THE EARTH AS AN OBJECT OF ASTROPHYSICAL INTEREST IN THE SEARCH FOR EXTRASOLAR PLANETS

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Abstract: The potential discovery of Earth-like planets around other stars will need, apart from a sophisticated technological development, the design of techniques for identifying the most representative parameters of their atmospheres and surfaces. The search for life will constitutes the holy grail of this search. However, for many decades the observations will provide data with low spatial and spectral resolution. In the meantime, the Earth will be for us a sort of Rosetta stone to interpret the exoplanet's spectra. Here we present a review of the main results of simulations and observations looking at our planet with nil or low resolution. In other words, we will study "The Earth seen as a Exoplanet".

1 Introduction

1.1 The Earth System

The study of our planet has been classically divided between different branches covering distinct layers and processes (geology, meteorology and climatology, for example). Step by step the need to understand the Earth as a global system has emerged. A synergistic and interdisciplinary action is necessary for this purpose,which constitutes the core of the Earth system sciences.

The Earth system is powered by the Sun, that drives the chemical and physical processes in our atmosphere. The system is also powered by the Earth's interior, manifested in events such as volcanic eruptions.

The study of the Earth system as a whole has two main applications. First, the evaluation of climate change with special attention to the recent global warming [1] and second the search of terrestrial planets around other stars. We will concentrate our study here on the latter.

1.2 The Earth-Exoplanets Connection

In the 1980s the observation of "The Sun as a Star" provided the role of the Rosetta stone to interpret the observations of sun-like stars differing in mass, age and level of magnetic activity [2]. This solar-stellar connection had, and has, a double avenue, because the stellar observations also contributed to a better understanding of the solar magnetism. In a similar way, we expect that observations of "The Earth as a Planet" will provide the key to understand the future observations of earth-like exoplanets.

Our Solar System contains four terrestrial planets, and three of them posses a thin atmosphere. Only one, the Earth, has an atmosphere with an important amount of oxygen coexisting with methane, a pair that indicates an essential property of our planet: life. Living beings are all based on the carbon chemistry but they differ in some aspects relevant to its remote detection. Depending on the energy source we have photosynthetic and chemosynthetic. The presence of oxygen in the atmosphere distinguished between anaerobic and aerobic and the level of complexity discriminated between unicellular and multicellular. Finally, we have the question of the emergence of intelligence and technology among one of the multicellular species. In the evolution of our planet, life has not been a passive agent affecting the composition of the atmosphere. From the tiny bacteria to technological civilizations we can expect to see the life signatures in the atmosphere of exoplanets.

Earth has maintained the conditions for habitability during the last 4.000 Ma allowing the presence of liquid water at the surface. This was possible through a complex interplay between the solar luminosity, the geodynamics of our planet and the atmospheric composition of the atmosphere. The theory of stellar evolution has been tested and developed by observations of several stellar types at different times of their evolutions. Similarly it is reasonable to expect that the future observed population of planets would exhibit a wide range of planet types and evolutionary stages. A copy of the Earth may be observed at any evolutionary phase. The most dramatic change suffered by our planet affected the composition of the atmosphere. Extraterrestrial observers would obtain different spectra of our planet depending on the epoch of the observation. The earliest epochs would have been dominated by CO_2 and water vapor, while in recent times, together such spectral features the bands of molecular oxygen, O_2, and ozone, O_3, will also be present.

Depending of the mass of the terrestrial planet, we could have a planet without atmosphere (Mercury-like), an Earth-like planet or, for larger masses, an ocean planet. Another parameter to be changed during the planetary evolution is the albedo. There are geological indications that the Earth suffered two snowball events, a time when our planet was almost completely covered by snow and ice [3]. Moreover, if one is interested in searching for other Earth copies at the same evolutionary stage, over the past million years the Earth has spent approximately 90% of the time into ice ages.

The occurrence of ice ages is caused by a combination of orbital parameters. One can only guess what the orbital parameters of exo-earths will be, but guided for the only example we have one should a priori expect ice age earths. A large extent of ice will increase the surface albedo making the signal to noise improve an allowing an easier detection than an interglacial Earth.

Waiting to the detection of the first Earth–like planets, reliable tests need to be developed to interpret these new data discerning, for instance, between Venus, Earth and Mars–like planets. Later we may be able to infer whether life is common or not in the universe by observing the evolutionary stages of millions of planets. For monographs and reviews about this topic see [4] and [5].

2 The Earth as a member of a dynamic system

Observed from space the fundamental parameters to be determined for an exoplanet would be those related to the geometry and global suface/atmospheric properties. For example, the measurement of angular radius and the knowledge of the distance to the parent star, would allow us to determine the dimensions of the planet. The determination of the orbit around the star, the mass.

Most of the planets of the Solar System have almost circular orbits. However, large and chaotic variations in the eccentricity of giant planets can produce severe perturbations in the orbit of Earth-like planets affecting the habitability conditions. We can therefore define the Dynamical Habitable Zone (DHZ) as the region where physical conditions at the terrestrial planet's surface remain stable during long periods of time, and are compatible with the development of life.

2.1 Relevant parameters

The Roche limit, d, is the distance within which a celestial body held together only by its own gravity will disintegrate due to the tidal forces of a second body, exceeding the first's gravitational self-attraction.

$$\mathrm{d} = \mathrm{R}(2\frac{\rho_{\mathrm{M}}}{\rho_{\mathrm{m}}})^{1/3}$$

where R is the stellar radius, ρ_M the stellar density and ρ_m the planetary density. For a fluid planet, tidal forces cause the satellite to elongate, causing it to break apart more readily.

A Hill sphere is the gravitational sphere of influence of an astronomical body in the face of perturbations from another heavier body around its orbit. The radius of the Hill sphere is given by

$$\mathrm{R_H} = \mathrm{a}(\frac{\mathrm{m}}{3\mathrm{M}})^{1/3}$$

where m is the mass of the smaller body, orbiting around the heavier body of mass M at a distance a. Orbits at or just within the Hill sphere are not stable in the long term. In the Solar System the planet with the largest Hill sphere is Neptune (0.775 AU).

