the Pontifical Academy of Sciences

De Natura Rerum: Exoplanets and ExoEarths

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Que l'homme contemple la nature dans sa haute et pleine majesté…

que la Terre lui paraisse comme un point.

Blaise Pascal (1623-1662) *Pensées*

Introduction

At the 2004 Plenary Session of the Pontifical Academy of Sciences on *Paths of Discovery*, I presented a paper with the title *The case of exoplanets* [Léna 2005]. It was then close to the 10th anniversary of the discovery of the first exoplanet in 1995. There is no point in repeating here this paper. But in the last decade, the discoveries on this subject have been so considerable that, the 20th anniversary coming, it is worth addressing the topic again. During the first decade 1995-2004, only 133 exoplanets had been discovered by an indirect method, and the first direct image of an exoplanet was not even confirmed. Today in our Galaxy containing the Earth, statistics begin to indicate that on average every star has a planet, which means over 100 billions of exoplanets for this galaxy alone, of which nearly 2000 are now identified and more or less characterized.

How does the subject of exoplanets relate with the *Evolving concepts of nature*, the title of this Plenary Session? In the 2005 paper, I recalled the long history of a quest which began metaphysically with Democritus, was disputed theologically during the Middle Age, provided phantasies to poets and writers, until it emerged as a scientific problem, to be addressed with the investigative methods of astronomy during the 19th century. Along this path, Giordano Bruno, who expressed ideas close to Lucretius's ones, was condemned to the fire for multiple reasons, including this one. Bruno still awaits some kind of rehabilitation by the Church, a gesture I personally hope for. Finally the discovery of a planet, comparable to Jupiter but closer to its star 51 Pegasi than Mercury is close to the Sun, was made in 1995 by Michel Mayor and Didier Queloz [Mayor & Queloz 1995].

Lucretius (98-55?), in his poem *De Natura Rerum*, aimed at transmitting to the Roman world the ideas of Epicure. He writes:

But by no means can it be thought probable, when infinite space is open in every quarter,[…] that this one globe of the earth, and this one heaven, have been alone produced;[…] especially when this world was made by merely natural causes, […] and to no purpose; […] For which reason, it is irresistibly incumbent on you to admit that there are other combinations of matter in other places, such as is this world, which the ether holds in its vast embrace. (II, 1051-1081) [Lucretius].

There is no finalism, no specific purpose in Lucretius. *Nature* for him is only a convenient word, a concession to his Roman public, not a deity or a metaphysical entity. Only random motion and matter create the world, as experienced by humans [Serres 1977]. Does it therefore belong to the *nature of things* to produce habitable planets and life, just as it is in the nature of quarks to produce the atomic elements, themselves producing the millions of molecules? The success of Aristotelian physics and their relay by Thomas Aquinas made Lucretius's views forgotten until the Renaissance and the Enlightenment. But, with the proliferation of exoplanets, a scientific approach becomes possible.

In this short talk, it will be impossible to render justice to the vast amount of observations and publications in this exploding field of research. One can simply try to indicate some trends and outstanding results, defining a new and less anthropocentric concept of *a planet*. Questioning the significance of these discoveries feeds back on the Earth itself and on the emergence of complexity, life and spirit on our *Pale blue dot* and, further, in the whole universe.

From 2004 to 2014, ten years of discoveries

What is a planet?

Twenty years ago, with the example of only one planetary system, ours, defining an exoplanet was inevitably somewhat "heliocentric", if not anthropocentric, including a preconception of what such an object could be [For a discussion, see Schneider *et al*. 2012]. The International Astronomical Union definition for our own Solar system, which led to the exile of Pluto from the Sun's planets, was given in 2006:

A “planet” is a celestial body that (a) is in orbit around the Sun; (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape; (c) has cleared the neighbourhood around its orbit.

With the wealth of recent discoveries, the definition has to take a broader, temporary and more empirical view, such as in Table 1, which uses mass, density and possibly distance of the planet to its star as discrimination criteria. But more exotic situations are encountered, which lead to expand this glossary (Table 2). IAU current definition of exoplanets [IAU 2014] is:

Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are planets (no matter how they formed). The minimum mass/size required for an extra-solar object to be considered a planet should be the same as that used in our Solar System. Sub-stellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are brown dwarfs, no matter how they formed nor where they are located. Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not planets, but are sub-brown dwarfs.

