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How Comets and Asteroids Influenced Our Concept of "Solar System" from Antiquity to the 19th Century

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PLAN

TEXTE

1. Introduction

1 The[1] notion of “Planetary System”, including the Sun, the Moon and the planets, arose early in the astronomical models of the cosmos due to the specific orbital trajectories of these bodies against the background of the “fixed stars”. Early astronomers described the regular planetary movements in geocentric models that gave an accurate description of the world given the precision of the observations of the time.

2 However, transient astronomical phenomena such as comets did not follow the predicted regular patterns of the heavens and were relegated to the terrestrial realm as atmospheric exhalations or meteorological events.

3 We will describe in this article how the continuous study of comets and, later, of asteroids helped to put into question or further validate the concepts of the “Solar System”, that is as a system encompassing

the physics of all planetary bodies, through time. First, astronomers had to recognize that comets were celestial phenomena, but behaving differently from the other planets. Second, the precise study of the cometary orbits was pivotal in validating the gravitational theory developed by Sir Isaac Newton in the 17th century and lead Sir Edmond Halley to successfully predict the return of a comet by the mid-18th century. The validation of this prediction by astronomers definitely placed the comets as members of the Solar System, following the same rules as defined by the new gravitational model of the Universe. Finally, by the 19th century, another family of small solar system bodies, the asteroids, further broadened the families of objects belonging to the Solar System. From their studies scientists started to realize that these objects evolved in the Solar System but also impacted regularly with the Earth, further strengthening the link between all planetary bodies and their common evolution since the beginning of time.

4 Thanks to the studies of comets and asteroids, the concept of “planetary system” emerged strengthened from the fact that the diversity of objects found in the Solar System follow the rules of the gravitational model of Newton, but also because their detailed studies made people realize the many different links between the planets, the Sun and their common origin.

2. The Antiquity and the description of comets as terrestrial phenomena

5 Comets have been known to mankind for a long time, and were often considered as heralds of disasters or messengers of the gods [2]. As an example, Marcus Manilius (1st century AD) summarized the effect of comets on Earth in his *Astronomica* in the following way:

> Or God in Pity to our humane State, sends these as Nuncio’s of ensuing Fate, never did Heaven with these fires vainly burn; deluded Swains their blasted Labours mourn, and the tired Husband-man to fruitless Toil compels his Oxen in a barren Soil: or the lethiferous Fire their Bodies kills, wasting their Marrows out with lingering Ills,

> People consumes, whole Towns depopulates, whilst flaming Piles conclude the public Fates [3].

6 The only notable exception to this interpretation was the appearance of Cæsar's comet of 44 BC (C/-43 K1) which has been widely regarded as a sign of the apotheosis of the great ruler as illustrated in fig. 1[4].

Fig. 1. Coin illustration of Cæsar's comet of 44 BC (C/-43 K1)

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7 The first recorded historic observation of comets is detailed in *The Annals of Lü Buwei* (*Lüshi Chunqiu* attributed to Confucius) which describe events that occurred between 722 and 481 BC. Out of three comets that were observed, the first is described as follows:

