THE SEARCH FOR LIFE OUTSIDE THE SOLAR SYSTEM

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1 Introduction

The question of the existence of Life elsewhere in the Universe occupies a peculiar position in science: it belongs to the 'avant-garde' of well formulated scientific problems, and nevertheless can be understood by any layman. This is because the root of the question is essentially subjective, and in fact there is no reason to hide that it is even affective: 'Do poeple ressembling ourselves exist and live among the stars we see at night?'. Today, particularly with the discovery of extra-solar planets, the search for Life outside the Solar System is becoming a scientific reasonable goal. Nevertheless one prerequisit is to have an idea of what we want to search for, i.e. an idea of what we mean by 'Life'. In order to miss the fewest conceivable forms of Life, we should start with as few *a priori* assumptions as possible. Let us briefly sketch an argumentation in 7 steps:

1./ Contrary to what is usually claimed by biologists, the very essence of Life is a subjective notion. It is, at first, only recognized as such on *a priori subjective* grounds. In terms of modern psychology, 'Life' is, to begin with, an 'object-relation' built on affect and various forms of identifications, introjection and incorporation. Everyone's experience shows the importance of a priviledged criterion: richness of subjective exchanges with *us*.

2./ It is only in a second step that the 'object' is detached from the initially subjective relation and becomes an objective 'living system'.

3./ Then, in a third step, physical analysis of a system judged as living exhibits an essential attribute: it has rich physical exchanges with its surrounding, implying that its structure is sufficiently complex. Physically speaking, a complex system is an out of thermodynamical equilibrium system.

4./ Out of equilibrium systems can spontaneously acquire a complex structure only after a long natural process of self-complexification (amplification of instabilities). In biological terms, this means *Evolution*. This requires a *permanent source of high neguentropy.*

5./ Due to the second law of thermodynamics, a complex system is unstable. Thus there must be a continuous *regeneration* mechanism which maintains the complex structure. This mechanism necessarily requires *exchanges* of matter and energy with the *surrounding.* In biological terms, this means alimentation and photosynthesis

6./ If alimentation is not sufficient, there is another mechanism named *reproduction.* On the Earth, we know two such reproduction mechanisms: mitosis and sexual reproduction.

7./ Another reasonable requirement is that, in order to minimize the expenses in energy, the structure of the system should be as stable as possible, or its evolution as steady as possible. This is well implemented by some kind of *memory*, together with a reading mechanism. The genetic code is a good example of such a memory. On the other hand, the stability of the systems also requires the *stability of the environment.*

The above requirements are too general to serve as guidelines for actual searches of Life outside the solar system. We need more specific hypotheses on the physical constitution of living systems. There are several possibilities: chemical (organic) systems, electromagnetic plasmas, solid state physics, liquid electronics, liquid crystals, others ? ...

2 Remote detection of Life

2.1 Remote signatures of Life

Once Life has been objectivated as a complex, out of equilibrium, system, its remote detection leads to the search for out of equilibrium samples of particles. This can be done in two different ways:

1./ One can search remotly for out of equilibrium populations of constituents (atoms, molecules, ions, ..) present in situ where the Life has developed. I will come back to this strategy in section 5.

2./ One can search for out of equilibrium populations of particles reaching the observer, or 'signals'. It is the strategy usually called SETI (Search for Extra-Terrestrial Intelligence). Because the word 'Intelligence' refers to some kind of intention, it poses yet unsolved philosophical problems [13], [14]. I therefore prefer to just call this strategy 'Search for Complex Signals'. These particles could *a priori* be of any sort. Because of the magnetic field present in the interstellar space, charged particles are not suited for that purpose. Presently, only two kinds of stable neutral particles are known: the photon and the neutrino (leaving aside the graviton). The search for electromagnetic signals in the radio or optical domain has led to several projects such as Phoenix or OSETI. They are reviewd by J. Tarter in these Proceedings. To give an open minded touch to the present contribution, let me remark that the yet unexplained ultra-high energy ($\geq 10^{20} eV$) cosmic rays, whose origin is not explained by any known natural acceleration mechanism (photons are exluded and new exotic objects such as 'vortons' have been invoked), could well result from accelerators built by a technologically advanced 'civilization': these accelarators would produce some 'leaks' in the form of ultra-high energy neutrinos, which we detect on Earth [3].

