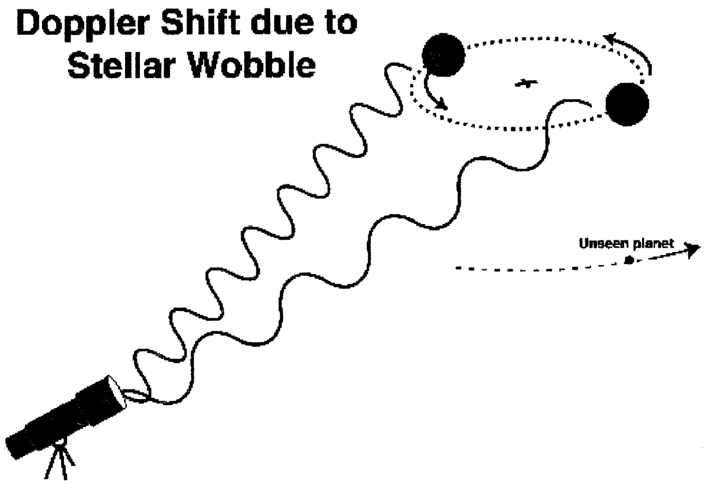

Figure 1. Stellar-wobble. The wobble of a star induced by an orbiting planet (courtesy G. Marcy).

by the planet. When the planet makes a revolution around its parent star, both objects are in fact in orbit around their common centre of mass (see Figure 1, courtesy of G. Marcy). The star's orbit is diminished a great deal by the ratio of the planet's mass to the star's mass.

For the observer, the small orbit of the star results in the perturbation of three of its observables: its radial velocity (the velocity along the line of sight), its position on the sky and the time of arrival of any signals emitted by the star. A slight complication arises due to the inclination of the planet's orbit – if the planet is orbiting in an edge-on orbit the variations of radial velocity and time of arrival of signals are maximal. The three observables are perturbed with a period equal to the planet's orbital period and with an amplitude proportional to the planet's mass. The measurement of this amplitude therefore gives a determination of the planet mass.

A pulsar emits regularly spaced signals, which arrive at Earth early and late if a planet perturbs the pulsar. The first planets were discovered by this method by Wolzsczan and Frail around the pulsar PSR 1257 + 12. They detected four, or perhaps five, such planets. The precision with which the time of arrival of the signals can be measured is so high (a few microseconds) that planets as light as the Moon can be detected.

If there are civilizations on external planetary systems, they could see a 13 m s^{-1} radial velocity variation in our Sun caused by Jupiter, with a 12-year period. Figure 2 shows the 50 m s^{-1} periodic variation of the radial velocity of the star 51 Peg as a function of time. One cycle takes 4.23 days. This was the star measured

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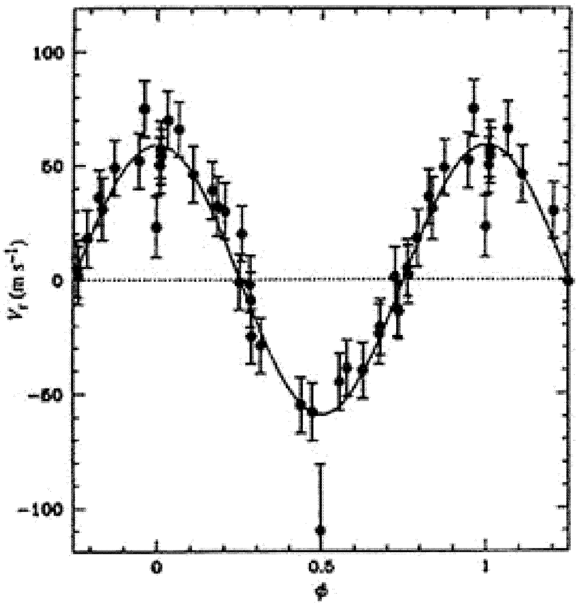

Figure 2. The original radial velocity variation of the star 51 Peg: the first proof for an extrasolar planet around a solar type star (Mayor and Queloz 1995).

by Mayor and Queloz, and the figure is the evidence for the first planet ever detected around a solar-like star. The planet is somewhat less massive than Jupiter. After this first discovery of a single planet in an extrasolar planetary system, a significant step was the detection, by the same method, of three planets around the star Upsilon Andromedae.