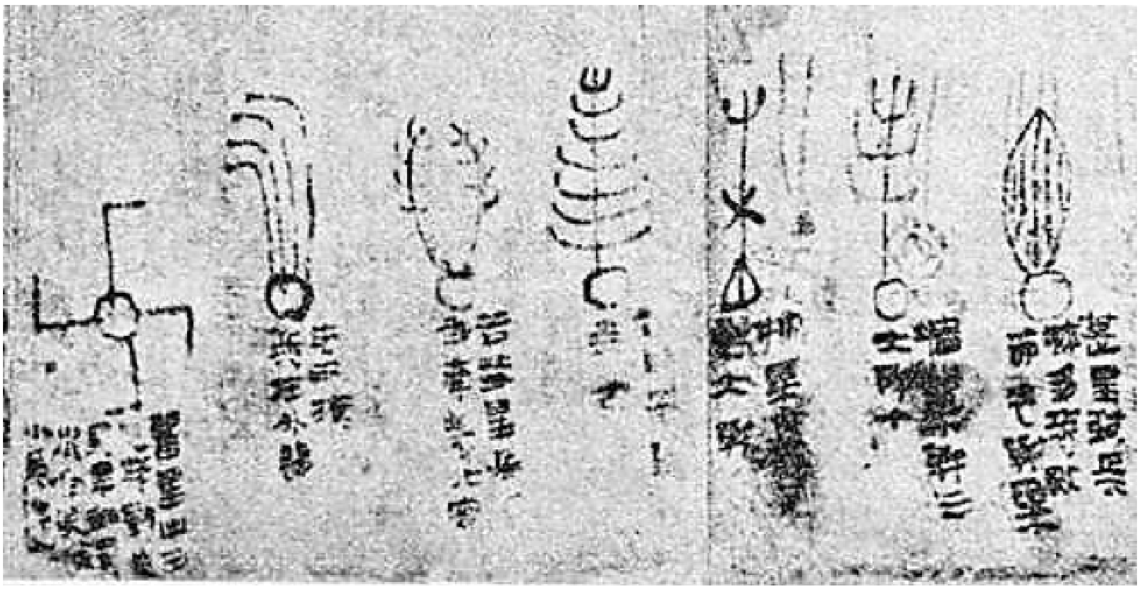
> In the 4th year of Wen Kung, Prince of Lu, [611 BC] in the Autumn of the 7th month, there was a comet which swept in the Pei Tow [The Great Dipper] [5].

8 This may have been a return of Halley's comet. It is remarkable that Chinese astronomer have never missed to observe each return of Halley's comet from 240 BC to 1986 AD. Their observations were very accurate and they even noticed early on that the comet's tail orientation was directed in the opposite direction from the position of the Sun in the sky as stated in Halley's comet record of 837 as:

> If the comet be a morning star its tail should point west and if it be an evening star its tail should point east [6].

9 This peculiar orientation of the cometary tails and their various morphologies (linear, curved, and multiple tails) are illustrated on the silk manuscript *Tianwen qixiang zazhan* (Miscellaneous Prognostications Concerning Astronomy and Meteorology) probably copied around the eleventh year of Emperor Gaozu of Han (ca.195 BC) [7] as shown in fig. 2. Few records of other observations of comets from ancient civilizations exist, with the possible records of Halley’s comet on Babylonian tablets for its 164 BC and 87 BC apparitions [8].

Fig. 2. Comets recorded on the silk manuscript *Tianwen qixiang zazhan*



(Miscellaneous Prognostications Concerning Astronomy and Meteorology, public domain image from Wikimedia)

10 The ancient Greeks developed a set of rational explanations for this natural phenomenon. However, because of the belief that the heavens were the perfect realm of the gods and because of the inherent difficulty in correctly assessing the distances for celestial events, comets were thought to be atmospheric in origin. Aristotle (384-322 BC) formalized his theory on comets in his *Meteorologica* where he described them as originating from turbulences in the atmosphere. He starts by criticizing previous theories of comets as possible planets since they present very different trajectories and brightnesses. Espe-

cially many comets can be seen simultaneously in the sky, and their trajectories are not restricted to the zodiac where the planets evolve. Aristotle’s meteorological theory of comets is based on dry exhalations from the atmosphere that reach the celestial sphere of fire and start burning there.

> We know that the dry and warm exhalation is the outermost part of the terrestrial world which falls below the circular motion. It, and a great part of the air that is continuous with it below, is carried round the earth by the motion of the circular revolution. In the course of this motion it often ignites wherever it may happen to be of the right consistency, and this we maintain to be the cause of the “shooting” of scattered “stars”. We may say, then, that a comet is formed when the upper motion introduces into a gathering of this kind a fiery principle not of such excessive strength as to burn up much of the material quickly, nor so weak as soon to be extinguished, but stronger and capable of burning up much material, and when exhalation of the right consistency rises from below and meets it. The kind of comet varies according to the shape which the exhalation happens to take [9].

11 This links the comets to the phenomenon of shooting stars but makes it longer lived. Aristotle goes on to correlate comets and their fiery composition to predict fiery and dry years. He then uses the same argument to explain the Milky Way as a similar meteorological phenomenon. Aristotle’s theory of comets was quite successful in explaining the sporadic and irregular apparitions of comets and why they do not follow the zodiacal band.