Table 1. Denominations of the “simple“ exoplanets

Denomination

Physical structure

Mass range

Examples

Jupiter like

Gaseous giant

50 ME < m < 1000 ME

Hot Jupiter

Gaseous Giant

42% of confirmed planets

50 ME < m < 1000 ME

Close to parent star

51 Peg b

Hot Neptune

Gaseous

10 ME < m < 50 ME

Gliese 436b

Mini Neptune

Gaseous (H and He)

#10 ME

Kepler 11 b, f

Super Earth

Solid

2 ME < m < 10 ME

Kepler 62 e, f

Earth-mass planet

Solid

1 ME

a Centauri Bb

ExoEarth

Solid, Habitable zone

1 ME < m < 10 ME

Jupiter mass = 320 ME. Neptune mass = 17 ME

Table 2. Denominations of more complex cases of exoplanets

Denomination	Physical structure	Examples
Pulsar planet	A planet left over around a pulsar	PSR 1257+12 b,c,d
Rogue planet	A lonely planet without star	CFBDSIR 2149-0403
Ocean planet	A planet covered with rocks in fusion, or liquid water	Gliese 1214 b
Circumbinary planet	A planet orbiting a double star	Kepler 16 b
Excentric planet	A planet with a high eccentricity orbit	HD 80606 b
Core planet	An evaporated gas giant	Corot 7 b (?)
Exomoon	A moon orbiting a planet	

Both Tables are adapted from [Wade 2013].

Since 2004, search methods have diversified and became more systematic, as two space observatories and new ground based instruments have been in operation. The result is given in Fig. 1, with 1832 planets confirmed today [The Exoplanets Encyclopedia 2014]. Over 4000 additional detections, made from space, await confirmation with a follow-up from a terrestrial observatory.

The bulk of the confirmed discoveries comes from two methods: the Doppler measurement of the periodic variations of the star velocity (e.g. the HARPS instrument from Geneva Observatory at the ESO La Silla telescope in Chile), detecting planets in the mass range from a few Earth mass ME to the Jupiter mass (320 ME); the star photometry showing a transiting planet in front of its star (e.g. the France/COROT and NASA/KEPLER observatories in space), able to detect planets of very low mass, down to 10-4 ME .

Measurements made with these two methods lead to the main physical properties of a planet (mass, radius, density) and their orbital characteristics (number of planet per system, orbital separations, eccentricities, geometries). Obtaining a direct image of an exoplanet is very difficult because of the intense radiation of the parent star and requires sophisticated coronographic techniques. Several tens of exoplanets are now imaged [Neuhaüser & Schmidt 2012]. They have masses comparable to Jupiter, as they need to scatter enough light from their parent star to be directly observed. Hence Doppler and transit photometry remain today the main source of discoveries and characterization of exoplanets. The quest for lower mass planets, in order to approach the mass of the Earth, has some symbolic importance and is very active. The first exoplanet with Earth-like mass, named Gliese 581e, was observed in 2009.

Some outstanding results

It is impossible here to give a fair picture of the exoplanets landscape, which can be explored in specialized references which provide detailed reviews on various aspects of the subject: a broad and excellent update on the field [Battacharjee & Clery 2013; Seager 2013; Wade 2013; Howard 2013]; the composition of planetary atmospheres [Tinetti, Encrenaz & Coustenis 2013; Seager & Deming 2010]; the direct imaging of planets [Neuhaüser & Schmidt 2012]; their formation from discs around the parent star [Williams & Cieza 2011]. Dedicated websites provide an updated picture of the subject [The Exoplanets Encyclopedia; NASA Exoplanet Archives] and offer tools to classify and analyze the wealth of ever increasing data. A newsletter [Norton 2014] provides regular information on publications. The present paper has essentially borrowed its information and figures from these sources, trying to extract some of the salient facts, in order to give an idea of the current developments.

Parent stars. *Which stars do have one or several planets?* Although stars similar to the Sun were the first search targets, planets exist around almost all types of stars, from hot and short-lived ones (A-stars) to cold and long-lived ones (M stars), even from pulsars to binary stars. M dwarf stars are particularly interesting, These stars are extremely abundant in the Galaxy, as in any galaxy; their low surface temperature, hence negligible ultraviolet emission, are favorable to a complex molecular composition of the planetary atmosphere; their lifetime is long, again favorable to complex chemical evolutionary processes. Enough cases are now known to begin estimating the average occurrence of exoplanets in our Galaxy, leading to an average number of one planet per star [Cassan *et al.* 2012] (some stars having systems with many planets).

