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L’invention du système solaire (XVIe-XVIIIe siècles)

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Introduction: the invention of the solar system (16th-18th centuries). Writing the history of a recent astronomical concept: the planetary system. Epistemological relevance and methodological precautions

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Didier Foucault

PLAN

TEXTE

1 Astronomers first realised that they needed the concept "planetary system" with the discovery of exoplanets in 1995. And yet, since Antiquity scholars have learned to distinguish between the planets, the Sun and the Moon, by observing that their trajectories differed from those of the "fixed stars", and by developing geocentric models describing their movements in a structured Cosmos. The astronomical revolution of the 16th and 17th centuries, which, after Copernicus, came up with the expressions "planetary system" and "solar system", giving the Sun a central role in a planetary dynamic that henceforth included the Earth, expanded the range of what was visible and explained the dynamics of astral bodies orbiting our star, showing that the planets themselves could also be at the centre of comparable systems.

2 For some time after the Copernican revolution, the solar system was the only planetary system known to modern astronomy. Once other planetary systems were discovered, everything that had been learned in almost five centuries of astronomical work suddenly acquired a new dimension: this body of knowledge became a sort of reference point for understanding other planetary systems, for what we already know about our own Solar System and its components is a much more solid foundation than anything that can be deduced from the still tenuous data collected by observing exoplanets.

3 Therefore, studying the origin and development of the concept "planetary system" to the present day is both intrinsically legitimate and useful to planetary science and astrophysics in helping them address the theoretical challenges they face with the daily discovery of new planetary systems, of course provided this is done with rigour and method.

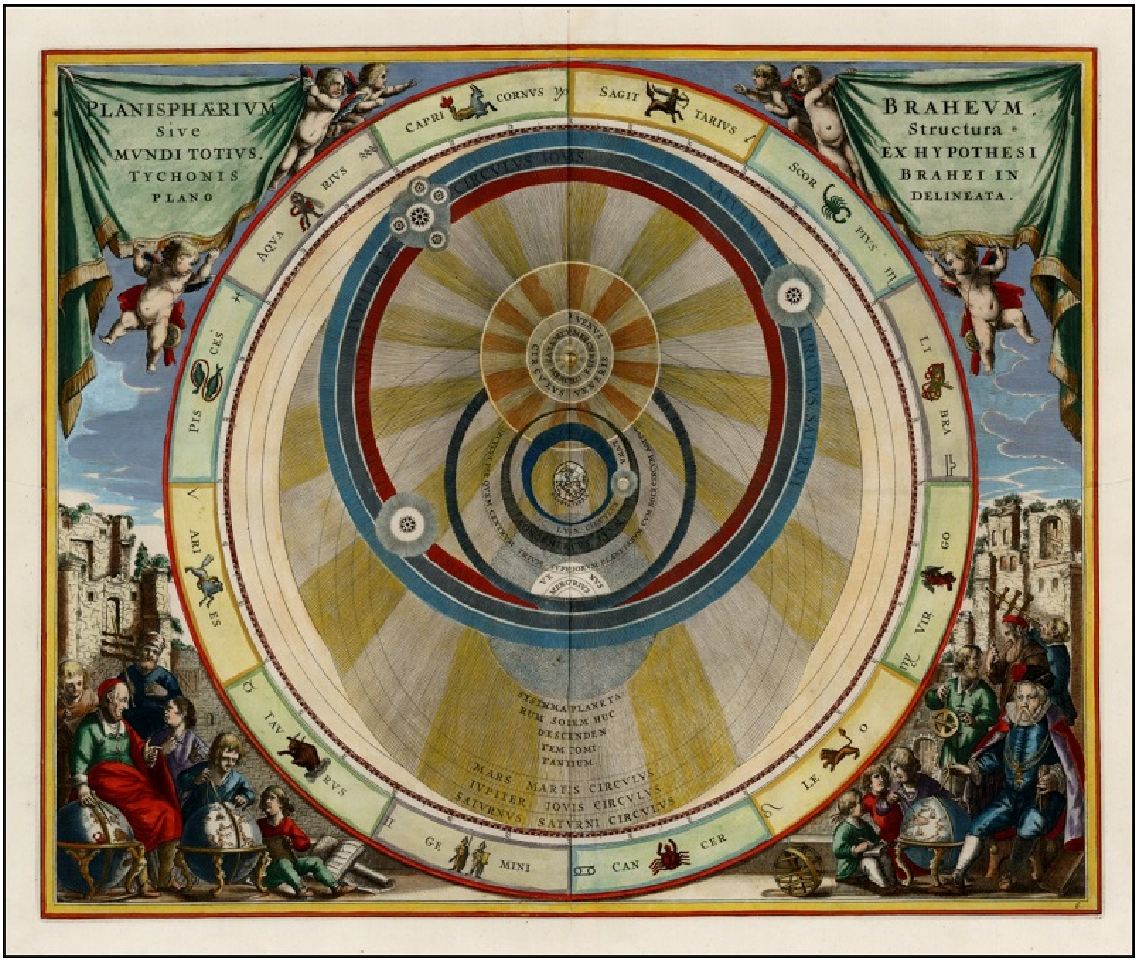
1. "Planetary System" in the lexicon of Copernican astronomers

4 It seems to have been Kepler who, in his *Astronomia nova*, first used the expression "*systemata planetaria*",[1] attributing it to the Danish astronomer Tycho Brahe. While always referring to Brahe, Kepler uses this notion several more times in his treatise in a slightly different form; for example: "... *Sol ipse in centrum mundi* (Copernico) *vel saltem in centrum systematis Planetarii* (Tychoni) *veniat* [... the Sun itself [sits] at the centre of the world (according to Copernicus) or at least at the centre of a planetary system (according to Tycho)]".[2] In fact, Kepler, as this passage makes clear, uses the term to distinguish it from the "world system", which refers to an overall, organised conception of the Cosmos, since the two scholars considered that the latter has a centre: for Copernicus this is the Sun and for Tycho, the Earth. On this particular point, Tycho remained faithful to Aristotle and Ptolemy, but his new contribution was to have identified, within his geocentric system, another system formed by five planets (Mercury, Venus, Mars, Jupiter and Saturn) that move around the Sun, while at the same time being drawn along by the Sun as it orbits the Earth. It is this secondary system that Kepler calls *systemata planetaria/planetarii*, or planetary system. However, in the *Epitome*, pub-

lished in 1620, the expression clearly takes on a different meaning: "2. Are all the orbs of the five planets, with the Earth at their centre, driven by a circular motion around the Sun, as if the Sun were enclosed within them? 3. Does the Sun sit at the centre of the entire planetary system...?"[3] In this case, there can be no mistake: by using "planetary system", Kepler refers exclusively to the system formed by the Sun and the six planets (including Earth) that revolve around it, with the notable exclusion of the fixed stars.