The precision in radial velocity measurements is presently 3 m s^{-1}, which would enable the detection of planets like Saturn. But there is no hope with similar techniques to detect a planet like Earth since the radial velocity perturbation produced by such a planet is only 10 cm s^{-1}.

The closer a planet is to its parent star, the larger the radial velocity variation it produces in the star. By contrast, the further away from its parent star, the more a planet produces a displacement of position of the star, which can be measured by the techniques of astrometry. On the other hand, the period of the orbit of a planet distant from its star is very long. That is why the first planets discovered by radial velocity variations were so close to their star. The present capability to detect direct displacements are just marginally sufficient to detect planets like our Jupiter, although no measurements have in fact been successful.

2.3. Planetary transits

If a planet happens to transit across the face of its sun, it can produce, under favourable circumstances, a temporary drop for a few hours in the sun's light. The depth of the drop is given by the star-to-planet surface ratio: it is 1% for a Jupiter-sized planet, 0.01% for an Earth-sized planet. The orbital plane of the planet must be correctly oriented: the probability that an orbit is edge on enough is 0.5% for a planet at 1 AU from its star and decreases (increases) with increasing (decreasing) distance. The precision with which measurements of the star's brightness must be made is not over-demanding. Jupiter-size planets can be detected in this way from the ground, and one can detect Earth-sized planets from space. This is presently the simplest method capable of detecting Earth-like extrasolar planets today and measuring their diameter.

Late in 1999, the first planetary transit was detected from the ground (around the star HD 209458), leading to the first determination of the radius of an extra-solar planet. The star had previously been measured from space using the Hipparcos satellite and a record of a previous transit was found in the satellite's archives.

The Hubble Space telescope made a spectroscopic study of the transit in 2000, with the result that the spectral lines of sodium were detected and were attributed to the planet's atmosphere, as predicted from theoretical reasoning. This is the first time that this has been achieved. A secondary eclipse of the planet by a star, which is at present under study, should lead to the determination of the light from the planet itself which, when compared with its size and reflectivity, should give information about its material composition.

2.4. Gravitational lensing

According to Einstein's theory of gravitation, any massive body bends light rays passing close to it that originated from a star behind. The image of the background star is magnified as if by a lens. Lensing is thus a way to detect indirectly the massive body, even when it is invisible, in particular when it is a planet. If, due to mutual motions in our Galaxy, the foreground (invisible) planet is moving on the sky relative to the distant background star, the apparent luminosity of the background star changes with time. The resultant magnification factor can reach values up to 100 when the planet lies at a distance of several thousand light years, i.e. as far as the Galactic Centre. The method is thus suitable to detect very distant planets. A lensing event is seen only once (as the two bodies make their once and only alignment). This makes the lensing method less attractive. Nevertheless, it can produce statistical results. Astronomers have shown by this method that less than 25% of stars have Jupiter-mass companions at distances larger than 3 AU.

3. Present findings and first lessons

Since the discovery in 1995 of the planet orbiting 51 Pegasi, 80 planetary systems have been discovered. There are presently ten times more planets known outside the Solar System than within. Seven of the planetary systems have two or three planets and for the pulsar PSR 1257 + 12 there are five planets. In addition to planets in orbits around stars, about 18 objects have been detected through their thermal infrared emission. They can be interpreted as hot planets with a mass of about 15 times that of Jupiter and a temperature from 1500 to 2000 degrees. They are not associated with any particular stars and are thus sometimes called 'free floating' planets. They have either been formed as single objects in dense clouds made of gas and dust or have been expelled for some reason (stellar encounters, planet–planet encounters) from their parent planetary system.

