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FROM THE SOLAR SYSTEM TO EXO-PLANETARY SYSTEMS HISTORICAL AND EPISTEMOLOGICAL CONSIDERATIONS

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Abstract. We relate the path of the knowledge, from the world centered on the Earth, and the stars located in the sphere of fixed, to the progressive discovery that stars are suns with multiple planet systems.

Keywords: History, Solar system, Extrasolar planets

1 Introduction

How did the Solar System come out as a physical entity, an object? How and when did we understand that many such systems actually exist? As a preamble, let us note that, whereas we use to refer to the system made of our Sun and its cortege of planets as the Solar System, on the contrary, systems made of any other star accompanied by planets are referred to as planetary systems rather than stellar systems, the later designation being reserved to multiple stars. Before the name solar system came in use, men knew it as the world system.

2 Antiquity

For centuries, the mathematical model established by Claudius Ptolemeus (c.90 A.D.-c.168A.D.), combining his own observations with those of many predecessors including Hipparchus (190-120 B.C.), had been the reference for predicting the positions and motions of stars and planets. Based on this model, motions of celestial objects would be calculated by combining the motions of a series of nested spheres. In the Ptolemaic representation, the Earth is the center of the world. A series of mobile spheres correspond to the motions of the Moon and the planets known at that time. The last sphere is the sphere of fixed stars which rotates as a solid body. So our world was spherical, limited by the "sphere of the fixed".

The question was raised very early in the Antiquity by Greek philosophers: Can other worlds possibly exist outside the sphere of the fixed stars, similar or not to our own? This question is known as "the debate on the multiplicity of worlds". Obviously, at that time, those words did not assume the same meaning as they do nowadays. Indeed, in the context of our knowledge and our understanding today, the locution "multiplicity of worlds" suggests the existence of planets orbiting remote stars unrelated to the Sun. In the past, stars glued on the sphere of the fixed were far from being considered as other suns. Multiple worlds were conceived as outside the closed world centered on the Earth and containing any visible celestial body inside the volume delimitated by the sphere of the fixed. The existence of other worlds, similar or not to our own, may be in infinite number, was considered a possibility, out of reach of our observations. It was conceptually acceptable to imagine such hypothetic and inaccessible worlds centered on a planet which could shelter living creatures. The oldest known references about such other worlds come from the Greek philosophers, in particular Democritus (470-365 BC) and Epicure (342-270 BC). *"There is an infinite number of worlds of different sizes: some are larger than ours, some have no sun or moon, others have suns or moons that are bigger than ours. Some have many suns and moons. Worlds are spaced at differing distances from each other; in some parts of the universe there are more worlds, in other parts fewer. In some areas they are growing, in other parts, decreasing... There are some worlds with no living creatures, plants, or moisture."* Democritus. *"There is an infinity of worlds both like and unlike our world. For the atoms being infinite in number, as was already proved, are borne on far out into*

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space. For those atoms which are of such nature that a world could be created by them or made by them, have not been used up either on one world or a limited number of worlds, nor again on worlds which are alike, or on those which are different from these. So that there nowhere exists an obstacle to the infinite number of worlds". Epicure, disciple of Democritus, *"Letter to Herodotus"*. Plato (427-348 BC) and Aristotle (384 -322 BC) were of the opposite opinion : *"...it follows from the same evidence and by the same compulsion, that the world must be unique. There cannot be several worlds."*Aristotle.

3 Middle Age

In the course of the Middle Age, another parameter came into the picture: the scientific theory had to comply with the religious doctrine. Concerning the multiplicity of worlds, there were however two competing theological interpretations. The first one stated that, according to the Biblical account of the creation, God creates one and only one world, thus leaving no room to other worlds. The other interpretation, on the contrary, stressed that since the Bible does not specify that God did not create several worlds, the omnipotence of God implies that He could create other worlds. The question of other worlds gave birth to a violent controversy. In 1277, Etienne Tempier, the bishop of Paris, condemned 219 beliefs which he considered heretical since they contravened the power of God. One of these beliefs was that *"the First Cause cannot make many worlds"*.

The system of the world according to Hipparchus and also to Ptolemy implied that the whole world beyond the Moon was perfect. The perfect geometrical figures being the circle and the sphere, celestial bodies had to assume perfect motions (i.e. circular motions). The sky was immutable. However, it had been known for long that astronomical observations of planetary motions did not correspond to the perfect figure. Planets did not follow plain circular trajectories. Observed motions, particularly the apparent retrograde motions of some planets, were then explained by circles moving on other circles, that is epicycloids or epicycles. As astronomical observations grew in precision epicycles were added to epicycles, until the system reached deterrent complexity.