5 In the 17th century, in the tumult that followed the work of Galileo, cosmological research gradually moved beyond Tycho Brahe's short-lived and somewhat baroque system, focusing instead on the "two chief world systems", to quote the title of the book that brought the wrath of the Inquisition down on Galileo. Overshadowed by this confrontation, the notion of planetary systems became of far less interest to scientists. But it was not abandoned totally. As evidence, we might draw attention to the map entitled *Planisphaerium sive Muni totius Tychonis plano*, published in 1661 (Fig.1), which contains the mention "*systema planetarum ...solem...comitantium*" [system of planets accompanying the Sun] to indicate, as Kepler does in the *Astronomia nova*, the space covered by the five planets centred on the Sun in the Tychonian system, or the *Description and Use of the Planetary System Together with Easy Tables* (1674) by the English astronomer Thomas Streete, the first use of the expression in the title of a book.

(Fig. 1). Tycho Brahe's World System



(Planisphaerium sive Muni totius Tychonis plano. In A. Cellarius, Harmonia macrocosmica, 1661).

6 The notion then gradually began to spread. In the 1762 edition of the *Dictionnaire de l'Académie Française*, for example, the entry for "System" specifies (in French): "... We also call System, An assemblage of bodies. *The planetary system*". Although quite what was understood by this expression is unclear, this is not the case in Samuel Pye's work published in London in 1766 entitled, *The Mosaic Theory of the Solar, or Planetary System*, which clearly compares the system derived from Copernicus's theories with the Book of Genesis. [4]

7 This rare use of the expression "planetary system" may seem paradoxical to us today because, if we consider the major issues that inspired scientific research after Newton, the precision of this notion offers greater heuristic potential than "world system", which was

nonetheless used more frequently. Indeed, it was precisely because the conditions for observation and astronomical calculation at the time made it difficult to investigate much beyond the solar system (which gained a new element in 1781 with the discovery of Uranus), that there was no clear distinction between "world system" and "planetary system". Thus, even though Book III of Newton's *Mathematical Principles of Natural Philosophy* is entitled *De systemate mundi*, it mainly deals with the laws of gravity applied to the celestial bodies that make up the Solar System alone.[5] A century later, in 1787, an "*Exposition abrégée du système du monde*" (Shortened version of the World System) by the Regius Professor Jacques-Antoine-Joseph Cousin begins in a similar vein with, "The celestial bodies that make up our planetary system are divided into principal planets, that have the Sun as the centre of their motion, and secondary planets, called *satellites*,[6] that rotate around the main planet."[7]

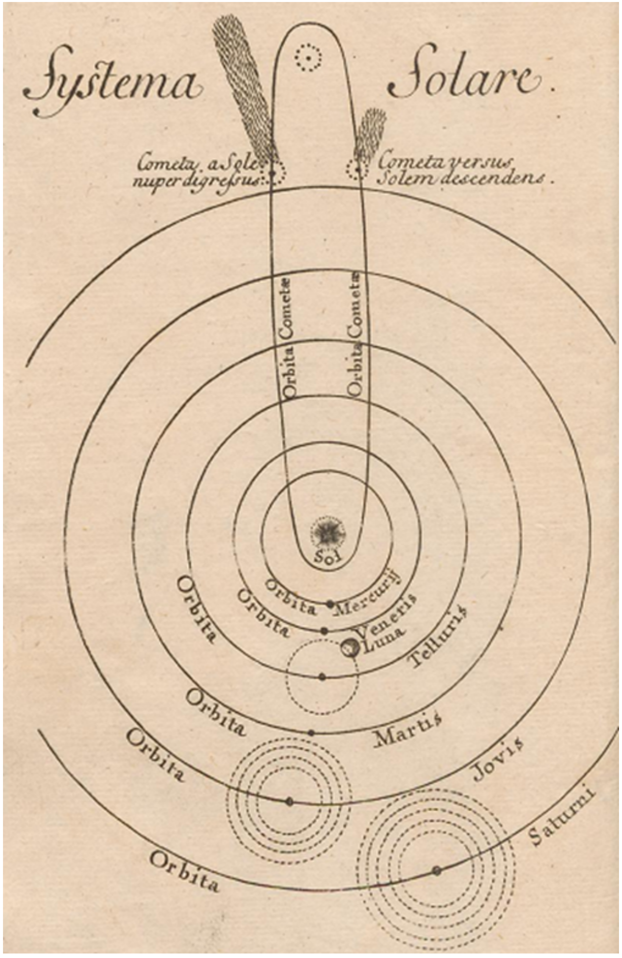
8 Last but not least, in 1796 Pierre Simon Laplace published his masterly *Exposition du système du monde*,[8] but one can observe, with Jacques Merleau-Ponty and Bruno Morando, that he restricts himself to presenting "a theory of the solar system", i.e. a "very small part of the universe".[9]

2. "Solar system" and secondary planetary systems

9 Astronomy has therefore long concentrated on the only known planetary system, the solar system, showing only a limited interest in the other formations in the universe. I should add that, while heliocentrism, as a world system, was commonly called the "Copernican system" from the earliest decades of the 18th century, it was not until the end of that century that people timidly began to speak of a "solar system". In 1696, William Whiston's A *New Theory of the Earth* opened with a representation of the *Systema solare* that displays an actual planetary system *stricto sensu* (Fig. 2).[10] The Sun is at the centre and is surrounded by the "orbits" of the planets. The orbits of the Moon, the four satellites of Jupiter and five satellites of Saturn are also shown. Remarkably, an elliptical "*Orbita cometae*" stretches from near the Sun to beyond Saturn, meaning that it is considered to be a real

part of the system, whereas it can in no way be considered a "world system" since no stars are represented.