2.2 Habitability Zones

Once a complex process called 'Life' has been chosen from the list above, a 'habitable zone' (HZ) is a region of the Universe where the physical conditions (temperature, density, pressure, radiation content, matter content etc) are favourable for the development of that form of Life. One can schematically suggest the following HZ for each category of 'Life':

(a) chemical (organic) systems: planets at 300 K (see section 3)
(b) electromagnetic plasmas: interstellar medium
(c) solid state physics: solid planets, asteroïds, ... [10]
(d) liquid electronics, liquid crystals: planets at 200 - 250 K.

3 Chemically-based Life.

A standard conservative choice is to restrict the search for life to chemical systems. There is no real scientific reason for such a restriction other than strategic prudence. We can then specify further more restricting hypotheses:

1./ Consider only *carbon-based organic chemistry*

2./ Require the presence of *liquid(s)*: favors the convective and hydrodynamical mixing of molecules

3./ The liquid must be *water*: it is a very good dissolvent and is abundant in nature.

4./ Require the existence of a *solid/liquid interface* to enhance the exchanges between molecules.

From the above 'decision tree', the safest environment which our imagination has yet found is an 'habitable' planet. It is a planet having the following characterisctics:

- It is in orbit around a 'main sequence' star (i.e. a star burning steadily its light elements into heavy elements) for its source of out-of-equilibrium photons.
- It must be a solid planet to allow for a liquid-solid interface; this excludes (giant) gaseous planets of the Jupiter type.

- It is at the right distance from the star to allow for liquid water. A planet orbiting at a distance a around a star with a radius R_* and a temperature T_* acquires, by heating an equilibrium temperature T_P given by

$$T_P = \frac{(1-A)^{1/4}}{\sqrt{2}} \left(\frac{R_*}{a}\right)^{1/2} T_* \tag{1}$$

where A is the mean 'albedo' (reflectance) of the planet surface. For instance, by Eq. (1), the equilibrium temperature of the Earth ($A = 0.39$), heated by the Sun ($T_\odot = 5770K$), is

$$T_\oplus = 280K$$

(the actual mean temperature of the Earth's atmosphere is 287 K).

Thus, from Eq. (1), a planet having a temperature $\simeq 300 \pm 20K$ (to allow for liquid water) must be located at a distance a from the star given by (for $A = 1$):

$$a = R_* \left(\frac{T_*}{300}\right)^2 \tag{2}$$

Depending on the type of the central star, this distance runs from $\simeq 0.1$ AU for cool ($T_* = 3000K$) dwarf stars to $\simeq 2$ AU for hot ($T_* = 6500K$) larger stars (1 AU, or Astronomical Unit is the Sun-Earth distance). Other stars evolve too rapidly to have stable temperature conditions.

4 Detection of habitable zones.

The potential success of a given detection method depends naturally on its technological limitations, but also on the different characteristics of the planets and satellites: their mass M, radius R and distance a from the parent star (I assume circular orbits). I will describe some of the methods considered today.

4.1 Habitable single planets.

1./ Gravitational perturbation of the star:

When a planet is in orbit around a star at a distance a, the star makes around the center of mass of the system an orbital revolution with the same period P on a circle with a radius $a_* = a(M_P/M_*)$. This motion leads to the periodic modulation of three observables of the star with a period P and an amplitude respectively given by:

1.1/ Radial velocity:

$$\Delta V_R = \frac{M_P}{M_*} \times \frac{GM_*}{a} = 10 \left(\frac{M_P}{M_\oplus}\right) \left(\frac{M_*}{M_\odot}\right)^{-1/2} \left(\frac{a}{1\mathrm{AU}}\right)^{-1/2} \mathrm{cm/s} \qquad (3)$$

1.2/ Astrometric position:

$$\Delta\alpha = \frac{M_P}{M_*} \times \frac{a}{D} = 0.3 \left(\frac{M_P}{M_\oplus}\right) \left(\frac{M_*}{M_\odot}\right)^{-1} \left(\frac{a}{1\mathrm{AU}}\right) \left(\frac{D}{10\mathrm{pc}}\right)^{-1} \mu\mathrm{arcsec.} \qquad (4)$$

where D is the distance of the planetary system to the observer.