4 Sixteenth century - Heliocentrism

In 1543, Nicolaus Copernicus (1473-1543), in his book *De Revolutionibus*, had the brilliant idea to establish the Sun at the center of the world. Doing so, he drastically simplified the system of epicycles. The heliocentric system had taken the place of the geocentric system. The modern description of the solar system is still basically unchanged. But, how about the sphere of the fixed ? One of the first observational evidence against the immutability of the sky was the surge of a "New Star" in 1572. This star has been accurately observed by Tycho Brahe (1546-1601). It is described in his book *De Nova Stella, (About a New Star)*. The modern astronomical word *Nova* has its origin in this book. However, we know now that the stellar phenomenon observed by Tycho Brahe was what we nowadays call a *Supernova*. When this star appeared, it was very bright, then its luminosity decreased. Tycho Brahe could not determine its parallax, and after several months of observations, established that its position did not vary with respect to the fixed stars. So there was a new star attached to the sphere of the fixed. This implied that contrary to the many century belief, the sky is not immutable.

By the end of the sixteenth century, Giordano Bruno (1548-1600) defended the idea of multiple worlds, inhabited by a multiplicity of living beings. His argument was theological. The power of God being infinite by nature, His creation could not be limited to only one finite world. Yet, Bruno's multiple worlds were not unobservable abstractions, he adopted the Copernican system, and he considered that stars are Suns, with planets. *"That is how the excellence of God is magnified and the greatness of His empire is demonstrated. He is not glorified in only one Sun, but in countless suns, not in only one Earth and one world, but in thousands of thousands, no, an infinity [of worlds]." "Innumerable suns exist; innumerable earths revolve around these suns in a manner similar to the way the seven planets revolve around our sun"*. Giordano Bruno was sentenced to death and burnt in Roma by order of the Inquisition. Since the nineteenth century, he is sometimes considered as a martyr for science. Actually, his religious beliefs against the dogma, estimated as heretical, were probably more important for the sentence.

5 Seventeenth century - Plurality of Worlds

In 1609, Galileo Galilei (1564-1642) pointed an optical instrument, his refracting telescope towards a number of celestial objects. The tremendous harvest of results that followed was reported in *Sidereus Nuncius, (The*

Sidereal Messenger) a book published quite rapidly. In particular, he discovered satellites, i.e. moons, orbiting around planet Jupiter. This result demonstrated that celestial objects may be orbiting around something else than the Earth. So the Earth was not anymore the centre of the world. Browsing the Milky Way with his telescope Galileo discovered that the milk is made of a multitude of stars. So the number of stars in the sphere of the fixed increased dramatically. Galileo considered every star as a Sun.

As for Bruno and Galileo, René Descartes (1596-1650) in his book *Le Monde ou le Traité de la lumière (The World or Treatise on Light)*, takes it for granted that the number of stars is infinite and each star is a Sun. His book was written in 1632 and 1633, at the time of the trial of Galileo, but for fear of the Inquisition, this book was published only in 1664, after the death of Descartes.

Christiaan Huygens (1629-1695) evaluated the distance to Sirius by comparing its luminosity with the Sun luminosity. His evaluation was based on the assumption that the Sun and the stars are similar objects.

In 1686, Bernard le Bouyer de Fontenelle (1657-1757) published *Entretiens sur la Pluralité des Mondes*, translated in English as *A Discovery of New Worlds* or *Conversation on the Plurality of Worlds.* It was a real "best-seller" , in the modern acception. The book was quite often re-edited and translated in many languages. Its influence was great throughout Europe. *"Les étoiles sont autant de soleils dont chacun éclaire un monde." (Every fixed star is a sun illuminating its surrounding worlds)* Fontenelle assumed that the Moon and all planets might be inhabited. He considered that the inhabitants might be different from humans. He also envisaged a broad diversity of forms of life on earth even under extreme conditions. Fontenelle wrote his book 76 ans after the decisive observations of Galileo, giving a measure of the progresses of astronomy in between. During the 18th century, the possibility of life on planets orbiting stars other than our sun was commonly accepted.