(Fig. 2). The First Representation of the 'Solar System'

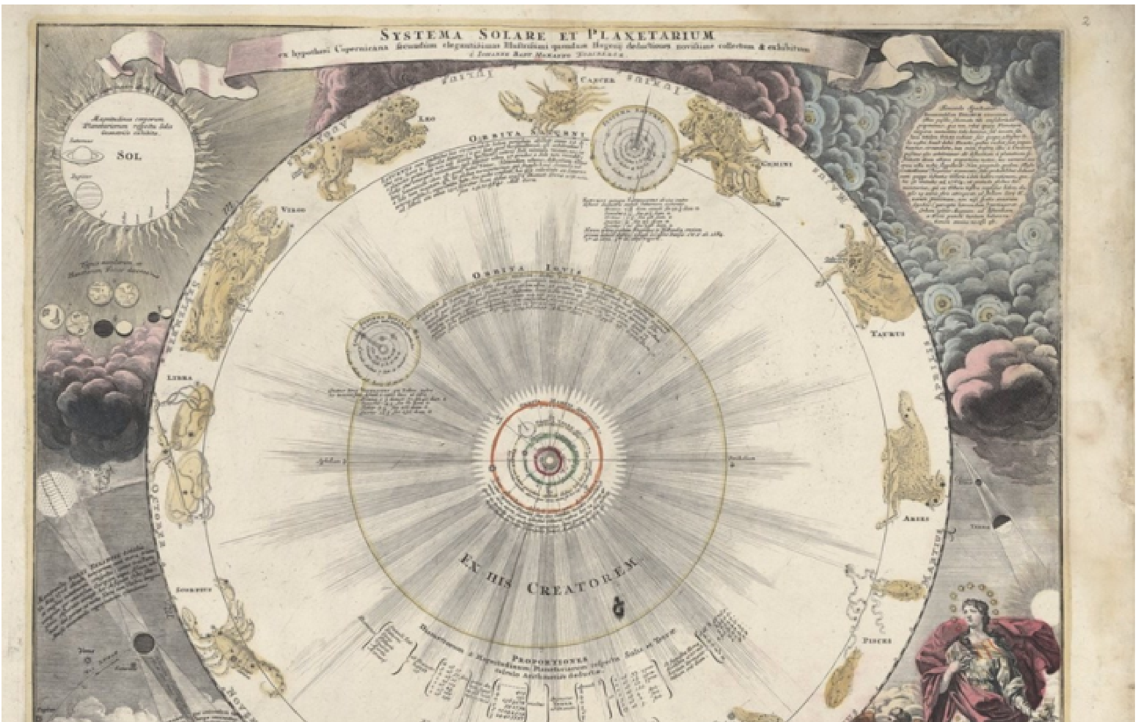


(A New Theorie of the Earth, from its Original, to the Consummation of All Things, by W. Whiston, Printed by R. Roberts, London, 1696).

10 It was therefore only late and very slowly that the term "solar system" entered scientific discourse. In 1702, another Englishman, David Gregory,[11] in his *Astronomiae physicae and geometricae elementa*, took up the expression. It has been suggested that John Locke first coined the term "solar system" in his *Elements of Natural Philosophy* in 1706. The following year, it appeared for the first time in Latin in the title of an astronomical essay, *Ausfürliche Erklärung über zwei neue homännische Charten als über das Systema solare et planetarium copernico-hugenianum und europam Eclipsatam* [Complete explanation of two maps by Homman on the solar and planetary system of

Copernic and Huygens and the eclipse in Europe] by Johann Gabriel Doppelmayr, written in German and published in Nuremberg on 10 May 1706 (Fig. 3). I should here point out that while Doppelmayr uses both expressions – "solar system" and "planetary system" – he does not consider them to be synonymous, as he only used "planetary systems" to refer explicitly to the secondary systems formed by the Earth, Jupiter and Saturn and their respective satellites.[12]

(Fig. 3). The Solar System and its Planets according to Homann and Doppelmayr



(J-B. Homman, J. G. Doppelmayr, Systema solare et planetarium : ex hypothesi Copernicana secundum elegantissimas Illustrissimi quondam Hugenij deductiones, novissime collectum et exhibitum à Iohanne Bapt. Homanno, Noribergae, 1742).

11 Such examples show to what extent scholars hesitated in naming the systems formed by a planet and the satellites orbiting it. This is certainly not unrelated to the time it took scientists to name the celestial bodies that make up these secondary planetary systems. When, in his *Sidereus nuncius*, Galileo first mentioned his discovery of the

moons of Jupiter, he used the expressions *stellula* [small star], *stella* [star], and *sidus* [heavenly body, star], sometimes associated with the qualifier *vagans* [vagrant], before considering that these stars are *planetae medicei* [Medici planets], naming them after the reigning family in Tuscany.[13] It was Kepler, in 1611, who first used the word *satelles* [bodyguard, companion] to describe these stars wandering around Jupiter, in his N*arratio de observatis a se quatuor Jovis satellitibus erronibus.*[14] But, while he originally qualified these *satelles* as *Iovialis* [belonging to Jupiter], he soon began to use the term indifferently for the two planetary systems known to him at the time, the Earth's and Jupiter's.[15] However, he sometimes used other words to designate satellites. He even used *planeta*, accompanying it with a qualifier: *planeta jovialis*[16] [for Jupiter] or *secundarius planeta* for the Earth [17] or Jupiter[18], as opposed to the six *planetae primarii*[19] He also uses *pedissequa* [follower] or *comes* [travelling companion] as synonyms.[20]