The tidal forces between two objects tend to synchronize the orbital and rotational periods in order to preserve the angular momentum of the system. For an earth-like planet in a circular orbit this distance was estimated by [6] as:

$$\mathrm{R_{TL}(t) = 0.027(P_0 t/Q)^{1/6} M^{1/3}}$$

where $\mathrm{P_0}$ is the original rotation period and Q the solid plus ocean dissipation rate. For the Earth $\mathrm{P_0} = 13.5$ hours and $\mathrm{Q} = 100$ [7].

2.2 The Solar System: Rule or exception?

Two thirds of the stars are members of binary or multiple stellar systems. This surely complicates the stability of the planets encircling one of the members of the system. We can consider two types of stable orbits for Earth-like planets around a binary system: a) S-type with planets encircling one component of the binary system. In fact, 19 extrasolar giant planets have been detected in such orbits [8]. b) P-type with planets encircling both components of the binary stellar system. No exoplanet with this orbit has yet been detected, but close binary systems are not included in the current surveys.

Holman & Wiegert (1999) [9] have investigated the regions of the phase space, where planets can persist for long times around stellar binary systems. They get the best fit for the critical semi-major axis as:

$$\mathrm{a_c} = (1.60 \pm 0.04) + (5.10 \pm 0.05)e + (-2.22 \pm 0.11)e^2 + (4.12 \pm 0.09)\, m$$

where $m = m_2/(m_1 + m_2)$

Musielak et al. (2005) [10] simulations indicate that the stability of Jupiter-type planets depends on both the distance ratio between the star and the planet, and the mass ratio of the possible stellar companion(s). Lissauer et al. (2004) [11] have studied the formation of terrestrial planets in binary star systems.

The planets of the Solar System are characterized by their almost circular orbits. However, more than one third of the extrasolar planets detected so far have large eccentricities ($\mathrm{e} > 0.4$). But even if the extremes in stellar insolation near periastron and apoastron are damaging to liquid-water environments, such worlds might still be habitable (cf. [12]), if they receive a stellar flux that, when averaged over a complete orbit, is not too different from the nearly constant flux received by the Earth from the Sun . The time-averaged flux over an eccentric orbits is given by

$$< F > = \frac{L}{4\pi a^2(1-e^2)^{1/2}}$$

where L is the star's luminosity, e is the eccentricity of the planet, and a is the distance between the planet and the star.

If hot giant planets are present in the system, simplifying the problem to circular and co-planar orbits we can consider three main types of stable orbits for terrestrial planets (Figure 1).

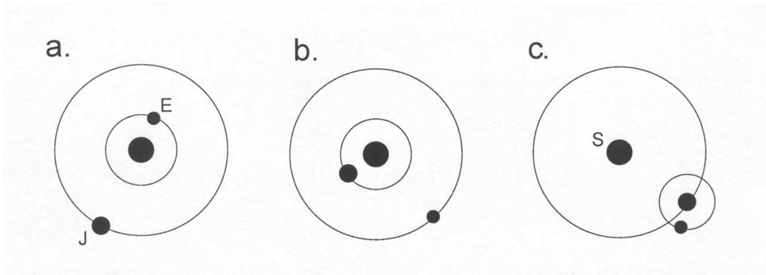

Figure 1: Three main types of stable orbits for terrestrial planets: a) A Solar system configuration , b) A hot giant planet orbiting close to the star and c) Terrestrial planet orbiting a giant planet.

Stable orbits of terrestrial planets inside the DHZ exist only if the orbits of the giant planets are located sufficiently far away from either the inner or outer edge of the habitable zone [13].

Williams et al. (1997) [14] have studied the possibilities of habitability of moons rotating around hot giant exoplanets placed within the habitability zone. The satellite need to be large enough ($>$ 0.12 Earth Masses) to retain a substantial and long-lived atmosphere. A lower limit of 0.23 Earth masses is needed to sustain plate tectonics, a crucial mechanism to compensate for the gradual brightening of a star as it ages. What is questionable is the ability of the giant planets to retain their moons as they migrate inward.

We must keep in mind that not all the planetary environments that might be habitable are necessarily within the habitable zone. The terrestrial example shows the existence of subterranean and suboceanic life that could have multiple counterparts in the Universe. Europa and Titan are two good examples in the Solar System.

The circular orbit of Jupiter in our Solar System promotes the stability of circular orbits among the other planets (excepting Pluto). With all probability, the Solar System has kept its present configuration, because there is not enough mass in the vicinity of the giant planets to produce gravitational interactions, giving rise to the migration of the planet inwards [15]. Therefore, it is pertinent to ask whether the Solar System is special in some way compared with the majority of planetary systems to be found in the galaxy [16]. The answer to this fundamental question needs a more complete observational work.

A gravitational couple on the equatorial bulge of a planet, exerted by the Sun and the Moon in the Earth's case, causes precession of the rotation axis, as well as nutation, which changes the obliquity. Gravitational interactions with other planets give rise to a similar processes. When the rates of precession of the spin axis and orbit axis come into resonance, large and chaotic excursions in obliquity can occur. Laskar et al. (1993) [17] showed mathematically that if Earth did not have a large moon, and if it was spinning at the same rate as it is now, its obliquity would vary chaotically. Simulations by Ortega et al. (2005) [18] indicate that an earth–like planet with high obliquities should lead to a darker surface.

3 The energy balance of the atmosphere

The Sun's energy is the main driver of the Earth's climate system. However, not all of the sunlight reaching the Earth is used, some of it is reflected back to space by the earth's atmosphere (clouds and aerosols) and surface (Figure 2). The albedo of a planet is a unit-less quantity defined as the ratio between the amount of energy that the planet receives from its parent star (sunlight in the case of the earth) and the amount of this sunlight that is reflected back to space.

The energy that is not reflected back to space is absorbed by the land and oceans, and it is then re-emitted in the form of heat (infrared radiation). If the planet had no atmosphere, this heat would all escape to space, but in the earth's case some of it is trapped by the atmospheric gases, increasing the planet's surface temperatures (Figure 2). The mechanism is known as the Greenhouse effect, a naturally occurring heating process resulting from the fact that certain atmospheric gases, such as water vapor, carbon dioxide, and methane are able to absorb longwave radiation. The present enjoyable 15 °C average global temperature of the Earth, would turn to -18 °C without the effect of greenhouse gases.