As often happens in science, what has been found by extrasolar planet searches was largely unexpected. The first discoveries of extrasolar planets have provided great surprises and a few conclusions can already be drawn. We have learned important lessons from these discoveries.

- First, the global result is that about 5% of main sequence stars have a giant planet at a distance less than 2 AU. Before 1995, astronomers had no idea whether planetary systems were very rare or not. There could for instance have been less than one planetary system for 1000 stars. By themselves these discoveries are very precious information for planetary formation theory. The theoreticians have now to explain this proportion. And it immediately raises a new, important question. This proportion being valid for giant planets, does it hold for small, solid, Earth-like planets? It could indeed *a priori* be very different, as the formation and evolution mechanisms of Earth-like and Jupiter-like planets are significantly different (see the accompanying article by Thérèse Encrenaz). This question is, of course, important for future searches for life on Earth-like planets.
- A second conceptually important consequence comes from the discovery of the planet in transit over the star HD 209458. The planet has a mass of 0.6 that of Jupiter and its radius is 30% larger than Jupiter. Not only does this constitute proof that the stellar wobble is due to a planet and not to other causes (such as stellar oscillation, small companion black hole, etc), it also rules out the possibility that the planet is made of solid rocks instead of gas. In that case, its radius would have been about a third of, instead of 1.3 times Jupiter's radius. Thus, from transits we can learn about the planet's constitution.
- On the other hand, the definition of what is a planet has become

somewhat less clear than it was a few years ago. Some stars have companions analogous to planets, called brown dwarfs. They are very low mass stars, too small to create their own light through nuclear burning. Only if their mass is above 13–15 Jupiter-masses, can they burn deuterium. As a convention, a planet has, until now, been defined as an object unable to burn deuterium, having thus a mass below 13–15 Jupiter-masses. As an alternative definition, one could also say that a planet is an object formed by condensation of a core in a disk accompanying its sun, whereas a brown dwarf is formed like a star, by condensation of an individual portion of an interstellar cloud. The two definitions were thought to coincide. But the discovery of free-floating objects with masses that appear to be below 15 Jupiter masses and of an object in a planetary system with a mass of 17 Jupiter masses makes the distinction between planets and brown dwarfs less clear.

- While astronomers were expecting to find planets around stars like the Sun, the first planets were discovered around stars where they were not expected, namely around pulsars. It is not clear how these planet–mass objects were formed. Have they survived the supernova explosion that created the pulsar? If so, they should have very eccentric orbits as a result of the explosion. The planets of PSR 1257 + 12 are orbiting almost in circles. Perhaps they have condensed from the exploding material? If so, this is a completely new planet formation mechanism.
- The first giant planets were found 100 times closer to their parent star than expected. Jupiter-sized planets were expected to form at a distance from 4 to 5 AU from solar-type stars. This is the distance at which the temperature is below 160 K, to allow for the formation of icy cores of giant planets. It was thus a complete surprise to find planets in the hot zone as close as 0.05 AU from their parent star, where the temperatures are as high as thousands of degrees. The solution to this problem seems to lie in the notion of orbital migration, introduced 10 years earlier in order to explain a completely different astronomical problem. When a planet has started to grow in a protoplanetary disk of gas and dust, it creates a local hole in the disk by gravitational attraction. The hole shears into a circular gap in the disk. There are then tidal forces between the planet and the inner and outer edge of the gap. These tidal forces pull the planet inwards toward the star.
- Half of the planets have orbits with unexpectedly large eccentricities. These large eccentricities are mostly not well understood. One planet orbits the star 16 Cygni B, which is in a binary star. The eccentricity of its orbit comes perhaps from perturbation by the companion star 16

Cygni A. In other cases, the eccentricity of the orbits might be the result of migration: during their migration (at different rates) one planet can expel another from the system and see its own orbit perturbed.

4. Future perspectives

These first discoveries have encouraged astronomers to accelerate their searches and many projects are presently ongoing or under study.