12 The other astronomer to have discovered the moons of Jupiter, Simon Marius, uses many terms to describe them but does not use *satelles*,[21] whereas he was in contact with Kepler, who had suggested that he name them Io, Europe, Ganymede and Calisto.[22] This lexical vagueness remained throughout the following decades. Thus, on 5 June 1655, when Huygens announced to Frans van Schooten the discovery of Saturn's first satellite, Titan, he spoke only of *noviluna* or *luna. Luna* also appears in the anagram sent shortly afterwards to John Wallis and Kinner, and "*lune*" in his correspondence in French with Chapelain the following year. On 6 July 1656, Roberval informed him that he had been spreading the news about "*la lune de Saturne*". However, when he wrote to his brother, on 6 November 1655, he used a different expression, "*satellite saturnien*".[23] The changes in the aspect of Saturn had troubled scholars since Galileo's observations, until Huygens, equipped with a very powerful telescope, further enhanced knowledge of the planet's environment by revealing the existence of a ring. The uncertainty surrounding this vocabulary finally resolved to produce the terms for the bodies that orbit a planet (its satellites and rings). Huygens himself and many others used both the terms "world" and "system", but adding "Saturnian" or just "of Saturn".[24] Newton himself, although he frequently wrote of *satelletes*,

also used *planeta*, distinguishing between *planetae circumjoviales* and *planetae primarii* or *circumsolares.* [25]

13 Despite the obvious analogy with the Earth-Moon system, to which Galileo first drew attention [26], most scholars of the 17th century hesitated considerably regarding the inclusion of the three known secondary planetary systems in a single idea, which itself was closely related to the idea of the main system that revolves around the Sun. In fact, it was mainly on the basis of Newton's work that the law of gravity places these four systems within a universal theoretical framework that could also be applied to any subsequent discoveries. For Newton indeed, the force that keeps the satellites of Jupiter and Saturn, the Moon and the six "primary" planets in their orbits, centres on the body around which they turn; that force is inversely proportional to the square of the distance to its centre and proportional to the quantity of matter contained in each. [27]

3. The discovery of exoplanets and extending the theoretical scope of the "planetary system"

14 Excited by the discoveries of modern astronomy, scientists and writers quickly postulated a plurality of other worlds; in other words, other planetary systems. In Antiquity, many pre-Socratic thinkers supported this idea. Later, in classical Greece, although some scholars agreed with Aristotle in rejecting it and assuming the geocentric system and the immutability of the heavens, the Epicureans in particular continued to teach it until Roman times, as the second book of Lucretius's poem *De Natura rerum* [*On the Nature of Things*] testifies. Considered as heretical by medieval Christianity, the plurality of worlds timidly resurfaced as an idea in the philosophical debates of the late Middle Ages, notably with the publication of Nicholas de Cusa's *On Learned Ignorance*. It was, however, in the last decades of the 16th century, in the wake of Copernicus's work, that the themes of the infinity of the universe and the plurality of worlds seriously reemerged. Giordano Bruno made them the central theme of his treatise *On the Infinite, Universe and Worlds*; he was burned at the stake by the Inquisition in Rome in 1600 for refusing to retract on this

point. By showing the irregular surface of the Moon, sunspots, and the satellites of Jupiter, Galileo's astronomical telescope undermined the idea that the Earth enjoyed special status in the Cosmos and, consequently, implicitly accredited the notion that these bodies might not be any different from Earth and could even be inhabited. Philosophers and astronomers then seized upon these various issues to try and incorporate them into their own ideas about the universe (Descartes, Fontenelle, Huygens). Some saw them as a way of reconciling the new astronomy with the teaching of the Bible (Wilkins, Borel), while others made use of them in fiction, where an imaginary journey would serve as an implicit criticism of contemporary society or for describing utopias (Kepler, Campanella, More, Godwin, Cyrano de Bergerac). [28]

15 However, while this notion became and remained a popular literary theme from as early as the 17th century, this does not mean that it should be considered as a genuine epistomological concept: scientific proof of the existence of a single object (the solar system, even with its accompanying systems orbiting the planets of the main system) cannot alone be an epistemological concept. This is why it took more than three centuries for the notion of planetary system to finally emerge from the realm of science fiction and be taken seriously by astronomers.

16 In 1985, the astronomers who were preparing to watch the return of Halley's comet could still complain, like Mario Rigutti:

> Despite the great strides made in astronomy in recent decades, the origin of the solar system is still a matter of hypotheses and conjectures. Although there has been no shortage of research, and even though it has been carried out with all the means provided by modern techniques and with the use of all types of the most suitable instruments, both on Earth and in space, our planetary system is the only one actually known. [29]

17 Yet humanity was on the verge of overcoming this limitation. In 1995, when the scientific community was evaluating the announcement made in 1992 of the discovery of two planets orbiting the pulsar PSR B1257+12 by the Polish astronomer Alexander Wolszczan, two Swiss astronomers working at the Haute-Provence Observatory, Michel

Mayor and Didier Queloz, discovered the exoplanet 51 Pegasi b. It was the first time that a planet outside the solar system had been formally identified. A very large number of stars of the same nature were then spotted in different parts of our galaxy. Since then, discoveries have progressed almost exponentially, to such an extent that the figures need to be revised practically every day: on 20 February 2018, 2795 planetary systems had been formally authenticated, 622 of which were multiple planet systems, i.e. a total of 3729 exoplanets. [30]

18 Thus the notion of "planetary system", originally formulated as a way of describing the structure of the solar system and then as a philosophical and astronomical hypothesis, has thus become universal and a cosmological concept defining any system formed by a star (or, in a secondary role, by any astral body) and by the bodies orbiting around it: planets, dwarf planets, natural satellites, comets, asteroids, clouds or discs of dust, rocks or blocks of ice, to which must be added gases, charged particles, plasmas, magnetic fluids...

4. From Antiquity to Newton: conceptualising the constituent notions of a planetary system

19 It is therefore entirely legitimate to consider that Copernicus laid the first foundations of the modern notion of a planetary system. But before this founding moment, centred on the solar system, is it justified to look even more deeply into the history of the concept? [31]

20 Other historians of science have indeed addressed this problem. One such was Georges Canguilhem, who studied *La formation du concept de réflexe aux* XVII*e* *et* XVIII*e* *siècles*, and around 1840 physiologists included it as a part of their own field of science. Let us read how Canguilhem justified his approach:

> If [a] concept, logically sketched out or formed in such a context, is later captured by some theory that uses it in a context and meaning different from the former, this does not mean that the said concept is condemned to lose all its meaning within the initial theory. Because there are some concepts that are theoretically versatile...In any case, we cannot admit that the success of a concept in a given theor-

> etical field should constitute a sufficient reason for limiting the search for the places of its birth to the same type of theoretical fields. [32]