3.1 The balance equation

The temperature of a planetary surface results from the balance between the incident energy and that emitted by the surface and atmosphere. Considering the planet in radiative equilibrium (i.e. power in equals power out), we have that the planet's surface temperature, T_s, is

$$\mathrm{T_s = S/4\sigma(1-g)(1-A)\,T^4}$$

where S is the solar constant, A is the Bond albedo, σ is the Stephen-Boltzmann constant and g is the normalized greenhouse effect of the Earth's atmosphere [19]. This means that the Bond albedo, together with the parent's star irradiance and the greenhouse effect, directly control the planet temperature.

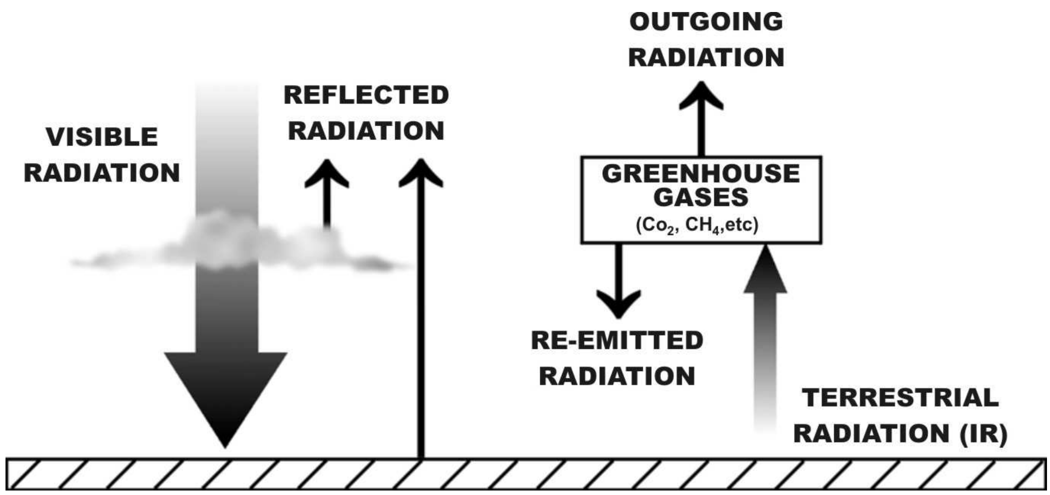

Figure 2: The main components of the Earth's climate system

3.2 Rotational Modulation in albedo

There are big differences between spatially resolved or unresolved measurements of a planet. For example, remote sensing satellites on earth's orbit can determine vegetation leaf indices, plankton blooms, saharan storms and city lights, but all these features disappear in the noise when global averages are taken. For an extrasolar planet observation, at least for the few next decades, any photometric or spectroscopic observations will be globally integrated measurements.

The albedo is a very variable property. At local scales, the albedo depends on the surface type (ocean, desert, ice,..), the given meteorology for the day (amount of clouds and aerosols) and the solar zenith angle - or time of the day - (the albedo is a bi-directional property). If we were to observe the Earth from far away without geographical resolution, at planetary scales, the sunlit half of the earth's for example, the albedo becomes less variable.

Still the global albedo varies because of the north-south asymmetry of the continental land distribution, the seasonal changes in the extent of snow and ice cover, and the seasonal changes in meteorological parameters, more specifically the clouds. This changes are indicative, as all seasons are, of a non-zero planet obliquity, i.e., solar heating angle is what determines the cloud and weather patterns.

There is one methodology to obtain globally-integrated measurements of the sunlight reflected by Earth. Observations of the earthshine, the ghostly glow on the dark side of the Moon, provide direct estimates of the Earth's albedo. The brightness ratio between the bright crescent of the Moon and that of the dark side is proportional to the earths's albedo, although several geometric factors need to be accounted for [20] [21]. From earthshine observations, it has been determined that for the Earth, the photometric variability in the visible range is around 15-20% at diurnal and seasonal time scales.

Thus, because of its particular continental distribution and cloud amount, from photometric observations of the Earth it would be straight forward to determine its rotational period (the length of an earthy day). Models indicate that integration over 3-5 days would be enough to determine that length within minutes. However that might not be so easy for other extrasolar planets. If the planet has no strong surface features, as is the case for Mercury or Mars, or it is completely covered by clouds, as is the case for Venus and the giant planets, determining the rotational period may be an impossible task. In fact, Earth may well be the only one of the major planets for which a rotational period can be easily established from a distance of several AU.

Thus, the requirements for photometric determination of the rotational period seem to be a total or partial view of an inhomogeneous surface, with relatively large contrasts such as oceans and land, or large-scale structures in the atmosphere whose mean lifetime is of the order of the planet's rotational period or larger. In the later case, the rotational period can be established for the top of the atmosphere but not for the planet's surface.

The albedo of a given planet may also change in time. For example 2300 and some 700-800 million years ago, the Earth underwent an epoch of extreme glacial temperatures know as the 'Snowball Earth' events. At theses times, the extent of the sea ice is believed to have reached as far as the tropics. Because of the high albedo of ice, the averaged albedo of the Earth must have been much larger than the present's day 0.3 value. In Figure 3 we have simulated an extreme snow-ball earth, with the planet completely covered in ice, with the present day cloud amount and distribution and without any clouds (such cool temperatures could produce a much drier atmosphere and lower cloud amounts). If the extreme snowball Earth is free of clouds, we obtain an albedo of about 0.7 (close to that of Venus). If clouds are present, the albedo decreases to 0.5-0.55. For a completely overcast Earth we would have an albedo of 0.5. Thus, based on the albedo value it would be possible to distinguish a snowball Earth from an overcast earth. Note however that this holds true only for a planet with very similar atmospheric properties to Earth. If the chemical composition of the atmosphere or clouds is different these quantities will vary. For example the albedo of Venus, with a CO_2 atmosphere overcast with thick clouds of concentrated sulphuric acid, has an albedo of 0.77 that could be confused with a snowball Earth if only photometry observations were available.