"Les cieux sont peuplés de corps lumineux qui, semblables à notre soleil, font vraisemblablement rouler des planètes dans différentes orbites". (Skies are crowded with luminous bodies, which, similar to our sun, most likely drive planets on various orbits) Condillac, Cours d'étude pour l'Instruction du prince de Parme (1775) Condillac again : *"et l'univers est un espace immense, où il n'y a point de désert. Notre imagination est aussi embarrassée à lui donner des bornes qu'à ne lui en pas donner" (Universe is an immensity where there are no deserts. Assigning or not assigning limits to its immensity is an equal challenge to our imagination).*

6 How did planets form: nebula or catastrophe ?

Earliest models for the formation of planetary systems adopt the evolutionist scheme, assuming that planet birth is a natural part of the star formation process. According to the ideas formulated by Descartes (1633), the early universe is crowded with whirlpools. Heaviest elements tend to concentrate at the center of each vortex, giving birth to central stars, while the lightest ones stay at the periphery and form planets. One century later, Emmanuel Kant (1724-1804) in 1755, proposed a scenario where star formation occurs by collapse of a swinging material cloud, a swinging nebula. Then Pierre-Simon de Laplace (1749-1827) in 1796 developed the mathematical principles necessary to control the model. During the collapse, the angular momentum must be preserved; hence the centrifugal force creates a disc in the plane perpendicular to the main rotation axis. Then the disc splits into concentric rings out of which planets will form. Catastrophic models, on the contrary, assume that planets result from isolated, violent cataclysmic events. According to Buffon (1707-1788) in 1741, a comet colliding the Sun would snatch a cloud of debris which would later condense into a planet. By the beginning of the XXth century, the collisional scenario was generally favoured. The swinging nebula scenario suffered from arguments in relation with sharing angular momentum between the Sun and planets. At that time the Solar system was the only known system, there was no indication concerning the frequency of the phenomenon. Obviously, depending on the adopted scenario, the probability for a star to be escorted by a swarm of planets changes drastically. In the catastrophic scenario, planets are formed under accidental circumstances and this is not expected to occur frequently. On the contrary, in the swinging nebula picture, planets form naturally under common circumstances. In the recent decades, the situation changed drastically and the catastrophic scenario lost its precedence. During year 1995, the astronomical community experienced a strong excitement : for the first time evidence was given for the existence of a planet orbiting a star which was not the Sun. The star is known as 51 Pegasi. The planet was betrayed by small variations of the central star's radial velocity. The discoverers, Michel Mayor and Didier Queloz, two Swiss astronomers operating at Observatoire de Haute Provence, used a new camera they had developed to monitor small radial velocity variations in a selection of nearby stars. They were actually in search of the slightest sign of an extrasolar planet, but what they got was surprisingly different from what they expected. The planet orbited around 51Peg with a period of 4.23 days. According to the laws of celestial mechanics, such rapid radial velocity variations imply a planet much closer to

the central star than Mercury to the Sun, but the amplitude of the observed variations signed a mass equivalent to Jupiter. Planetology at that time admitted that giant planets like Jupiter or Saturn would necessarily be icy, requiring orbits that keep them away from the heat of the central star, that is long period orbits. Jupiter's period is 12 years. So the first extrasolar planet ever found imposes immediately a new category, it is a "hot Jupiter". Had the new thing been more conformist, the discoverers would have needed years of efforts before getting the result. Yet it is their merit to have identified in quasi real time the anomaly and to give it the right interpretation against their own prejudices. A quarter of a century later in 2019, there are more than 4000 planets identified in 3039 systems, out of which 658 are multiple. Every day brings its lot of new discoveries. The sample survey achieved by the dedicated space telescope Kepler establishes that there are more planets than stars in the Milky Way, that is hundreds of billions. Based on this flood of new facts, scenarios of planetary formation had to be completely re-considered. Recent models almost universally accepted, keep the idea of star and planets born from a nebula in a unique process, but they give a major importance to mechanisms of migration. Planets were born very far from the central star and do migrate on the long range towards the center. So planetary systems around stars are common and it is tempting to admit that a large fraction of them are more or less similar to our good old Solar System. Implying, in the back of minds that circumstances permitting the surge and evolution of life could be rather common. However...

7 Inhabited ?

However, a result published in 1993 shows that the development of life on earth might result from a highly improbable random event. This event is not the product of an imaginative fiction; it came as a result of extremely rigorous investigations in celestial mechanics. Laskar, Joutel and Robutel (*Nature*, vol. 361, 1993) demonstrated that on the very long range, the Earth axis would not be kept at almost stable inclination with respect to the plane of the ecliptic unless it is constrained to do so by a specific stabilising mechanism. And this specific mechanism is the Moon. Without the Moon, the so-called inclination which controls seasons and climate would be subject to large amplitude chaotic variations making the development of evolved and complex forms of life impossible. However, there is a general agreement that the Moon itself is the result of a random cataclysmic collision. The catastrophic theory is back. Is the solar system sheltering a very developed life on a planet with stable climate a unique or very rare in the Galaxy ? Future will give the answer may be, or certainly.

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