21 In other words, if we apply his remarks to the development of the concept of planetary systems, its actual theoretical context, which gives the concept its richness, should not prevent us from looking in other contexts, in other visions of the universe, for elements that could have participated in its emergence in Early Modern times, even before it was formulated and defined in terms of contemporary cosmology. A few remarks on the conditions under which the astronomical revolution of 16th and 17th centuries took place will explain this position:

22 - When Copernicus placed the Sun instead of the Earth at the centre of the Cosmos, he upset the very nature of this cosmic centre and not the fact that the Cosmos is organised around a centre. Now, this notion of a centre, whose origins date far back in the astronomical tradition, beyond the Greeks and as far as the Babylonians, is preserved in the Copernican conception of a planetary system. A study of how ancient astronomers expressed this theory and attempted to formulate it based on their observation of the heavens is therefore fully part of the research we wish to undertake. In particular, we want to examine the cosmological theories that succeeded one another up to eve of the Copernican revolution: the theories held by the Mesopotamians, the Greeks, the Arabs and mediaeval Christian scholars.

23 - As a corollary of the notion of a centre, we have the circular and regular motion of the astral bodies around this centre. Despite Kepler's corrections, there is a dynamic pattern here that is all the more worthy of attention for being based on practice and instruments for angular measurement of the position of celestial bodies, which modern astronomy has not fundamentally called into question. This also supposes the idea of predictability (or that of retroactive determination) of the position of these bodies and thus that these studies can be expressed mathematically (through geometry and, later, trigonometry and algebra). Whether these are largely guided by astrological concerns is irrelevant here, since they are based on the paradigm (clearly formulated by Pythagoras and Plato, before being taken up by Aristotle, Ptolemy and the astronomers who followed

them) of a celestial world governed by numbers and mathematical figures. And despite occupying a very different mental universe, modern astronomy, from Kepler, through Newton, right up to Einstein, in no way challenges this.

24 - While the ancient astronomers imagined an eighth heaven forming a celestial arch on which the visible fixed stars were placed, they noticed that certain bodies moved independently, remaining in a relatively narrow section of the heavens that they named the Zodiac. “Below” the twelve constellations they described, there were seven bodies that did not follow the immutable movement of the stars. Two were of remarkable size: the Sun and the Moon; they called these luminaries. The other five were more difficult to observe, even though the light they emit does not flicker like that from the stars. Their relative movement deep in the heavens is indeed much slower; it only becomes apparent after multiple observations, night after night. They are wandering stars (in Greek *planêtês*: “wandering, vagrant”) from which Latin derives *planeta* and English “planet”. Very early, in Antiquity, certain features of the trajectories of the planets were studied and accurately described: notably the retrogradations, by which they seemed to reverse their motion. In the same way, the duration of these bodies’ revolutions was fairly well known; it served as a basis for determining the major divisions of time (day, month and year).

25 As a result, even if the geocentric system is, strictly speaking, an imaginary planetary system, it constitutes a theoretical matrix that has a certain relevance and cannot be excluded from the history of planetary systems. In many respects its oldest periods, those in which the elements that compose it began to be identified, belong to the prehistory of the concept of planetary system, and to its protohistory for the most elaborate schema, the one developed by Aristotle and especially by Ptolemy, later enriched by Arab and Christian scholars of the Middle Ages. Without this slow development over the millennia, thanks to meticulous observations and calculations, neither Copernicus nor his successors would have been able to make the progress they achieved in astronomy. At most, like the Pythagoreans or Aristarchus of Samos in Antiquity and many others, they might have been able to imagine a heliocentric scheme but without solid rational and experimental foundations.

26 However, if we look more closely at what the astronomical revolution was, it is clear that Copernicus only really got things started. While refocusing interest on the Sun was of decisive epistemological significance, as well as reducing the Earth to the status of an ordinary planet, this by no means meant that he fully realised the structure of this entire planetary system. Thus, between the middle of the 16th and the end of 17th centuries, the Copernican system was progressively refined, eventually settling on the idea of a “solar system” capable of accepting more and increasingly complex elements without any need to rethink its basic structure.

5. Preliminary methodological and epistemological precautions

27 Before closing this overview and in order to show the complexity of the influences between ancient and modern astronomies, and in spite of the fundamental disruptions that occurred after Copernicus, let us take one last example, which is at the very heart of the modern conception of planetary systems: the theory of universal gravitation. Before discussing it, we need to guard against an error that often taints the history of science: anachronism. To seek the origin of a concept in the past does not mean to postulate that it had been hidden from the beginning of time and was only gradually brought to light by scholars. Concepts are not eternal Platonic “ideas”, Aristotelian “forms” or scholastic “essences”, existing in some kind of a vacuum; they are theoretical constructions produced by humans in their attempts to understand the phenomena they observe. They only properly make sense within a given conception of the world, which may be a mixture of various rational or irrational elements (notably religious and magical). To grasp these ideological constructions, or here, cosmological theories affected to varying extents by cosmogonic or astrological perceptions, we must free ourselves of the mental outlook of the time and environment in which we live. The philosopher of science and historian of astronomy, Alexandre Koyré, issued a clear warning on this point:

> It is sometimes necessary not only to forget the truths that have become an integral part of our thinking, but even to adopt certain

> modes or certain categories of reasoning, or at least certain metaphysical principles that, for people of the past, were as valid and reliable bases of reasoning and research as the principles of mathematical physics and the data of astronomy are for us. [33]

28 This is the case when we look at the notion of attraction. In ancient cosmology inspired by astrological thinking (we should not forget that Ptolemy is the author of an astrological treatise, *The Tetrabiblos*, [34] which was at least as influential as his great astronomical treatise, the *Almagest*) [35] the bodies in the universe, in particular those of the superlunar world (the macrocosm) and those of the sublunar world (the microcosm) exert influences on each other. Thus, for example, observing the rhythm of the tides, ancient scholars saw how they matched the phases of the Moon and, to a lesser extent, the positions of the Sun. [36] If we accept the existence of these occult, hidden, mysterious influences, we can provide perfectly satisfactory explanations for the tides. But for a mechanical rationalist, this hypothesis is worthless: for these scholars (such as Galileo, who was very hostile to anything related to astrology and hermeticism) [37] such assumptions are pure fantasies. Newton, who, as we know, was keenly interested in the occult (especially alchemy), had no such objection. All the observational data and calculations that proliferated in his century, on the dynamics of both physical bodies (investigated by Galileo, among others) and celestial bodies (following Kepler's work), did not invalidate his hypotheses but on the contrary confirmed them. Thus, he ignored the epistemological obstacles that held back mechanical physicists (especially the Cartesians) and postulated a "universal attraction" that, for the first time, linked the laws of physics to those of astronomy in a unifying theory. What was the mysterious nature of this attraction? No-one knows and Newton did not attempt to explain it. [38] Yet for more than three centuries, attraction has been the basis of all astronomical calculations and those for preparing interplanetary flights to bodies very far away from our Earth.