1.3/ Time of arrival of periodic signals

$$\Delta T_A = \frac{M_P}{M_*} \times \frac{a}{c} = 0.015 \left(\frac{M_P}{M_\oplus}\right) \left(\frac{M_*}{M_\odot}\right)^{-1} \left(\frac{a}{1\mathrm{AU}}\right) \mathrm{sec.} \qquad (5)$$

where c is the speed of light. The best targets for having periodic signals are pulsars, for which several planets have been found (see the table; updates are on the World Wide Web at the URL: http://www.obspm.fr/planets).

As is developed in more details by M. Mayor in these Proceedings, the resolution achievable for radial velocity (1 m/sec) and astrometric (a few μarcsecs.) measurements does not allow to detect terrestrial planets in their habitable zone. There is nevertheless a hope in an extreme but plausible situation: for a 'super-Earth' of say 5 Earth masses in the habitable zone of a $M_* = 0.5 M_\odot$ K5-type star (having thus a temperature of $\approx$ 4,400 K), the amplitude of the V_R modulation is about 1.2 m/s with a period of 100 days. With a precision of 1 m/s for individual measurements, such a modulation can be detected at a 4 sigmas level after 4 orbital periods, i.e. within about 1.1 year.

2./ Direct imaging.

This method faces a difficulty: due to the wave-like nature of light, a stellar image always makes a diffraction halo having an opening angle λ/B where B is the telescope aperture. To separate the planet from this stellar halo, one must use a telescope (or a combination of telescopes) with an aperture (or a baseline) B such that

$$\theta = \frac{a}{D} \geq \frac{\lambda}{B} \qquad (6)$$

where λ is the observation wavelength. This translates into the following condition for the baseline B:

$$B \geq \lambda\frac{D}{a} = 20 \left(\frac{\lambda}{10\mu}\right) \left(\frac{D}{10\mathrm{pc}}\right) \left(\frac{a}{1\mathrm{AU}}\right)^{-1} \mathrm{m} \qquad (7)$$

Table 1. Catalog of extrasolar planets (January 1998)

Star distance	$M_P[.\sin i_P]$ Jup. Mass (J) Earth Mass (E)	a_P AU	P_P years (y) days (d)	eccentricity
PSR 1257+12 300 pc	3.4 (E) 2.8 (E) 0.3 (J)	0.36 0.47 40	66.54 (d) 98.22 (d) 170 (y)	0.0182 0.0264 ?
51 Peg 13.7 pc	0.47 (J)	0.05	4.2293 (d)	0.0
ups And 16.5 pc	0.68 (J)	0.057	4.611 (d)	0.109
55 Cnc 13.4 pc	0.84 (J) > 5 (J)	0.11 > 4	14.648 (d) > 8 (y)	0.051 -
rho Crb 18 pc	1.1 (J)	0.23	39.645 (d)	0.03
16 Cyg B	1.5 (J)	1.72	804 (d)	0.67
47 Uma 13.4 pc	2.8 (J)	2.11	2.98 (y)	0.03
tau Boo 15 pc	3.87 (J)	0.0462	3.3128 (d)	0.018
70 Vir 22 pc	6.6 (J)	0.43	116.6 (d)	0.4
PSR B1620-26 3.8 kpc	< 10 (J)	20	100 (y)	-
HD 114762 28 pc	10 (J)	0.3	84.5 (d)	0.25

In order to avoid redhibitory complications due to atmospheric turbulence, it is necessary to go to space.

3./ Transit of the parent star.

If the orbital plane of the planet is correctly oriented, it produces a drop in the star light during transits of the star disk by the planet. The detection of a transit in the star lightcurve requires three conditions:

3.1/ The orbital plane of the planet must be correctly oriented: for random orientations, the geometric p probability is

$$p = \frac{R_*}{a} \tag{8}$$

For an Earth around a 1 $R_\odot$ star, this probability is 0.5%. Since, in addition, the star must be photometrically monitored continuously over at least one entire orbital revolution of the planet, this makes the transit method very inefficient for large a and favors small a since then p is larger and the required time base is shorter.