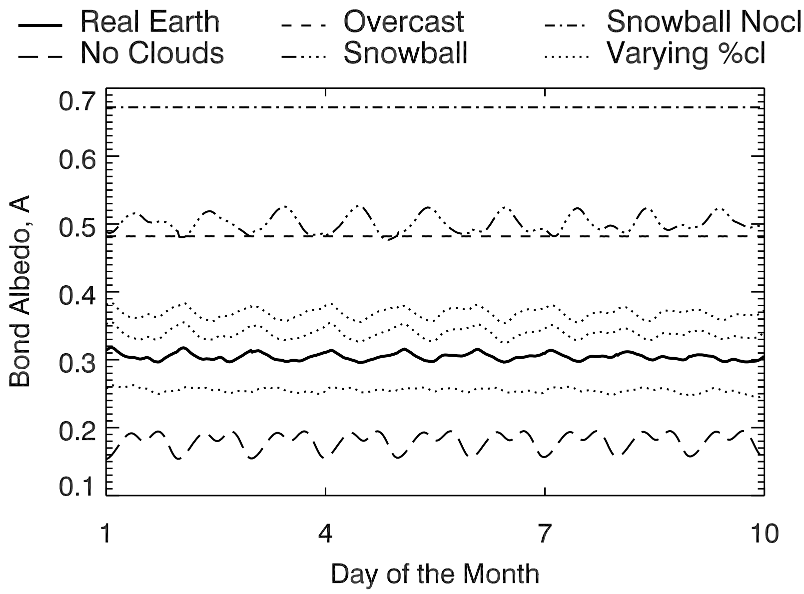

Figure 3: Mean hourly Bond albedo simulations for the Earth during the first 15 days of June 2000. The different linestyles indicate several possible states of the Earth's atmosphere and surface. The thick solid line represents the real Earth albedo using real-time cloud cover and land surface. "No Clouds": A cloudless Earth with the real surface properties. "Overcast": a completely overcast (with water clouds) planet Earth. "Snowball" : a snowball Earth (all ground is frozen ice or snow) but covered with the real cloud amount."Snowball Nocl": a cloudless planet Earth during a glaciation. "Varying %cl": real planet Earth albedo but changing the mean cloud amount at each point of the Earth by -10, +10 and +20 % from bottom to top respectively.

Ford et al.(2003) [22] presented light curves for an unresolved Earth and for possible earth-like planets simulated by changing the surface features.

4 Problems for the detection of Earth-like planets

4.1 Brightness ratio

A planet orbiting around a star emitting a flux F_* acquires by reflection a brightness given by F_{rfl}. The ratio of both fluxes is given by (see [23])

$$\frac{F_{rfl}}{F_*} = \frac{A_{pl}}{4}(\frac{R_{pl}}{a})^2\phi(t)$$

where A_{pl} is the planetary albedo, a is the distance between the planet and the star, R_{pl} is the radius of the planet, and ϕ(t) is the orbital phase factor given by

$$\phi(t) = 1 - \sin i \sin(\frac{2\pi t}{P})$$

where i is the inclination of the planetary orbit with respect to the sky plane and P the period of the planet around the star.

On the other hand, the ratio between the thermal flux of the planet (centered in the IR range) and the stellar flux is given by the expression

$$\frac{F_{th}}{F_*} = \frac{R_{pl}}{2a}^2$$

Figure 4 shows the ratio of fluxes where we can see the advantage of observing in the infrared owing to the better contrast (1 part in 10^6) with respect to the visible (1 part in 10^9)

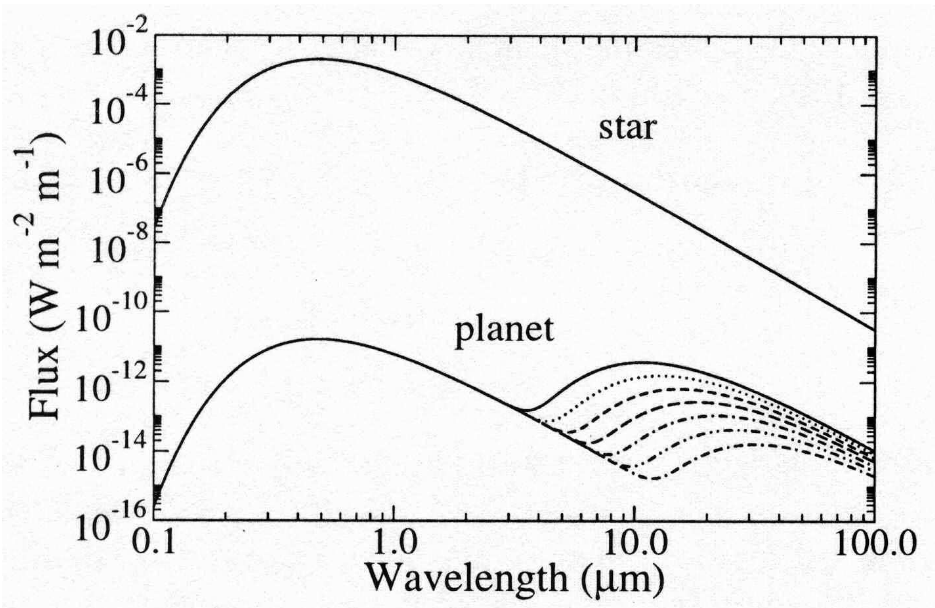

Figure 4: Flux of a solar-type star (upper solid line) at 5 pc, and the planetary flux (lower lines) of a Jupiter-like planet at 5.2 AU from the star, with and age of 0.125 (solid-line), 0.25, 0.5, 1.0, 2.0, 4.0 and 8.0 (dot-dash-dash line) Gyrs. Adapted from Fig. 2 of Stam et al. (2004) [24].

Here, we will briefly consider the limitations of the present-day techniques for the detection of Earth–like planets.

4.2 Astrometry

The astrometric signal, θ, of a planet with mass m_{pl}, orbiting a star with mass m_* at a distance d in a circular orbit of radius a is given by

$$\theta = 3\frac{m_{pl}}{m_E}(\frac{m_*}{m_{Sun}})^{-2/3}(\frac{P}{yr})^{2/3}(\frac{d}{pc})^{-1}$$

where θ is expressed in microarcseconds. To detect an Earth-like planet orbiting a solar-like star with a period of 1 year and observed at 5 pc of distance we would need a resolution of 0.6 μas, far beyond the present capabilities. Sozzetti (2005) [25] describes past and present efforts using this technique. The future Space Interferometry Mission (SIM) will achieve a precision of 1 μas, enough to detect Jupiter-like planets [26].