29 It is clear, then, that it would be dangerous to recklessly incorporate the ancient notion of attraction into a study of the development of modern cosmology, just as it would be to completely exclude it by disassociating it from the rest of the mental universe in which it originated.

Conclusion

30 To conclude these series of remarks, clearly it is important to look at the historical conditions that, since Antiquity, have made it possible to envisage cosmic systems around the Earth, provided that we take the proper methodological precautions. These cosmic systems, mostly consisting of planets, may seem like early versions of what we now mean by “planetary system”. It is equally important to study how some elements of these systems were not abandoned when the theories that supported them collapsed, but were used during the astronomical revolution and recomposed in the theoretical representation of the solar system. Moreover, we need to examine how understanding this system became more complex as new areas of planetology arose, starting in the 19th century (although I have not mentioned this subject above). This has gained momentum in the last fifty years, marked by space exploration and the sending of numerous probes in different directions of the solar system. Finally, with so many exoplanets being discovered in the extrasolar galaxy, and the concept of planetary systems becoming universal, it would be fruitful to explore the way these discoveries help bring forth new models of planetary systems, different from the solar system, and to see how these models yet to be built deal with the issues raised by the study of the solar system. Such subjects is certainly a work in progress to be completed by scientists of the future; but a lucid and rigorous look back at the experience of past generations and their theoretical and methodological contributions may well prove useful to planetologists confronted by this crucial stage of their discipline.

NOTES

1 *Astronomia nova*, Heidelberg, 1609, 129 (III- 22). To my knowledge, Michel-Pierre Lerner was the first to attribute the creation of the phrase “planetary system” to Kepler. M-P. Lerner, *Le monde des sphères* (Paris: Vrin, 2008), 210.

2 J. Kepler, *Astronomia… op. cit.* 169 (II-33). Another example: “By what physical cause is the circular trajectory of the centre of the planetary system (for Tycho) or of the Earth (for Copernicus) or the epicycle carrying the axis (Ptolemy) increased or decreased?”; he explains what he means by

centrum systematis planetarii in a note (III-22, page 125). For the French translation used by the author, see J. Kepler, *Astronomie nouvelle* (Bordeaux: J. Peyroux 1979), 156/216.

3 "2. *An orbes omnes quinque planetarum, & Terrae illorum médii, circa Solem circumducti sint, sic, ut Sol in omnium complexu sit. 3. An sol occupet centrum ipsum totius systematis planetarii...*". In J. Kepler, *Epitome astronomiae copernicanae, Fancofurti, Ioannes Godefridius Schönwetterus* (1635), 535 (IV, V). All subsequent footnotes refer to this edition.

4 The expression only starts to become common from the 1780s. See *Astronomy Improved: or*, *A New Theory of the Harmonious Regularity Observable in the Mechanism or Movements of the Planetary System* (anonymous, Newhaven: 1784); W. Jones, *The Description and Use of a New Portable Orrery, on a Most Simple Construction, Representing in Two Parts – The Motions, and Phenomena of the Planetary System* (London: 1787).

5 I. Newton, *Philosophiae naturalis principia mathematica* (London: Joseph Streater, 1687), 401 et seq. It is true that Newton's main concern was to justify the centripetal force introduced in Book I and the gravitational force introduced in Book III. Also note that at the end of the treatise, Newton hypothesises the existence of extrasolar planetary systems: "And if each fixed star is the centre of a system similar to ours, it is certain that, as everything is the result of the same design, everything must be subjected to one and the same Being" [*Et si chaque étoile fixe est le centre d'un sistême semblable au nôtre, il est certain que tout portant l'empreinte d'un même dessein, tout doit être soumis à un seul et même Être*]; but this is in the style of a philosophical apology and not a scientific argument. Quoted in *Principes mathématiques de la philosophie naturelle* (Paris: Saillant, 1759, trans. É. du Châtelet), 175 (2).

6 J-A-J. Cousin, *Introduction à l'étude de l'astronomie physique* (Paris: Didot l'aîné, 1787), 1.

7 "*Les corps célestes qui composent notre systême planétaire se divisent en planetes principales qui ont le Soleil pour centre de leur mouvement, et en planetes secondaires, qu'on appelle satellites, qui tournent autour de la planete principale.*"

8 Republished in the *Corpus des œuvres de philosophie en langue française* (Paris: Fayard, 1984).

9 J. Merleau-Ponty, B. Morando, *Les trois étapes de la cosmologie* (Paris: Robert Laffont, 1971), 86. Quoted by M-P. Lerner, *Le monde des sphères... op.*

cit. 217.

10 William Whiston or Wiston (1667-1652) was an English pastor, theologian and mathematician. His *New Theory of the Earth* [*Nouvelle théorie de la Terre*] is an attempt to reconcile the teachings of the Bible with the scientific discoveries of his time. Believing that the great catastrophes were associated with the passage of comets, and sharing Newton's astronomical ideas as well as the hypothesis (put forward by Cassini and proven by Halley) that they returned regularly after following an elliptical orbit around the Sun, he deduced that the Flood was caused by the same comet that he had observed in 1680.