4.1. Future ground-based and space-based facilities

Radial velocity searches. From 2003, the European Southern Observatory (ESO) will make radial velocity searches in a dedicated programme with the 3.6 m telescope at La Silla. A Swiss programme, monitoring 800 stars on a dedicated 1.5 m telescope, started in 1998, at La Silla. The 10 m Keck telescope in Hawaii is monitoring 400 stars. Several other groups conduct similar radial velocity searches, or plan to do so, with more moderate precision.

Astrometric searches. The Space Interferometric Mission (SIM) is also a NASA project devoted to astrometry. The nominal goal for astrometric precision is a few millionths of second of arc. As far as extrasolar planets are concerned, this will give to SIM the capability to detect Saturn-mass planets up to 45 light years away and Earth-mass planets out to 15 light years. The GAIA project, to be launched by ESA in the coming years, will measure the position of 1.5 thousand million stars in the Galaxy with a precision capable of detecting ~ 25 000 extrasolar Jupiters.

Imaging. On the ground, large telescopes such as the Keck Telescope, ESO's VLT and the Large Binocular Telescope will try to search for planets by imaging in the coming years, with different interferometric techniques. However, their imaging performances are not yet well known. In space, the projects are more clearly identified (although the situation is evolving rapidly).

The NGST space mission (Next Generation Space Telescope) is a large (6.5 m) telescope, the successor to the Hubble Space Telescope. To be launched after 2009, if approved, NGST is a NASA project in which ESA has a 15% participation. ESA is presently studying whether it could contribute a camera equipped with a coronagraphic mode, which could detect Jupiter sized planets orbiting nearby stars.

Other space projects, based on interferometric nulling, were initially motivated by exo-biological purposes. They led to the Darwin project, presented in 1993 as an ESA cornerstone candidate, quickly followed by the NASA Terrestrial Planet

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Finder (TPF). Darwin was, in its initial configuration, a free-flyer mission made of five 1.5 m telescopes separated by 20 to 100 m, while TPF was initially based on a rigid linear structure.

Transits. In July 1999, the Hubble Space Telescope monitored the brightness, continuously over nine days of 20 000 stars in the globular cluster 47 Tucanae. No planets were found, although astronomers expected to detect 15–20. This may be due to the low content of planet-forming elements in the cluster's stars. Alternatively it may be that frequent close encounters between stars in this dense cluster have resulted in the expulsion of planets from the system.

In the near future, three similar space projects will get underway.

- COROT is an ESA/CNES mission to be launched in 2004. Half its mission is to detect planetary transits. As of October 2001, it is, in fact, the only presently approved space mission largely dedicated to the search for extrasolar planets. With its 25 cm aperture, its telescope should detect, during its two and a half years of operation, tens of planets with radii down to about 2 Earth radii at orbital distances up to about 0.5 AU from their parent star. Some of these planets should fall in the 'habitable zone' of their parent star.
- The NASA mission KEPLER project, to be launched in 2007, is entirely devoted to the search for planetary transits. It is much more ambitious than COROT. Its telescope has a 1 m aperture and it views 100 square degrees of sky at a time. It should be able to detect, after 5 years of operation, a few hundreds of Earth-like planets in the habitable zone of stars.
- Finally, ESA is studying the Eddington mission for a possible launch in 2008. It is a kind of super-COROT, with both stellar seismology and planet finding objectives. Having a performance less than KEPLER, it should nevertheless detect several tens of Earth-like planets at 1 AU of the parent star. It is presently a reserve mission and the final decision for its launch depends on ESA's budget and schedule.

Extra-solar planetary environments and comets. Given the extreme difficulty to detect extrasolar planets, it seems premature to try to detect their surrounding minor bodies such as rings and extrasolar comets. Surprisingly, some of these are detectable even more easily than planets themselves.

(a) *Rings*. The rings of extrasolar planets have such a low mass (less than an Earth mass) that they have no observable dynamical effect on their sun's motion. But, like Saturn's rings, they can be significantly more extended than their parent planet (their surface being four times larger). They are thus easier to observe than simple planets, by direct imaging and transits.