4.3 Radial velocity

This technique is based on the periodic variation of the star's radial velocity, ΔV, induced by the presence of a planet. From the application of Kepler's laws we have

$$\frac{(m_{pl}\sin i)^3}{(m_* + m_{pl})} = \frac{P}{2\pi G}\Delta V^3(1-e^2)^{3/2}$$

and if $\mathrm{m_{pl}} \ll \mathrm{m_*}$ we have

$$\mathrm{m_{pl}\sin i = (\frac{P}{2\pi G})^{1/3}\Delta V(1-e^2)\,m_*^{2/3}}$$

expressing the planetary mass in Jupiter masses, ΔV in m/s, and the period P in years, we have:

$$\mathrm{m_{pl}\sin(i) = 3.5\times 10^{-2}\Delta V.P}$$

For an Earth–like planet ($m_{pl} \sim 0.01 M_J$) orbiting a solar–like star with a period of 1 year, we need a resolution in velocity lower than 1 m/s, again this is far beyond the present-day capabilities. Moreover, a better understanding of intrinsic stellar variations is needed.

4.4 Transits

For a transit of a planet across the stellar disk to be observable, the planet must be aligned with the star as seen from Earth with an inclination $i > \theta_T$, where $\theta_T = \cos^{-1}[(R_* + R_p)/D]$, being the distance planet-star. Ehrenreich et al. (2005) [27] simulated the transit of different Earth-like planets across G,F and K stars. Several planets, all far larger than the Earth, have already been detected using this technique.

4.5 Microlensing events

The gravitational microlensing effect occurs when the gravitational field of a planet and its parent star act to magnify the light of a distant background star. For the effect to work the planet and star must pass almost directly between the observer and the distant star. The key advantage of this technique is that it allows low mass (i.e. Earth-like) planets to be detected using available technology (see [28]). A notable disadvantage is that the lensing cannot be repeated because the chance alignment never occurs again. Also, the detected planets will tend to be several kiloparsecs away, and follow-up observations would not be possible.

5 The Earth Spectrum

5.1 Visible

The Earth spectrum in the visible is dominated by the Rayleigh scattering combined with the effect of diffuse reflection of the earth's surface and the clouds. In Figure 5 the reflection spectra of the different bodies of the Solar System are shown for comparison. These measurements allow us to distinguish the main characteristics and composition of their atmospheres, and to derive estimates of the amounts of each atmospheric component for the averaged atmospheric depth. For well mixed gases, we can get their mixing ratios independently of the fact that we are not able to sample down to the planet's surface. For non-well-mixed gases we get a relative idea of their abundances, which can be improved with models if other variables such as mass, radius and temperature profile are know.

The overall shape of the earth's spectrum in the visible region shows interesting and peculiar signatures. The most prominent is the Rayleigh scattering, the cause of the blue color of our sky and the main source of opacity in the Earth's atmosphere, which shows an enhancement towards the blue part of the spectra (Figure 5). Except Neptune, no other solar system body shows this strong Rayleigh feature, and in the case of an extrasolar planet detection, it would be relatively easy to distinguish between a Neptune-like or Earth-like planet. At short wavelengths (< 310 nm) ozone absorption and UV absorption due to upper hazes (giant planets) dominates over the Rayleigh scattering.

5.2 UV and X-rays

At shorter wavelengths, UV and X-rays are strongly absorbed by the Earth's atmosphere, and we see broad absorption bands of oxygen and ozone producing a decrease in the reflected spectra intensity. Therefore images in these bands give only information about processes taking place in the upper atmospheric layers. This spectral

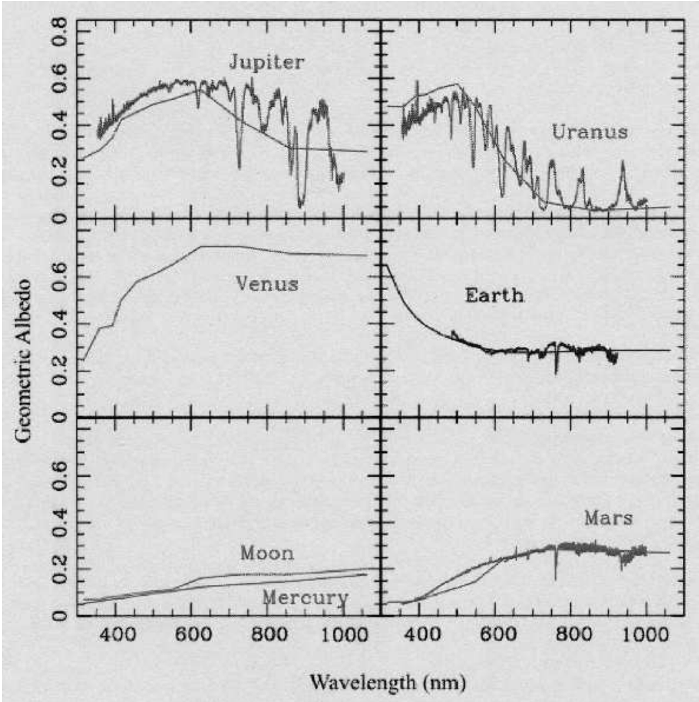

Figure 5: Spectral albedo for different planets of the Solar System and the Moon. Source: Traub et al. (2003) [29]

range is superimposed by different atomic and molecular lines that constitutes the airglow. As an example, we see the Earth glowing from space in the light of Lyman-alpha (Figure 6). The layer where this light is coming from is called the geocorona: a cloud of neutral hydrogen atoms that surrounds the Earth.

5.3 Infrared

The thermal emission of the Earth dominates the IR spectrum (see Figure 4). As corresponding to its effective temperature of 288 K, the IR brightness peaks around 10 μ and then decays slowly. It is superposed by different molecular bands corresponding to the most important atmospheric components (Figure 7). This range is the primary to study the atmospheric composition of the atmosphere of exoplanets.