11 D. Gregory (1661-1708) was a Scottish mathematician and astronomer best known for his work with Newton.

12 J. G. Doppelmayr, *Ausfürliche Erklärung über zwei neue homännische Charten als über das Systema solare et planetarium copernico-hugenianum und europam Eclipsatam* (Nürnberg: Johann Bapt. Homann, 1707), 4. Homann (1664-1724) was a famous German cartographer, whose collected works are published *Grosser Atlas über die ganze Welt* (1716). He collaborated for many years with Doppelmayr (1677-1750), a mathematician, astronomer and cartographer, who continued his work and reissued the *Atlas* with additions, at the publishing house in Nuremberg owned by Homann's heirs. Fig. 3, taken from the *Atlas* of 1742, is a reproduction of the one made after the total solar eclipse of 1706 and on which Doppelmayr's booklet forms a commentary. Other early uses of the term "solar system" in a title include: J. Neale, *The Description of the Planetary Machine, for which His Majesty has Granted his Royal Patent. With a Brief* Account *of the Solar System, from the Reverend M*r. *Whiston* (London, 1745).

13 G. Galilei, *Sidereus nuncius* (Francofurti: Zacharia Palthenius, 1610), 17 et seq. The full title says that the author names them "*Medicea sidera*".

14 J. Kepler, *Narratio de observatis a se quatuor Jovis satellitibus erronibus* (Francofurti: Zacharia Palthenius, 1611).

15 For example: "*… sic etiam Terram Luna sua, Iovem suis satellitibus…* ". See J. Kepler, *Epitome … op. cit.* 555 (IV, VI).

16 *Ibid.* 824 (VI, II), 873 (VI, VII).

17 *Ibid.* 452 (IV, III).

18 *Ibid.* 873 (VI, VII).

19 *Ibid.* 449 (IV, III).

20 *Ibid.*

21 S. Marius, *Mundus iovialis anno* M.DC.IX. *detectus ope perspicili belgici, hoc est quatuor Jovialium planetarum* (Norimbergis: 1614). In addition to *iovialis planeta*, used in the title (and also *secundarius iovialis planeta*, 34), we also find the following, generally together with the adjective *iovalis* (also used alone as a noun): *sidus* (5), *stellula* (12), *stella* (13), *corpus* (13, combined with *errans* 25), *corpusculum* (23), *circulator* (23), and *erro* (wandering, 26). Note: there is no page numbering in the treatise.

22 *Ibid.* 31. Marius had initially named the four satellites: “Saturn”, “Jupiter”, “Venus” and “Mercury”, describing them as “Jupiterian” (23-25); realising the confusion with the “primary” planets this could cause, he accepted Kepler's suggestion (32). Following a highly nationalist vision of astronomical nomenclature, and just as Galileo had dedicated them to the Medicis, he named them *Sidera Brandenburgica* (Brandenburg stars, 30) in honour of his own patrons. In 1620, Jean Tarde assumed sunspots to be planets and, on the same principle, named them *Borbonia Sidera* (Bourbonian bodies) in homage to the French royal dynasty.

23 Quoted by J. Marscart, “*La découverte de l’anneau de Saturne par Huygens*”, *La Revue du mois*, 1906, 77 et seq.

24 For example: “*Je travaille encore au système de Saturne qui ne me donne pas peu de peine*” [I am still working on Saturn's system which gives me considerable trouble]; letter to Claude Mylon, 8 December 1656; “*Je vous supplie de ne communiquer à personne ce que vous savez du monde saturnien, ni même de faire voir la figure que j’ai tracée, jusqu’à ce que j’aurais publié tout le système*” [I beg you not to communicate to anyone what you know of the Saturnian world, nor even to show the figure I have drawn, until I have published the whole system], letter to Ismaël Boulliau dated 26 December 1657, in which he lays out his theory of the Saturn ring. *Ibid.* 167. When Huygens first published his discoveries, he entitled his essay *Systema Saturnium* (The Hague: 1659); he then responded to the objections of scholars in the *Brevis assertio systematis Saturni sui* (The Hague: 1660).

25 I. Newton, *Philosophiae naturalis… op. cit.*, 402 et seq.

26 G. Galilei, *Sidereus nuncius… op. cit.*, 52-54. See *Le Messager des étoiles* [The Starry Messenger] (Paris: Le Seuil, 1992, trans. F. Hallyn).

27 I. Newton, *Philosophiae naturalis… op. cit.*, l. (III), prop. II et seq., 405 et seq.

28 See N. of Cusa, *De docta ignorantia*, 1440; 1st edition, in *Opera* (Argentorati: Martin Flach, 1488). Trans. H. Pasqua, *La docte ignorance* (Paris: Payot-Rivages, 2008); G. Bruno, *De l'infinito universo et mondi* (Venice: 1584). Latin text with translation J-P. Cavaillé, *De l'infini, de l'univers et des mondes* (Paris: Les Belles Lettres, 1995); T. Campanella, *Civitas solis* (Frankfurt: E. Emmelius, 1623). Trans. A. Tripet, *La cité du soleil* (Geneva: Droz, 2000); J. Kepler, *Somnium, seu opus posthumum de astronomia lunari* (Frankfurt: 1634). Trans. T. Miocque, *Le Songe ou l'astronomie lunaire* (Angoulême: Waknine, 2013); J. Wilkins, *The Discovery of a World in the Moon* (London: John Gillibrand, 1638). Trans. J. de la Montagne, Jacques Calloüé (Rouen: 1655); F. Godwin, *The Man in the Moone* (1638). Trans. J. Baudoin, *L'homme dans la Lune* (Paris : François Piot and I. Guignard, 1648); R. Descartes, *Principia philosophiae* (Amstelodami: Louis Elzevier, 1644). Trans. Father Picot, *Les principes de la philosophie* (Paris: Henri Le Gras, 1647); H. More, "Insomnium Philosophicum", *Philosophical Poems* (London, 1647); P. Borel, *Discours nouveau prouvant la pluralité des mondes* (Geneva: 1657). Trans. D. Sashott, *A New Treatise proving a Multiplicity of Worlds* (London: John Streater, 1658); S. Cyrano de Bergerac, *L'Histoire comique des États et empires de la Lune* (Paris: Charles de Sercy, 1657); S. Cyrano de Bergerac, *Histoire comique des États et empires du Soleil*, in *Nouvelles œuvres* (Paris: 1662). Critical edition by M. Alcover, *Les États et empires de la Lune et du Soleil* (Paris: Honoré Champion, 2004); B Le Bouyer de Fontenelle, *Entretiens sur la pluralité des mondes* (Paris: Vve C. Blageart, 1686); C. Huygens, *Cosmotheoros, sive de Terris coelestibus, earumque ornatu conjecturae* (The Hague: 1698). Trans. M. Dufour, *La pluralité des mondes* (Paris: Jean Moreau, 1702). Main studies on the subject: C. Flammarion, *La pluralité des mondes habités* (Paris: Didier, 1862); Dick Steven J., *Plurality of Worlds: The Origins of the Extraterrestrial Life Debate from Democritus to Kant* (Cambridge: University Press, 1982). Trans. M. Rolland, *La pluralité des mondes* (Arles, Actes Sud, 1989); A. Del Prete, *Bruno, l'infini et les mondes* (Paris: PUF, 1999); J. Seidengart, *Dieu, l'univers et la sphère infinie : Penser l'infinité cosmique à l'aube de la science classique* (Paris: Albin Michel, 2006).