Stars and planets are formed together from an interstellar cloud collapsing through a gravitational accretion process. If the formation of the parent star is well understood now, the concomitant formation of its planetary system is a process difficult problem, which is far from being solved today [Williams & Cieza 2011]. Yet, the first attempts of exoplanet population synthesis are made [Benz *et al.* 2014] to answer the question of the occurrence frequency of planets and of their mass distribution, knowing well these quantities for stars. We do not know how this process privileges the multiplicity of planets around a star, but one can assert that planet formation is a stochastic process.

Planetary orbits. *Do planets have circular or elliptical orbits?* The star being given, orbits determine the temperature of the planet, or its variations if highly elliptical. Contrary to the Solar System case, many orbits show high eccentricity, implying severe changes in surface temperature in the course of the orbital motion (Fig. 2). Giant gaseous planets may be very close to the parent star, reaching surface temperatures beyond 1000 K. Gravitational perturbations or viscous frictions with residual matter in the discs can modify the orbits, provoking migrations of planets: this explains why massive, Jupiter-like planets, formed far away from the star, have migrated and today are observed very close to the star (less than 0.01 AU!).

Density. *Can one distinguish rocky, telluric type planets from gaseous planets?* The density of a planet is determined by measuring its radius with the transit method (Fig. 3). The existence of rocky planets, such as Earth, Venus, Mercury and Mars, is clearly demonstrated. Some gas giant planets may be heated beyond the prediction of the simple hydrogen model. Smaller planets (less than 30 ME) are more scattered in size, probably because their diversity in composition and atmospheres. The planet KOI 314 c, found by NASA Kepler in 2014 at a distance of 200 light-years, has the mass of the Earth, but is 60% larger in size, a puzzle indeed [Cowen 2014].

Masses of the planets. *What do we know about the mass distribution?* The distribution of masses appears bimodal (Fig. 4), emphasizing the importance of low-mass population [Pepe *et al.* 2011]. Planets intermediate

in size between Earth and Neptune (10 ME) appear frequent. Around M stars, statistics obtained by the Kepler observatory (transits) indicate a high rate of planet occurrence. Earth-size planets (0.5 to 1.4 RE) are found in the habitable zone (see below) of ca. 15 % of the M dwarf and cold stars.

Atmospheric composition. *Do planets have atmospheres and of which kind*? The composition of atmospheres can be measured thanks to spectroscopic observations of the light of the star transmitted through the atmosphere during a primary transit, or of the infrared light emitted by the planet and disappearing during a secondary eclipse (Fig. 5). Initially limited to hot Jupiters (*Spitzer* NASA observatory), spectroscopic sensitivity will study SuperEarths and later Earth-like bodies.

An atmosphere at 1000K with standard abundances of elements will be dominated by H2, H2O and contain CH4, CO, CO2. All these molecules have been observed in hot Jupiters. SuperEarths will be very interesting due to evolutionary effects, which may have produced a great diversity of composition, atmospheres and surfaces, for example a planet formed of 50% of water.

Habitable zone. *Are certain planets more favorable for the search of life?* The concept of habitable zone around a star was first introduced in 1993, and has since become quite elaborate. The original idea is to establish, for a given star, the range of distances where liquid water could subsist at the surface of a planet orbiting this star, liquid water being connected to the question of life existence and evolution. But this simple-minded definition of *habitability* is complicated by the presence of a planetary atmosphere, which can lead to a strong greenhouse effect as in Venus, with high ground temperature, or a moderate one as on Earth, where it weakly raises the surface temperature, or no such effect on the colder Mars. Hence the great diversity of exoplanets leads to examine more closely the habitable zone [Seager 2013] (Fig.6). Although no ExoEarth has yet been found, located at the right place, two planets were detected by Kepler observatory with masses of 1.4 and 1.6 ME, both located in the classically defined habitable zone. And in April 2014, the planet Kepler-186 f, with 0.99 ME, was found within the habitable zone of its star. Additional criteria are needed to ensure a thin atmosphere – as on the Earth – rather than a thick one – as on Venus.