5.4 Microwaves

Most planetary bodies are cooler than a few hundred degrees and emit very short radio waves (microwaves). The amount of microwave energy emitted by a planet is a

Figure 6: The Earth's geocorona as viewed from the surface of Moon. Image acquired during the Apollo 16 mission (April 1972) with the Naval Research Laboratory's far–ultraviolet camera/spectrograph. The Sun is to the left and the Earth's North Pole is towards the upper left. Source: Carruthers *et al.* (1976) [30]

measure of its temperature [1]. Microwaves are very powerful tools for remote sensing of the earth. Some ranges of frequencies are attenuated strongly by vegetation and atmospheric water, while others have considerable power to penetrate even clouds and thick jungle canopies.

6 Polarimetry

The study of the polarization of a stellar-planet system is a very promising method for extrasolar planet characterization. Using polarization, one can produce an occultation of the starlight, allowing a clear detection of the surrounding planet(s). Moreover, the degree of polarization, P, provides information about the planet's composition. P is determined by

$$\mathrm{P} = \frac{\mathrm{I_r} - \mathrm{I_l}}{\mathrm{I_r} + \mathrm{I_l}}$$

[1] Non-thermal emission (e.g. synchroton processes) can also contribute to the microwave emission.

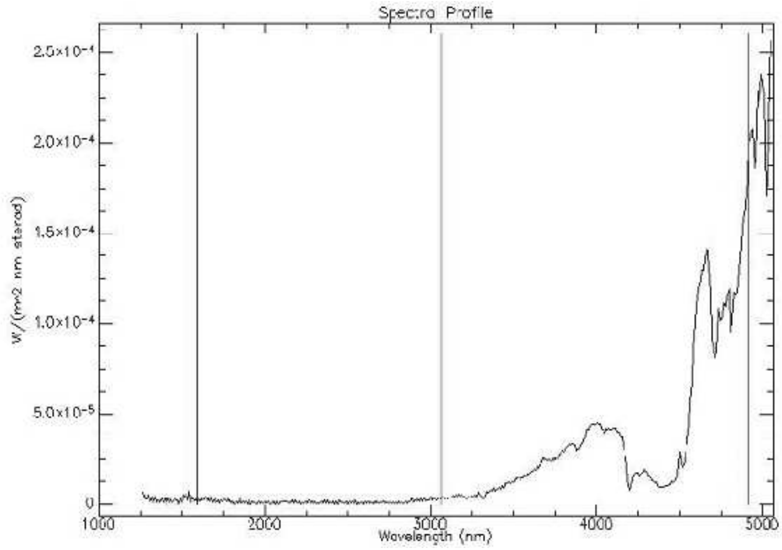

Figure 7: Infrared Spectrum of the Earth taken by the experiment VIRTIS onboard Rosetta during the March 2005 fly–by. Courtesy: ESA.

where I_l and I_r are the intensities polarized parallel and perpendicular to the plane containing the center of the star and the exoplanet.

Figure 8 shows the relevant geometry of the observations. The stellar light scattered by the exoplanet is linearly polarized. In the case of an unresolved system the observed polarization signal will be about 10^{-5}.

The flux and state of polarization of the planetary radiation can be described by a Stokes vector **F** (see [24])

$$\mathbf{F} = [\mathrm{F}(\lambda, \alpha), \mathrm{Q}(\lambda, \alpha), \mathrm{U}(\lambda, \alpha), \mathrm{V}(\lambda, \alpha)]$$

with α being the phase angle between the star and the observer as seen from the center of the planet (see Fig. 8). Here, Q and U describe the linearly polarized flux and V the circularly polarized flux. Now, assuming that the light of a solar–like star is not globally polarized (V=0) and adopting an adequate geometry (U=0), we have that

$$\mathrm{P}(\lambda, \alpha) = \frac{\mathrm{Q}(\lambda, \alpha)}{\mathrm{F}(\lambda, \alpha)} = \frac{\mathrm{Q}_{\mathrm{refl}}(\lambda, \alpha)}{\mathrm{F}_{\mathrm{refl}(\lambda, \alpha)} + \mathrm{F}_{\mathrm{ther}}(\lambda, \alpha)}$$

This way, polarimetric measurements improve the contrast exoplanet/star. Numerical simulations of polarization spectra of giant extrasolar planets have been made by Seager et al. (2000) [31] and Stam et al.(2004) [24]. Carciofi & Magalhães (2005) [32] and Selway et al. (2005) [33] studied the polarization signatures in planetary

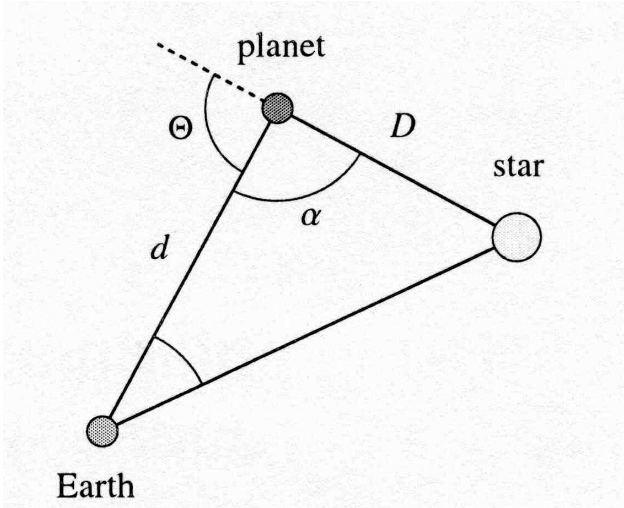

Figure 8: Distances and angles involved in observing an extrasolar planet. Adapted from Stam et al.(2004) [24]

transits and microlensing events, respectively. For information about the current instrumental projects aiming to get precisions of 10^{-7} given enough photons, see [34] and [35].

As with other techniques, global polarimetric observations of our planet will be the guideline. The POLDER experiment has measured polarization reflectances of the Earth from the ADEOS satellite [36].

7 Biosignatures and the search for life

Since Earth is the only known planet able to sustain life at a global scale, first efforts of determining the presence of life in other planets were based on biological experiments dependent on common features of life on Earth. We can divide the living organisms on Earth, and perhaps in some extrasolar planets, in three complexity levels: unicellular life, complex life and intelligent life.