29 "*En dépit du grand développement de l'astronomie de ces dernières décennies, l'origine du système solaire est encore matière d'hypothèses et de conjectures. Bien que les recherches n'aient pas manqué, et même qu'elles aient été réalisées avec tous les moyens que fournissent les techniques modernes et avec l'utilisation de tous les types d'instruments adaptés dans ce but, tant à terre que dans l'espace, notre système planétaire est l'unique effectivement connu.*"In M. Rigutti, "*Presentatione degli Atti*", in *Le Comete nell'astro-*

nomia moderna. Il prossimo incontro con la cometa di Halley (Napoli: Guida Editori, 1985), 9. Trans. D. Foucault.

30 Exoplanet team, *The Extrasolar Planets Encyclopaedia* [on line] http://exoplanet.eu/ [consulted on 23/02/2018].

31 Tycho Brahe's biographer, John Louis Emil Dreyer, seems to have been the first to have approached the question in his *History of the Planetary Systems from Thales to Kepler*, published in 1906 (republished by Cambridge University Press, 2014). Although his overview of ancient, medieval and Renaissance astronomical theories remains primarily centred on the object "planetary system", the author's approach is more descriptive than analytical; he does not establish a rigorous epistemological demarcation between "cosmic system" and "planetary system". This appears already in the preface: "In this book an attempt has been made to trace the history of man's conception of the Universe from the earliest historical ages to the completion of the Copernican system by Kepler in the seventeenth century. Among the various branches of physical science there is no other which in its historical development so closely reflects the general progress of civilisation as the doctrine of the position of the earth in space and its relation to the planetary system....What chiefly induced me to write this book was the circumstance that a number of legends on subjects connected with the history of the cosmical systems have been repeated time after time..." (1, 1906 edition).

32 "*Si [un] concept, logiquement ébauché ou formé dans un tel contexte, se trouve ultérieurement capté par quelque théorie qui l'utilise dans un contexte et un sens différents des premiers, cela ne fait pas que ledit concept soit condamné à n'être plus, dans la théorie initiale, qu'un mot vide de sens. Car il y a certains concepts théoriquement polyvalents... Il est exclu, en tout cas, que la vigueur d'un concept dans un terrain théorique donné puisse constituer une présomption suffisante pour limiter aux terrains théoriques de même composition la recherche des lieux de sa naissance.*" In G. Canguilhem, *La formation du concept de réflexe aux* XVII^e^ *et* XVIII^e^ *siècles* (Paris: Vrin, 1977, 2nd ed.), 6. Trans. J. Kerr.

33 "*Il est parfois nécessaire non seulement d'oublier des vérités qui sont devenues parties intégrantes de notre pensée, mais même d'adopter certains modes, certaines catégories de raisonnement ou du moins certains principes métaphysiques qui, pour les gens d'une époque passée, étaient d'aussi valables et d'aussi sûres bases de raisonnement et de recherche que le sont pour nous les principes de la physique mathématique et les données de l'astronomie.*" In

A. Koyré, *Mystiques, spirituels, alchimistes du* XVI^e *siècle allemand* (Paris: Gallimard, 1971), 77.

34 C. Ptolémée, *Manuel d'astrologie. La Tétrabible* (Paris: Les Belles Lettres, 1993, trans. N. Bourdin).

35 C. Ptolémée, *Almageste, ou Composition mathématique* (Paris: Hermann, 1927, trans. N. Halma, ed. annotated by Jean-Baptiste Joseph Delambre [1813-1816]).

36 According to Strabo, the first to put forward this hypothesis was the Stoic Posidonius of Rhodes (135-51/50 BCE). Pliny the Elder takes it up and develops it in his *Natural History* (Il, 97); Augustine mentions it in *The City of God* (V-6); Thomas Aquinas, by supporting it in his *Summa Theologica*, strengthens its authority in scholastic teaching. In addition, the role played by "sympathy" in Stoic physics and cosmology and Ptolemy's references to the action of the Moon on the tides in *The Tetrabiblos* tended to direct schools of thought in the late Middle Ages and the Renaissance, influenced by natural magic and hermeticism, towards this type of explanation. See in particular Gillet André, *Une histoire des marées*, Belin, Paris, 1998; Russo Lucio, *Flussi e riflussi. Indagine dull'origine di una teoria scientifica* (Milano: Feltrinelli, 2003).

37 This issue is addressed in the Fourth Day of the *Dialogue sur les deux grands systèmes du monde* (1632). See the French translation by R. Frédeux and F. De Gandt (Paris: Le Seuil, 1992), 599 et seq.

38 "How these Attractions may be perform'd, I do not here consider. What I call Attraction may be perform'd by impulse, or by some other means unknown to me. I use that Word here to signify only in general any Force by which Bodies tend towards one another, whatsoever be the Cause." [*Comment ces attractions peuvent-elles être produites, je ne l'examine pas ici. Ce que j'appelle attraction peut être produit par l'impulsion, ou par quelques autres moyens que j'ignore. J'use ici de ce mot seulement pour désigner d'une manière générale toute force en vertu de laquelle les corps tendent les uns vers les autres, qu'elles qu'en soient les causes.*] See I. Newton, *Opticks* (London), 335 [on line] https://www.gutenberg.org/files/33504/33504-h/33504-h.htm [consulted on 26/06/2018]. Quoted by A. Koyré, *Du monde clos à l'univers infini* (Paris: Gallimard,1988), 253.

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