(b) *Satellites.* Giant satellites of planets are, at least in the Solar System, at most as large as Earth-like planets. Detecting them by imaging is made more difficult by the light of their parent planet. The transit method is more promising and can be exploited in two different ways.

- Detection of the transit made by the satellite itself is marginally possible for the largest satellites (Titan-like) in front of a small star monitored with the highest accuracy (as in the case of the COROT and KEPLER projects).
- Even if the satellite transit itself is not detected, because of lack of photometric precision, the satellite advances or retards the timing of the transit of the giant planet by about 15 minutes for an Earth-mass satellite in orbit around a Saturn-like planet (this is very easy to detect).

(c) *Magnetospheres.* At least one planet in the Solar System (Jupiter) has a radio emission stronger than the (quiet) Sun. This is probably due to a strong magnetic field of internal origin, in which particle acceleration takes place, inducing strong non-thermal radio emission.

The strongest of these could be detectable at 45 light years with the best receivers (Jupiter itself would be detectable at 1 light year). Further in the future, a Moon-based radio telescope on the far side of the Moon would be free from man-made parasitic interference and of ionospheric absorption.

(d) *Comets.* The spectrum of the star Beta Pictoris shows rapidly varying (on time-scales of days) absorption lines. One can interpret this as caused by infalling evaporating comets at a rate of about one infall per day. This particular star is surrounded by an exceptional reservoir of comets. For an amount of comets equivalent to that of our Solar System, the expected rate of events is about one comet per month.

4.2. Search for life on extrasolar planets

A world is not a world if there is no life on it. That is why the ultimate goal of the quest for other worlds is to detect some kind of life, but what kind of life? That is the question.

What could be called ‘life’ is the subject of an immense debate, which cannot be fully treated here. Given its philosophical importance (Schneider 2002), let us nevertheless make just one remark: life cannot be defined (has it to be ‘defined’ at all?) by objective criteria such as self-reproduction, adaptation to an environment and evolution. It is first apprehended subjectively by being identified by us. In other words, there are, strictly speaking, not living organisms, but living relationships.

Habitable zones. To start with, let us restrict ourselves here to the standard conservative choice of carbon-based organic chemistry on a solid planet with liquid water. Liquid water has the virtue of facilitating chemical reactions and the growth of complex molecules. Indeed, fluid transportation of molecules is efficient and, as an excellent solvent, water can contain all sort of molecules. To have water and life, a planet must be sufficiently massive to retain its atmosphere, but not too much so as not to retain its hydrogen. Its mass must then be between 0.1 and 10 Earth masses. With pressure conditions given by this mass range, liquid water can be present if the planet temperature is about 20°C.

A planet orbiting at a given distance around a star acquires a temperature resulting from the equilibrium between the incoming flux of star light and the outgoing energy flux resulting from thermal radiation (planet cooling). By this means the mean Earth temperature is about 14°C. A planet's temperature is less if it lies at larger distances from its star and more if the star is hot. There is therefore a range of star to planet distances for which the planet temperature, say between 0 and a few tens of degrees C, allows for liquid water on the planet. Since liquid water is considered as an essential factor for the development of organic life, it defines the habitable zone around a given type of star. Depending on the type of the central star, this distance runs from 0.1 AU to 2 AU. For extremely hot stars, the habitable zone is larger than 2 AU, but they evolve too rapidly to have stable temperature conditions over the thousands of millions of years required for the development of life (unless one invokes less conservative scenarios).

Panspermia? What are the chances that organic life exists on extrasolar Earth-like planets? This probability is presently extremely poorly known because one does not understand in detail what are the exact required conditions (chemical composition, amount of water and solids, ionization degree, pressure, lightning frequency, etc) nor the stability of these conditions over the millions and billions of necessary years. More precisely, one does not know to what extent life and its biochemicals are robust to slightly different conditions from the Earth's.