7.1 Unicellular life

Methanogens, the more simple chemosynthetic bacteria, were probably the first organisms that appeared on Earth. They are responsible of the initial rise of atmospheric methane that also increased the temperature of the planet, warmed then by a fainter sun, and contributed to the development of more complex bacteria. These simple unicellular organisms are being searched in other planets in the solar system and have also been grown on a simulation of Martian soil in laboratory [37]. Three independent teams have recently detected methane in located equatorial regions of the Martian atmosphere [38][39][40]. Although this unexpected methane concentrations may turn out to have a geological origin [41], a living source remains as a plausible hypothesis. Another proposed candidate for habitability in the solar system is Saturn's satellite, Titan. On the contrary of all other solar system satellites Titan has an atmosphere, and many similarities to the abiotic (pre-life) earth's reducing atmosphere, which was composed of CH_4, N_2, NH_3, H_2, and H_2O [42]. Titan's atmosphere is a natural laboratory for organic chemistry. However, the satellite is extremely cold, doesn't have liquid water and has very little sunlight, three conditions considered essential for life. Present earth's biosphere is basically formed by organic matter generated, through photosynthesis, from carbon dioxide and water, with the input of solar energy. Early photosynthetic bacteria, such as cyanobacteria (blue algae), are believed to be responsible for the initial rise of oxygen in Earth 2,300 million years ago [43].

If we compare Earth's present atmosphere with that of an abiotic Earth we conclude that the biosphere is continuously regenerating gasses, which are in thermodynamic disequilibrium with the geochemistry of the rest of the planet. Therefore, any by-product of biological processes in non-chemical balance with other species in the atmosphere (as suggested by [44],[45] and [46]), constitutes an atmospheric biomarker. They are *indirect* consequence of biological activity and have been recently summarized in Table 2 of Gaidos and Selsis (2006) [47].

7.2 Complex Life

Complex life is constituted by highly specialized systems of cells, some of them capable of carrying out complicated functions. Photosynthesis of multicellular organisms is closely linked to several harvest molecules, being chlorophyll-a (Chl-a) the dominant on Earth. Chl-a behaves like an antenna, serving plants to collect solar energy. All healthy vegetation is chemically similar and shows green and infrared reflectance enhancement. The spectral inflexion point or red edge of the enhancement has been used to describe the variation in leaf and canopy chlorophyll concentration, since it may change depending on plant health conditions, specie and incident light. At Earth, vegetation may extend over large areas of the planetary surface allowing the direct detection of its pigments spectral signal from space. The detection of this signal represents an unquestionable indication of habitation. This red edge has been detected when observing a rather clear-sky green Earth's region with spatial resolution from the space [48], although its detection in globally integrated observations is controversial [49][50].

7.3 Intelligent life

At radio wavelength, the signals of our television and radio sets dominate the electromagnetic spectra of the Earth and are larger than the natural emissions from the Earth or the Sun. This gives this region of the spectra a very strong potential for the detection of such artificial signals in exoplanets. The SETI project is dedicated to this mission of listening to the stars.

Traditionally, this is considered the best range of the electromagnetic spectrum to search for and detect 'artificial' signatures emitted by an intelligent civilization. That might be an anthropogenic prejudice due to the fact that humans have chosen this specific technology for telecommunication processes, but there are certain advantages to the use of radio waves for interstellar communications, if such are ever to occur. For example there is almost nothing in outer space able to block or absorb radio frequencies, and it is easy to pin point the origin of such waves with accuracy. It is also quite easy to encrypt information within.

Rotational modulation of the radio emission of a Earth-like exoplanet will inform about the spatial distribution of the emitters and additionally about the distribution of the continents [51].

8 Conclusions

Although we are probably set for some surprises, the example of the Earth and the rest of the rocky planets of the solar system will be our guidance to classify and understand the multiplicity of planetary systems that might exist in our galaxy. However, the earth–extrasolar planets connection will work in both directions. When a substantial database of exoplanets becomes available, statistics of planetary formation and evolution will become possible. This will provide vital information in solving some of the questions about the formation and evolution of our own planet and the solar system, for which we still have no answers.

The current view on stellar evolution is very deterministic. The future and evolution of a star will depend on two basic properties, its mass and its metalicity. If these two quantities are know we can establish whether the star will go nova in a few million years or will end its days as a red giant. One of the few things that could change this deterministic 'future' of the star is the influence of companion stars.

For planets, the picture is a little more complicated. At first instance the mass of the planet, its composition, and the distance from the parent star will determine its habitability and evolution. But other factors can play a major role in its evolution. So, while to establish the solar-stellar connection we needed only to compare the stars, to establish the earth-exoplanets parallelism we will need to compare the planets but also the physical properties and evolution of their planetary systems as a whole.

Undoubtedly, one of the main concerns will be the search for life. If a planet has all the suitable original conditions to develop and sustain life, does life necessarily occur? And if it does, what are the average time scales for the development of bacteria, plants or intelligence?

We may also be able to determine how many of the 'rocky' planets that we detect have experienced a runaway greenhouse effect such as Venus, or how many have lost their atmosphere as Mars. What are the orbital and chance factors determining this planetary evolution? It would also be interesting to find out what is the role of meteorites, planet rotation and magnetic field, plate tectonics, etc. have on the development of planetary evolution, and ultimately on the habitability and life evolution on a wide range of planets. Ultimately we might even be able to answer the most important of these questions: are we alone?

References

[1] Intergovernmental Panel on Climate Change (IPCC), The Scientific Basis , J.T. Houghton, Y. Dong, M. Noguer, eds. (Cambridge University Press, 2001).

[2] Schrijver, C. J., Zwaan,C. 2000, Solar and Stellar Magnetic Activity, Cambridge: Cambridge University Press.