12 Ptolemeus reproduced Aristotle’s view on comets in his *Almagest*, which was to dominate astronomical concepts of the cosmos until the Renaissance. As such, Aristotle’s view on comets was probably one of the longest admitted theory in the history of natural philosophy [10]. However, one major drawback of this explanation was that, given the origin of the comets as fire located at the interface between celestial spheres, they would have to be elongated in the East-West direction and further observations showed that this was wrong.

13 Before we go on to describe more recent theories of comets, it is important to cite the work of Lucius Seneca (ca. 4 BC-65 AD) who dedicated a complete book of his *Quæstiones Naturales* to the origin of

comets. He compiled in his work many records of sightings of comets, and detailed a synthesis of the knowledge from those objects at the time. He notices that if comets were related to winds, then they should not appear in the absence of wind, and should be perturbed by violent winds, which is not the case. Seneca attempts to put the comets back into the realm of the celestial objects but concludes that the observations of such objects are too few to ascertain their nature, but that future generations pursuing knowledge may eventually uncover it.

> In view of this inquiry it will be well to ask whether comets are wholly analogous to stars and planets. They seem to have certain elements in common with them for example, rising and setting as well as their general form, although comets are more scattered, and end in a longer tail. They are alike, too, in their fiery bright appearance. So, if all the stars are earthy bodies, comets must share the same lot. But if the stars are pure fire and nothing else, remaining for six months at a time unbroken by the rapid whirl of the universe, then comets, too, may consist of some rarefied material, which is not broken up by the constant revolution of the sky. [… Comets] are not accidental fires, but in woven in the texture of the universe, directed by it in secret, but not often revealed. And how many bodies besides revolve in secret, never dawning upon human eyes? […] Many, too, that are unknown to us, the people of a coming day will know. Many discoveries are reserved for the ages still to be, when our memory shall have perished [11].

3. The Copernican revolution and the recognition that comets are celestial objects

14 The end of the Middle Ages and the Renaissance saw a renewal in using methods to explain natural phenomena. In the case of cometology (the science of comets), this was further helped by the improvements in accuracy of astronomical observations and better kept records. Peter of Limoges (1240-1306) measured the position and the motion of the comets of 1299 and 1301. Later, Geoffrey of Meaux (1310-1348) and Jacobus Angelus (1360-ca.1410) also wrote treatises on

the comets and the positions they observed using astronomical instruments. With the advent of more precise observations, the Aristotelian theory of comets as atmospheric phenomena was starting to become less tenable. The successive generations of astronomers would attempt to better measure the distances of the celestial objects, and in so doing would also determine the locations of comets in the Solar System, which would strengthen the Copernican revolution.

15 Levi Ben Gerson (1288-1344), credited with having invented the *Jacob's staff* for the measurements of angles between celestial bodies, was the first scholar to work out the theoretical basis for using parallax to measure the distance of comets and also was the first to mention a cometary observation in the context of astronomical observations of Mars in 1337.

> We also ascribed the absence of any increment in the size of Mars in Scorpio to the thickness of the vapors [edim] through which it was seen at that time. We then understood that this phenomenon took place because of the comet [kokhavmezunnav] that continued to appear for more than 3 months; that vapor came into being under Scorpio and its was drawn from there to somewhat below the north pole: there it burst into flame [hitlahavut] and it perished in Scorpio [12].

16 The Italian scientist Paolo Toscanelli (1397-1482) was the first to introduce precise charts of the trajectories observed for 6 comets from 1433 to 1472 [13].His method introduced the systematic study of comets opening the door to a set of discoveries that would be made by his followers. The first astronomer to attempt measuring the distance of comets using the parallax method was Georg Peurbach (1423-1461) who demonstrated that the comet of 1456 must have been at least 1000 German miles (more than 1 Earth radius) from the surface of the Earth. His discussion of the origin of comets remains entirely Aristotelian, though [14].