The search for life on exoplanets

The field of bioastronomy (or astrobiology) is developing very fast as an interdisciplinary and presently speculative field. It addresses the question of “exolife”. A *Study week on Astrobiology* was held at the Pontifical Academy in 2009 and its main conclusions [Astrobiology Study Week 2009], recalled below, remain valid today.

The present knowledge on the apparition and early development of life on Earth remains scarce. Firmly dated to 3.5 billions years ago with the discovery of simple prokaryotes cells, it might yet have happened earlier. RNA might have been the beginning of this primitive life, but we do not know if it happened only once or in several independent niches. Life on Earth has an extraordinary ability to adapt to the most extreme environments, once thought to be sterile, such as the deep reaches of the Earth’s crust. Species in deep sea’s hydrothermal vents demonstrate a rich source of possibilities for the emergence of early ecosystems, which do not involve photosynthesis and do not depend of the light from the parent star. Hence the conventional definition of habitable zone within a planetary system is overly conservative; conversely, the presence of water may not be sufficient to ensure habitability.

Numerous studies appear necessary to understand the history of oxygen on Earth, and its role around 800-600 millions years ago for the emergence of multicellular life forms. Many questions remain open on the origin of water and other volatile elements on the Earth. How did Earth acquire its complement of carbon, and in what form? How much organic interstellar chemistry survived inclusion in the protoplanetary disc and how much prebiotic chemistry did occur in primitive bodies like comets? In the solar system, the main targets for exploration are Mars, Titan, Enceladus and Europa. The sampling of a comet nucleus may provide important information, as the planned landing (Nov 12, 2014) on the cometary nucleus 67P/Churyumov-Gerasimenko.

Regarding exoplanets, several steps need to be considered. Although a general theory of planetary evolution, building up on the excellent knowledge available on the interstellar medium, appears for the moment out of reach, formation models must include geochemistry, considering the great variety of possible catalytic minerals. The best chance of going from organic chemistry to biochemistry is to find mechanisms and conditions that produce a limited number of organic compounds known to be intermediates in metabolic networks or biochemical synthesis.

In parallel, the determination of possible biosignatures on selected exoplanets and their search with telescopes, especially along the anoxygenic photosynthetic pathways, needs focused research. This may be guided by observing how the Earth, with life on its surface, appears seen from far away, as if it were an unresolved dot of light (Fig. 7). Atmospheric constituents demonstrating a long lasting out-of-equilibrium situation, as the presence of ozone lines in the Earth’s spectrum, are key features in this search for biosignatures.

Conclusion

In the last 10 years, the field of exoplanetary research has exploded. The observing tools from the first decade have been refined, multiplying by more than 10 the number of objects and revealing their diversity. A new generation of instruments has been prepared, with higher sensitivity and a better adaptation to the questions to be answered. Among them are the space missions GAIA (launched 2013), JWST (NASA, launch ca. 2020) and PLATO (under construction, ESA), the ground-based telescope European-ELT (not yet funded) (Fig. 8).

Yet, it is extremely difficult to predict how the field of exoplanet research will evolve in the next decade. The new and specifically planned instruments will certainly enrich quantitatively and qualitatively the collection of exoplanets. But the hope is faint to establish for these objects a diagram similar to the one Hertzprung-Russel diagram established for stars a century ago, showing that with two parameters only – surface temperature (i.e. colour) and absolute luminosity – one could classify and determine the properties of most of the stars, locating them on the famous Hertzprung-Russel diagram. It is hoped but quite unlikely that the diversity of physical, chemical and possibly even biological conditions on exoplanets will allow such a simplifying scheme. But this extreme diversity, produced by the intimate interplay between gravitational forces and electromagnetic forces at the scale of planetary systems, is a chance for finding surprises of all kind. It also challenges preconceptions of planets, derived from our own solar system.

Cosmology of the early universe allows to explore the transition from a universe entirely ruled by quantum unified fields to one dominated everywhere by matter and atoms; the chemistry in the interstellar medium reveals the transition from atoms to molecules everywhere; exoplanet research is now offering the field of investigation for the transition from molecules to life. Pierre Teilhard de Chardin described a universe of increasing and converging complexity, with successive emergences of matter, life and spirit. Astronomy unveiled the first, and is on the way to unveil the second!

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