Some reason for optimism comes from the fact that, even in its extreme conditions, interstellar space contains about 100 different organic chemical species (i.e. molecules with at least one carbon atom). There is a reasonable hope that these molecules serve as seeds for complex molecules; they are sometimes considered as prebiotic. A debate is currently underway to know their role in the appearance of life on Earth. Similarly they can have triggered the emergence of life on extrasolar planets.

Even if it is not the case, there is a second chance for the existence of life in other planetary systems. We at least know that there is life on Earth and astronomers have recently realized that there is a non-negligible interchange of material (essentially meteorites) between planets in the Solar System. Life may thus have spread from its origin throughout the Solar System. The suggestion has thus emerged that a similar exchange can take place between different planetary systems. Of course, the time scales are longer because the distances are larger. Meteorites or comets may have been expelled from our Solar System up to 3.5 thousand million years ago (when life first appeared on Earth) with biomolecules or even primitive micro-organisms on them. After a journey of a thousand million years or so in interstellar space, they may have been captured by nearby (up to a few tens of light years) planetary systems and have seeded any planets with suitable conditions for the development of life.

This is not entirely speculation. It has been demonstrated by laboratory and space experiments that biomolecules and even micro-organisms can survive space travel in interstellar conditions (low temperature, vacuum, UV radiation) and the shock experienced at a violent landing on a solid planet. Mathematical simulation has shown that the probability of expulsion of a meteorite or a comet by the Solar System is not negligible. The only point of mathematical debate is the probability of capture by an extrasolar planet. All these considerations are part of the hypothesis called *panspermia*, that there might be an 'inter-fertilization' between planetary systems.

Remote detection of signatures for life. Suppose an Earth-like planet is discovered in the habitable zone of its parent star. Is it possible to detect the presence of life on it? It may be possible to detect spectroscopic signatures of complex organic chemistry, or intelligent communications.

- *Oxygen*

A first line of argument rests on the observation that, on Earth, all the oxygen in the atmosphere is of biogenic origin. One is thus led to search for the spectral signatures of this molecule and of its by-product, ozone. Oxygen is at best detectable in the reflected spectrum of the planet, while ozone manifests itself in the thermal spectrum of the planet. The search for ozone is the driving goal of the Darwin project.

This argument suffers from at least one flaw. Water can photodissociate to produce oxygen under some circumstances other than biological. For instance, if as in Beta Pictoris, a large number of comets were to infall on a planet, the impact

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energy could dissociate the water. In addition, oxygen is a secondary product of terrestrial photosynthesis and we do not know to what extent it is accidental or universal. For instance, there are many photosynthetic bacterial species on Earth that do not deliver oxygen as a by-product of their photosynthetic activity, but sulphur instead.

- *Vegetation*

A more general signature rests on the observation that, whatever the details would be of an extrasolar biochemistry, it must make use of a molecular converter that absorbs star light and transforms it into chemical energy. On Earth, this converter is chlorophyll, but it could be other molecules on other planets. On Earth, chlorophyll absorbs up to 80% of sunlight in the band 400–750 nm. It would be seen as an absorption band of a few percent in the planet's spectrum at wavelengths where the star is the brightest. To minimize confusion with other similar spectral signatures (for instance absorption bands of silicates), the amount of absorption can be correlated with the planet's seasons.

- *'Intelligence'*

A third, completely different, approach is the search for complex signals from the extrasolar planets. This approach has a long prehistory tracing back at least to the 19th century when astronomers wanted to detect fires on Mars. In the 20th century, a more efficient technique started with the search for electromagnetic radio 'signals' in the SETI programme (Search for Extra-Terrestrial Intelligence). Of course, we do not know what the essence of intelligence is and this denomination reveals some naivety. But, independently of any eventual intention behind signals, it is not absurd to assume that, after complex bio-molecules and organisms, technical instrumentation-like structures might have developed on a planet. They could have natural leaks (such as spatially or temporally intermittent power sources) or they could emit organized signals. The search for signals was extended to the visible part of the electromagnetic spectrum (Optical SETI or OSETI), by several detection programmes started in the USA. It is the opinion of the author that the chances of success are small because there are very poor guidelines for the definition of the level of complexity of alien signals. In other words, the space of parameters to search in is too large for a chance of success. Detection of natural leaks such as city lights (one knows exactly what to search for) will have to wait several decades until we can make multi-wavelength cartography of an extrasolar planet, with a very large interferometer (hundreds of kilometres in dimension). But the goal is clear and unambiguous.