17 Johannes Regiomontanus (1436-1476) significantly improved the procedure for determining a comet's position, size, and distance. He published his reflections in his *De* cometæ magnitudine, longitudine ac de loco eius uero, problemata XVI, which describes in details the mathematical tools necessary to obtain the magnitude, position, dis-

tance and volume of the comet, without applying it to a concrete example[15]. However, Regiomontanus did apply those calculations to the apparition of the comet of 1472, the results of which were published in the treatise *De Cometis* attributed to him[16]. The treatise was published at a later point in 1548 and as an annex to the work of the astronomer Thaddaeus Hagecius ab Hayek (1525-1600) *Dialexis de novæ et prius in cognitæ stellæ* in 1574[17]. In this treatise, the parallax distance of the comet was calculated to be at least 8200 German miles, corresponding to 9 Earth's radii:

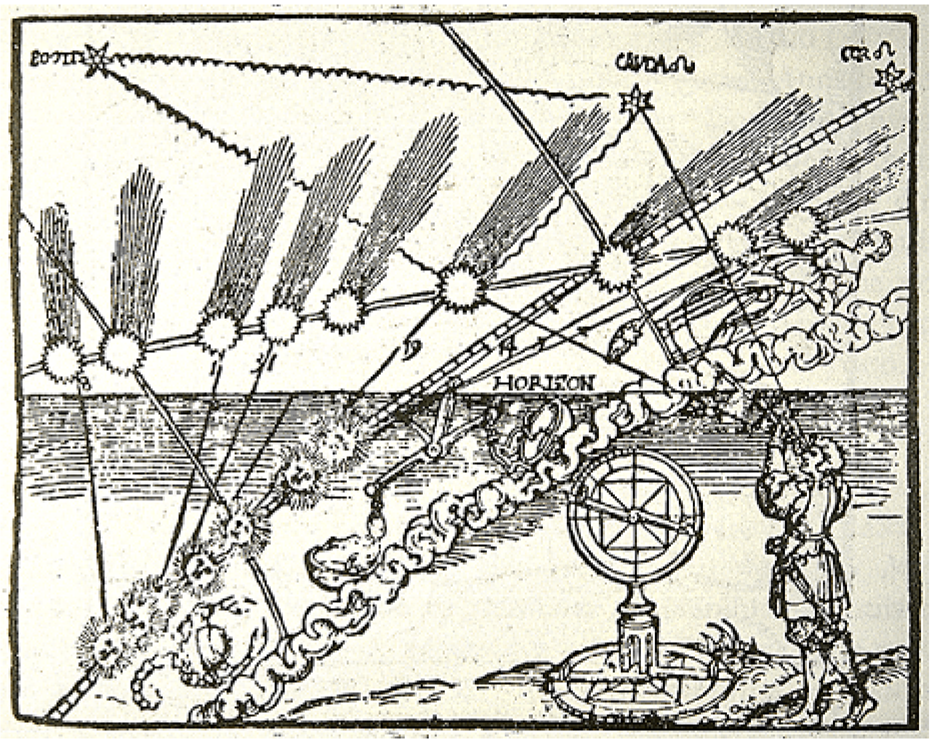
> According to this parallax it follows that the body of the comet is nine times the Earth's radius from the surface of the Earth, which is at least 8200 miles. This places it in the upper part of the highest regions of air and not in the region of fire, supposing a ten-fold symmetry of the elements. This is just as the philosopher determined according to On Generation[18].

18 Whoever was the author of the treatise, its publication is clearly the mark of a new type of study for the comets, as their distances start to be assessed and their trajectory better apprehended. While the calculated distances are relatively large for the time, they remain within the realm of the sublunary world, since the distance to the Moon was estimated to be at least 33 Earth's radii at the time, and therefore the Aristotelian view of the world was not invalidated by the observations so far.