3.2/ The duration of the transit is

$$D_T = \frac{P}{\pi} \times \frac{R_*}{a} \tag{9}$$

i.e. 13 h for an Earth. This duration is not very sensitive to a.

3.3/ The relative brightness drop $\Delta F/F$ is

$$\Delta F/F = \left(\frac{R_P}{R_*}\right)^2 \tag{10}$$

The photometric precision of the lightcurve must be better than $\Delta F/F$. For a 1 $R_\oplus$ planet the drop is 10^{-4}. In ground-based observations, the photometric precision is at best 0.1% [6]. But in space, one can reach a precision of the order of the photon noise, *i.e.* $\approx 10^{-4}$ for a magnitude 15 star with a 50 cm aperture telescope for a 1 h. exposure. The COROT space mission, to be launched in 2002 and mainly devoted to stellar sismology, will have the capability, as a secondary objective, to detect by this method a few tens of telluric planets [4].

4./ Gravitational lensing of a background star.

The planet can produce a gravitationnal amplification A_G of the light of background stars with a duration T_G depending on its transverse velocity V [5]. The amplification is, due to the caustics in the light propagation in curved space-time caused by the star+planet system, maximum when the planet sits on the Einstein ring of its parent star. Its radius is given by $R_E = \sqrt{4GM_*D}$ when the planetary system is at mid-distance D of a background star (amplified by the lensing). The probability that a star amplifies a background star is $\sim (R_E/\delta)^2$ where δ is the mean distance between two background stars projected on the sky. This probability is significant (but still as low as 10^{-6}) only for background stars in the Galactic bulge at 8 kpc. Thus the lensing effect can detect planets only a $\sim$ 8kpc/2 = 4 kpc. For such distances, $R_E \approx 5$ AU for a 1 $M_\odot$ star. When the planet sits on the Einstein ring, the star itself makes an amplification. Thus, the global amplification lightcurve by the planetary system has two features: a small, short duration (1 day for a Jupiter, a few hours for an Earth), planet amplification event superposed to a larger, long duration (days to months), stellar amplification event. Once the parent star makes an amplification, the probability that the planet amplification exceeds 5% is 20% [5] for a Jupiter-mass planet. For an Earth-mass planet, the amplification exceeds 1% only in $\sim$ 3% of cases [1]. Since $R_E \approx 5$ AU, one can only detect planets at 5 AU from their parent star, *i.e.* far from the habitable zone. Furthermore, a lensing event is seen only once and it is not possible to investigate the planet at 4 kpc any further by any other method. This makes the lensing method less attractive.

4.2 Habitable moons of giant planets.

The detection of these objects is impossible by any method perturbationg the star's observables [15]. There are three methods left for the search of these moons.

1./ Transits.

1.1/ Profile of the light curve:

Like the standard detection of transits of single terrestrial planets, a satellite of a giant planet can be detected by the superposition of the transits of the giant planet and of the satellite

1.2/ Timing of the giant planet transits:

Suppose a giant planet with a mass M_P has been detected by the transit method at a distance a of the star. Then, when a satellite makes an orbital revolution around the giant planet at a distance a_S with a period $P_S = \sqrt{a_S^3/GM_P}$, the latter makes around the center of mass of the system an orbital revolution with the same period P_S on a circle with a radius $a_P = a_s(M_S/M_P)$. This motion leads to a periodic modulation of the time of transits of the giant planet with an amplitude ΔT_T given by:

$$\Delta T_T = \frac{a_S}{V_P} \times \frac{M_S}{M_P} \tag{11}$$

where $V_P = \sqrt{GM_*/a}$ is the giant planet velocity. For a Saturn-mass planet at 0.5 AU from a 1 $M_\odot$ star, the numerical value of ΔT_T is:

$$\Delta T_T = 8 \left(\frac{a_S}{10^{-2}\mathrm{AU}}\right) \left(\frac{M_S}{M_\oplus}\right) \mathrm{min}. \tag{12}$$

The COROT space mission [4] will, as for single planets, be able to make such detections.