5. International context and the European involvement

5.1. Big science and small science

The description of the methods of detection and observation of planets has shown how difficult these are. It is thus not surprising that one had to wait until now to detect the first planets. Moreover their detailed study will require large and expensive astronomical facilities: large ground-based telescopes and interferometers such as ESO's Very Large Telescope or large space-based interferometers. There is a remarkable contrast between these major projects and measurement of a planet size by the transit method, accomplished with a very small (12 cm diameter) amateur telescope. This measurement can be (and has been) repeated by any good amateur astronomer with a similar telescope and an almost standard commercial CCD camera. No large interferometer will be able to measure the size of a planet earlier than 15 years from now.

There is an interesting lesson there. Although it seems not to be the general rule, in the battle between big (Goliath) science and small (David) science, David can sometimes still win. The large funding agencies and institutions sometimes forget (or do not want to see) this fact. In the 17th century, Descartes said 'I think, therefore I am'. Today's researcher too often seems to say 'I spent money, therefore I am'. This does not mean that very large facilities are not useful. It only means that one should not forget small ones.

5.2. Europe

Europe occupies a very good position on the international stage. It is represented by national institutions and space agencies and by two major organisations at the European level, the European Southern Observatory (ESO) and the European Space Agency (ESA, Cavallo 2000). The European Union is (as a single body and with the exception of a few grants at a very low level) absent in this domain. In addition to ESA and ESO, there are, of course, multinational European cooperations. Europe's excellent position is manifested by major first discoveries and by several promising ground-based and space-based projects. We can only present the main evidence here. The first planet ever detected in orbit around a solar-type star was discovered by two Swiss astronomers at the Haute Provence Observatory. It is this discovery that triggered the growing activity around the world in this new field of astronomy. In 1989, an American–Swiss group made the undoubted detection of a companion to the star HD 114762. The companion had a mass of at least 10 Jupiter masses, and an orbital period of 84 days. It had a very eccentric orbit and there were (loose) signs that the orbit was seen pole on (thus the real mass was probably larger than 13–15 Jupiter masses). The astronomical community concluded: (1) having an eccentric orbit, the companion

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could not have formed like a planet; (2) since its real mass was larger than the 13–15 Jupiter mass limit of planets, it was a brown dwarf. We know now that many planets have eccentric orbits but we will have to wait a while for unambiguous measurement of its mass. It may have been the first extrasolar planet discovered.

The discovery of the planet around 51 Pegasi was followed by the implementation of further programmes by European observers, not only the same group (now extended to a French–Swiss team) and equipment, but also at La Silla in Chile, and with ESO telescopes. ESO is currently building what will be the most accurate velocimeter dedicated to the detection of planets by radial velocity measurements, HARPS (High Accuracy Radial velocity Planetary Search). Another European group (EXPORT) has established a systematic detection programme at the UK Observatory at La Palma, in the Canary Islands. ESO is also preparing the Atacama Large Millimetre Array (ALMA), for the start of its operations in 2005. It will allow for astrometric detection of extrasolar planets.

In space, European projects are even more ambitious although, after the recent ESA ministerial conference, the budgetary situation is not very optimistic. First, the French–European COROT (COnvection, ROtation and Transits) satellite will give the first answer of a very important question: 'how frequent are Earth-like planets outside the Solar System?' ESA's more ambitious project, Eddington should detect about ten times more planets than COROT will. After Earth-like planets are (hopefully) discovered, it will be important to detect by imaging those that are in orbit around nearby stars and ultimately search for life on them. The Darwin project was chosen by ESA in 1993 as one of its potential future Cornerstones, for implementation when the technology is mature. This choice was followed six months later by the NASA proposal Terrestrial Planet Finder, based on the same principle as was Darwin. Another ESA Cornerstone is the GAIA mission, which will be able to detect about 25 000 planets in the Galaxy. This will constitute the richest gathering of planets for many decades.