19 Historically, the publications of Regiomontanus' cometary treatises occurred around 1531, at a time when three spectacular comets appeared in the sky (1531, 1532, 1533). This renewed the interest of astronomers in the properties of comets. A significant discovery that definitely linked comets to astronomical bodies was the observation that cometary tails are always directed in the direction opposite to the Sun. The Italian scientist Girolamo Fracastoro (ca. 1478-1553) observed the comets and first stated that the comet's tails were always directed away from the Sun: "*director semper in oppositam Soli partem*" in his *Homocentricorum sive de stellis*[19]. Petrus Apianus (1495-1552), known as Apian, was a German scientist who developed new instrumental designs for geographical and astronomical measurements. He carefully observed the trajectories of 5 comets from 1531 to 1539. He illustrated the fact that the cometary tails are sys-

tematically in the opposite direction to the Sun in his *Astronomicum Cæsareum* [20] as shown in fig. 3. Girolamo Cardano (1501-1576) and Johannes Vögelin (1500-1549) will attempt and discuss similar measurements [21].

Fig. 3. Observations of comet C/1532 R1 in October and November 1532 by Apian leading to the discovery that cometary tails are directed opposite to the Sun’s position in the sky



(Illustration from Apian’s *Astronomicum Cæsarum*, public domain image from Wikimedia)

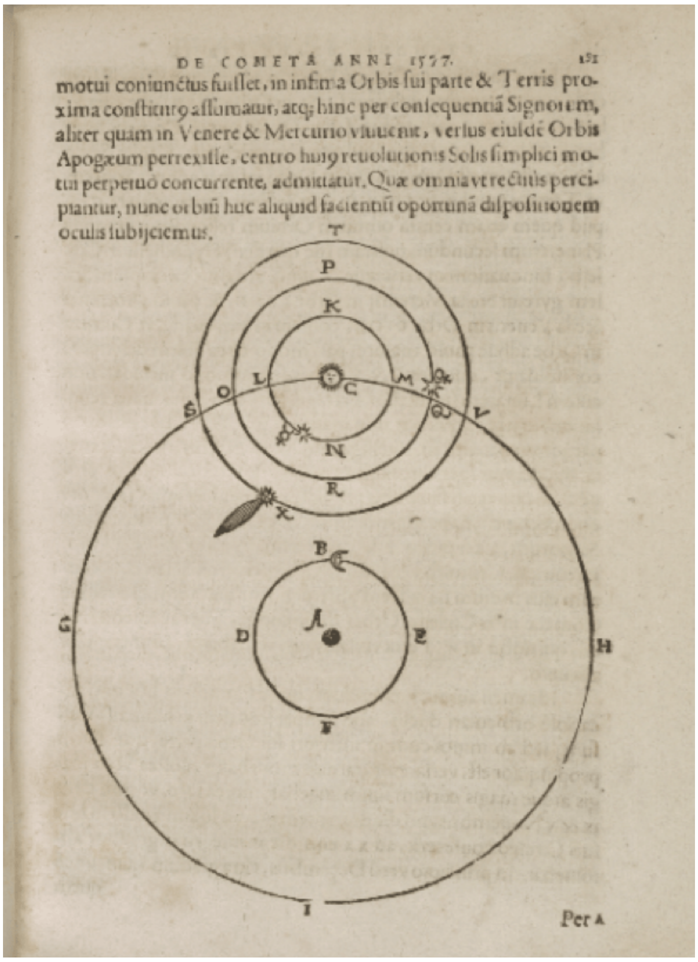
20 While Nicolas Copernicus (1473-1543) tackles the question of heliocentrism in his *De revolutionibus orbium cœlestium*, he does not make any particular mention of comets, and probably considers them to be part of the sublunar world, as most scientists of his time. The final realization that comets indeed belong to the stellar realm occurred at the end of the 16th century by the combination of several astronomical events.

21 Tycho Brahe (1546-1601) was a Danish astronomer who developed the highest accuracy database of celestial naked eye observations of his time, with position precisions reaching 1 arcminute or less [22]. On 11 November 1572, he observed a new bright star near the constellation

of Cassiopeia. Over several months of observation, Tycho Brahe realized that the new star did not change position with respect to the other stars and did not present any detectable daily parallax, indicating that the object was located very far, and probably belonged to the sphere of stars. He published the results of his observations in *De nova stella* [23]. This was the first time that the immutability of the stellar sphere was put into question by the observations.