[3] Hoffman, P. F., Kaufman, A. J., Halverson,G. P., Schrag,D. P. 1998, Science, 281, 1342

[4] Des Marais, D. J., et al. 2003, Astrobiology, 3, 219

[5] Kasting, J. F., Catling, D. 2003, Ann. Review Astron. Astrophys. 41, 429

[6] Peale, S. J. 1977, IAU Colloq. 28: Planetary Satellites, 87

[7] Burns, J. A. 1986, IAU Colloq. 77: Some Background about Satellites, 117

[8] Eggenberger, A., Udry, S., Mayor, M. 2004, *A&A* , 417, 353

[9] Holman, M. J., Wiegert, P. A. 1999, Astronomical Journal, 117, 621

[10] Musielak, Z. E., Cuntz, M., Marshall, E. A., Stuit, T. D. 2005, *A&A* , 434, 355

[11] Lissauer, J. J., Quintana, E. V., Chambers, J. E., Duncan, M. J., Adams, F. C. 2004, Revista Mexicana de Astronomia y Astrofisica Conference Series, 22, 99

[12] Williams, D. M., Pollard, D. 2002, ASP Conf. Ser. 269: The Evolving Sun and its Influence on Planetary Environments, 201

[13] Noble, M., Musielak, Z. E., Cuntz, M. 2002, *Astrophys. J.* , 572, 1024

[14] Williams, D. M., Kasting, J. F., & Wade, R. A. 1997a, Nature, 385, 234

[15] Thommes, E. W., Lissauer, J. 2005, Proc. STCI: Astrophysics of Life, Cambridge University Press, 41

[16] Beer, M. E., King, A. R., Livio, M., Pringle, J. E. 2004, *M.N.R.A.S.* , 354, 763

[17] Laskar, J., Joutel, F., Robutel, P., 1993, Nature 361, 615

[18] Ortega, J. A., Shukla, S. P., Seager, S., 2005, American Astronomical Society Meeting Abstracts, 207

[19] Raval, A., Ramanathan, V. 1989, Nature, 342, 758

[20] Qiu, J., Goode,P.R., Pallé, E., Yurchyshin, V., Hickey,J., Montañés Rodríguez, P., Chu, M.C., Kolbe, E., Brown,C.T., Koonin, S.E. 2003, Journal of Geophysical Research (Atmospheres), 108, D22, 4709

[21] Pallé, E., Goode,P.R., Yurchyshin, V., Qiu, J., Hickey,J., Montañés Rodríguez, P., Chu, M.C., Kolbe,E., Brown,C.T., Koonin, S.E. 2003, Journal of Geophysical Research (Atmospheres), 108, D22, 4710

[22] Ford, E. B., Seager, S., Turner, E. L. 2003, ASP Conf. Ser. 294: Scientific Frontiers in Research on Extrasolar Planets, 294, 639

[23] Schneider, J. 2002, Proc. I European Workshop on Exo-Astrobiology: ESA SP-518, 409

[24] Stam, D. M., Hovenier, J. W., Waters, L. B. F. M. 2004, *A&A* , 428, 663

[25] Sozzetti, A. 2005, Publications Astronomical Society Pacific, 117, 1021

[26] Takeuchi, T., Velusamy, T., Lin, D. N. C. 2005, *Astrophys. J.* , 618, 987

[27] Ehrenreich, D., Tinetti, G., Lecavelier Des Etangs, A., Vidal-Madjar, A., & Selsis, F. 2005, ArXiv Astrophysics e-prints, arXiv:astro-ph/0510215

[28] Beaulieu, J. P. et al. 2006, Nature, 439, 437

[29] Traub, W. A. 2003, ASP Conf. Ser. 294: Scientific Frontiers in Research on Extrasolar Planets, 294, 595

[30] Carruthers, G. R., Page, T., Meier, R. R. 1976, Journal Geophysical Research, 81, 1664

[31] Seager, S., Whitney, B. A., Sasselov, D. D. 2000, *Astrophys. J.* , 540, 504

[32] Carciofi, A. C., Magalhães, A. M. 2005, *Astrophys. J.* , 635, 570

[33] Selway, K. L., Hendry, M. A., Lucas, P. W. 2005, Protostars and Planets V, Proceedings of the Conference held October 24-28, in Hawai'i. LPI Contribution No. 1286., p.8352.

[34] Gisler, D., et al. 2004, Proceedings SPIE, 5492, 463

[35] Lucas, P. W., Hough, J. H., Bailey, J. A. 2005, Protostars and Planets V, Proceedings of the Conference held October 24-28, Hawai'i. LPI Contribution No. 1286., p.8480.

[36] Sridhar Anjum, V.N., Ghosh, R. 2004, Int. J. Remote Sensing, 21, 805

[37] Kral, T. A., Bekkum, C. R., & McKay, C. P. 2004, Origins of Life and Evolution of the Biosphere, 34, 615

[38] Krasnopolsky, V. A., Maillard, J. P., Owen, T. C. 2004, Icarus, 172, 537

[39] Formisano, V., Atreya, S., Encrenaz, T., Ignatiev, N., Giuranna, M. 2004, Science, 306, 1758

[40] Mumma, M. J., Novak, R. E., Hewagama, T., Villanueva, G. L., Bonev, B. P., DiSanti, M. A., Smith, M. D., Dello Russo, N. 2005, AAS/Division for Planetary Sciences Meeting Abstracts, 37.

[41] Lyons, J. R., Manning, C., Nimmo, F. 2005, Geophysical Research Letters, 32, 13201

[42] Schaefer, L., Fegley, B. 2005, AAS/Division for Planetary Sciences Meeting Abstracts, 37

[43] Walker, J. C. G. 1977, Evolution of the Atmosphere, New York: Macmillan.

[44] Lovelock, J.E., 1965, Nature 207, 568

[45] Lovelock, J.E., 1975, Proc. Roy. Soc. London 189, 167

[46] Hitchcock, Lovelock, J.E., 1967, Icarus 7, 149

[47] Gaidos, E., Selsis, F. 2006, ArXiv Astrophysics e-prints, arXiv:astro-ph/0602008

[48] Sagan, C., Thompson, W. R., Carlson, R., Gurnett, D., Hord, C. 1993, Nature, 365, 715

[49] Woolf, N. J., Smith, P. S., Traub, W. A., Jucks, K. W. 2002, Astrophysical Journal, 574, 430

[50] Montañés-Rodriguez, P., Pallé, E., Goode, P. R., Hickey, J., & Koonin, S. E. 2005, Astrophysical Journal, 629, 1175

[51] Sullivan, W.T., Brown, S., Wetherill,C, Bahcall,J.N., 1978, Science, 199, 377