5.3. The international scene

Whereas the search for extrasolar planets search was almost completely absent from the minds of European astronomers until the mid 1990s (with very few exceptions), US astronomers devoted substantial effort to designing ground-based and space-based projects from the 1970s. Several systematic strategic initiatives (TOPS: Toward Other Planetary Systems; ExNPS: Exploration of Nearby Planetary Systems) were organized by NASA in the early 1990s. Competition arising from the discovery of the planet in 51 Pegasi and the selection of Darwin by ESA boosted NASA's activity. The search for life on other planetary systems is (together with the study of the early universe) one of the two major scientific objectives of NASA's Origins programme. NASA has started a process of complete reassessment of its scientific objectives and 'telescope architecture'. Four academy–industry groups are conducting eight independent studies. This initiative has triggered a lot of new, and some audacious, ideas for the detection of planetary systems by imaging. On the opposite side of the world, the Anglo-Australian Observatory has developed a spectrograph, which has detected several planets.

The long-term aim of these studies, the detection of life outside the Solar System, is of common interest for the whole of mankind. It would therefore be desirable that the different nations try to cooperate in these ambitious and noble objectives and attempt to avoid unproductive competition. I do not know if this wish is realistic; in the real world, there is in astronomy, as in other domains, an interplay between competition and cooperation. From a pragmatic point of view, the study of extrasolar planets will require, with the exception of small telescopes used for the transit method, ever larger ground-based and space-based facilities. They will require increasing budgetary resources, beyond the capability of single nations, which will thus be forced to cooperate for budgetary reasons. This process has started first within Europe and is now wider with the ALMA project, which has recently acquired a global status (Europe, Japan and USA). ESA is cooperating with NASA in the NGST project, a possible joint Darwin/TPF mission. The scientists themselves are already cooperating in the framework of TPF since two of the four industrial studies are based on French–US and UK–US collaborations.

6. Conclusions

For the first time, we have a clear answer to a 2300 year old question: 'are there somewhere [i.e. around other stars] other worlds like ours ?' (Epicurus 300BC) The first discoveries have been full of surprises and we should be prepared in the future for the unexpected.

This new era of astronomy is becoming a strategic goal for space agencies. ESA was the first to propose a realistic mission (the Darwin project) dedicated to the search for life outside the Solar System but six months later it was followed by NASA (TPF, almost identical to Darwin). NASA's process of complete reassessment of this domain is evolving rapidly and, in order not to lose its excellent position, ESA has to take into account the new, better space projects that have emerged. There is always the danger that conservatism in Europe will be the best allies of its competitors.

One can already lay out a plan for the long-term future, with well-identified steps for a clear global strategy for the forthcoming century:

- first images of extrasolar planets (around 2005)

- detection of Earth-like planets (2005)
- search for spectral signatures of life ($>$ 2015)
- multipixel cartography of extrasolar planets ($>$ 2025)
- spectroscopic cartography of extrasolar planets ($>$ 2035)

Although this agenda can be reasonably predicted (with an approximation of 5–10 years), what is impossible to predict is what we are going to discover using these techniques. We are limited by our present imagination and we must be prepared for surprises. In the second half of the century, when the most interesting planets (possibly with signs of a biological activity) will have been identified, the pressure will become strong to design a mission to go there (in one way or another). 2050 may seem to be far in the future, but the astronomers who will make these discoveries may well be alive today. After the decision to visit a neighbouring planet, we will face a very serious problem. Going there will take several decades, and a new kind of horizon will emerge – the maximum distance an interstellar probe can travel in a human lifetime. Any view beyond that epoch would be even more speculative. In the meantime we can be sure that we live in an exciting epoch.

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