2./ Direct imaging

The angular satellite-planet distance is

$$\Delta\alpha = \frac{a_S}{D} \tag{13}$$

From equation (7), the baseline B required to separate the satellite from the planet at an observation wavelength of 2 μ is

$$B = 400 \left(\frac{a}{10^{-2}\mathrm{AU}}\right)^{-1} \left(\frac{D}{10\mathrm{pc}}\right) \mathrm{km} \tag{14}$$

3./ Lensing:

Here the method is similar to the detection of single planets by lensing. Since the planet-satellite caustics is very weak, one can only detect the star-satellite caustics and the global amplification light-curve is the superposition of the lightcurves due to the star-planet and star-satellite caustics.

5 Remote detection of chemically-based Life

5.1 A possible signature of chemically-based 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? The answer is that it is possible to detect spectroscopic signatures of what is perhaps dues to complex organic chemistry. The argumentaion rests on the observation that on Earth all the molecular oxygen and ozone in the atmosphere are of biogenic origin [8]. One can describe the photo-synthetic oxygen production by the following symbolic reaction:

$$\mathrm{CO_2} + \mathrm{H_2O} + h\nu \longrightarrow (\mathrm{CHOH}) + \mathrm{O_2} \qquad (\mathrm{PS})$$

In fact in vegetal and bue algae cells where this production takes place, the real process is extremely complicated and not understood in full details. It requires a large number of intermediary steps, involves at least 8 photons and needs the assistance of proteins and of di-chlorophyll. There is another way to produce oxygen, namely the photolysis of the water-vapor of the atmosphere:

$$H_2O + h\nu \longrightarrow OH + H$$

followed by the chain:

$$\begin{gathered} 2OH \longrightarrow H_2O + O \\ O + OH \longrightarrow O_2 + H. \end{gathered}$$

The hydrogen released by this mechanism evades from the planet by Jeans (*i.e.* thermal) escape. This is probably the process that has eliminated the water from the Venus atmosphere. But it is rather rapid and if it would have produced oxygen in the early Earth's atmosphere (and then stopped), there would presently be no continuous source of oxygen: the oxygen would (with the aid of plate tectonics) oxidise all the Earth's surface rocks and disappear in less than a few millions years. Thus to explain the present oxygen content of the atmosphere, one needs a continuous supply of oxygen, and presently the only known mechanism is the scheme (PS) mentioned above. This argumentation is enforced by the fact that there is no oxygen and no ozone in the atmospheres of Venus and Mars. Thus if one detects these chemical elements in the atmosphere of an extrasolar planet, it is an encouraging sign for the presence of 'Life' [9]. Of course, it will not be a proof and it depends on the definition of 'Life', but it will be sufficiently interesting to deserve further studies. If oxygen is present in the atmosphere of a planet, it can generate ozone by photodissociation and recombination. As we shall see in the next section, the detection of ozone may be easier than to detect oxygen.

5.2 Current projects for the detection of oxygen and ozone.

Oxygen can be detected by its absorption band at 760 nm [9]. The most evident way would be to detect this absorption in the optical spectrum of an image of the planet illuminated by its parent star. But this method would need to separate the planet from the star. one could envisage a space interferometer with a sufficient baseline (as given by (7)). But current opinion leads to the conclusion that we are far to master the metrology required to control the telescope positions with a precision of $\lambda/1000$. Another way is to detect the absorption feature of oxygen by absorption of the stellar light during a transit of the planet [11]. For a 1.5 $R_\oplus$ planet, having an atmosphere with a scale height of 10 km in transit in front of a dwarf M or

K star of radius 0.25 $R_\odot$, the depth of the absorption would be of the order of 8 10^{-5}. Only large photon collectors of the 25 m class, as proposed by several authors (see [2]), [12]), can detect such absorption features.

For technical reasons, it is presently more easy to detect the ozone absorption band at 9.6 μ than to detect oxygen in the visible. It is necessary for that to separate the planet from its parent star. Such a separation requires, at 9.6 μ, an interferometer in space with a baseline of at least 20 m [7]. This has led to the IRSI project (Infra-Red Space Interferometer) which is one of the two potential interferometric Cornerstones of the European Space Agency, to be launched (if approved) in 2015.

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