22 The great comet of 1577 (C/1577 V1) was a spectacular astronomical phenomenon visible for several months and followed by many astronomers in Europe who had observed the 1572 supernova. The comet was located near the Sun, which made the observations challenging, however, Tycho Brahe succeeded in observing the comet as often as he could and recorded the ephemerides of the comet from November 9, 1577 to January 26, 1578 obtaining parallax measurements of the comet. He demonstrated that the distance between the comet and the Earth was at least 6 times the one between the Earth and the Moon. This was detailed in Tycho Brahe’s *De mundi ætherei recentioribus phænomenis, liber secundus* [24]. In this publication, he also introduces his Tychonic system, a hybrid between the heliocentric and the geocentric systems, where the planets and comets orbit the Sun, who in turn orbits the Earth and the Moon as illustrated in fig. 4. Some other observers confirmed the supra-lunar position of the comet, such as Michael Maestlin (1550-1631) in his work *Observatio et Demonstratio Cometæ Ætherei, qui Anno 1577. et 1578. constitutus in sphæra Veneris, apparuit* [25]. Other observations, like the parallax calculated by Hagecius seemed to indicate a sublunar position for the comet [26] but, after exchanges with Tycho, he considered his calculations to indicate a supralunar orbit [27]. A detailed study of the influence of the great comet of 1577 on astronomical thought can be found in Hellmann’s work [28].

Fig. 4. Parallax calculations of the comet of 1577 from Tycho Brahe and the Tychonic system where the Moon orbits around the Earth, Venus, Mercury and comets rotate around the Sun, which orbits around the Earth. The outer planets (Mars, Jupiter and Saturn) are not illustrated here, but rotate around the Sun on circles that are larger than the illustration [29].



(Public domain image from Wikimedia)

23 Following Tycho Brahe’s very accurate observations of the supernova of 1572 and the comet of 1577, not only was the sphere of fixed stars impermanent, but unpredictable objects, such as comets, were then demonstrated to also evolve amongst the other more regular celestial objects. These observations put into question the whole Aristotelian description of the world. Tycho also spends some time describing the cometary tail phenomenon. He notices that stars can be seen through it while not through the comet’s head and explains it, as it was suggested by prior observers, to be formed by the rays of the Sun

being scattered by the body of the comet’s head assumed to be semi-transparent [30].

24 With the advent of the heliocentric system, and the demonstration that comets were in fact irregular celestial objects, it was clear that these new objects would need to be studied in the same way as the planets or the stars in order to understand the cosmos. It was therefore logical that to obtain a better understanding of those objects would require to determine precisely what orbits they followed during their passages through the sky. This would in turn give rise to the concept of “Solar System” as the ensemble of bodies orbiting the Sun.

4. Debates about comets during the 17th century

25 Equipped with Tycho Brahe’s most accurate observations of the celestial movements of the planets, Johannes Kepler (1571-1630) devised his three laws of planetary motion, notably to explain the relatively eccentric orbit of Mars. In order to arrive at his nicely laid out laws that govern the movement of the planets, Kepler had to remove from consideration the comets and other wandering bodies of the celestial sphere to correctly explain the planetary motion. Later on, he addressed the questions of cometary movements in his treatise *De Cometis*, where he argues that “it probably does not happen that those objects, which never return to the same place, move in circular paths: just the opposite is the case; it is therefore probable that their motion is rectilinear” [31]. He then goes on to provide rectilinear curves for the observations of the comets of 1607 and 1618, however the numbers did not fit the data particularly well [32]. One significant consequence of the Keplerian hypothesis for comets was that following linear paths, these ephemeral objects had to belong to the universe outside of the Solar System, the interstellar medium, which was an interesting extreme [33], after the Aristotelian hypothesis of terrestrial origin of the phenomenon. This was somewhat in line with the thoughts of René Descartes (1596-1650), a French scientist and philosopher, whose rationalist method became extremely influential, and who described the origin of stars as collapsed elements within vortices where remnants would remain at the borders and form comets

and planetary bodies who would then move between the considered vortices [34].

26 The Aristotelian hypothesis was still considered seriously at the time, even after the remarkable parallax measurements of Tycho, as Mario Guiducci (1583-1646), Galileo’s student published the same year his *Discorso delle comete*, commonly attributed to Galileo Galilei (1564-1642)[35]. In it, a terrestrial explanation for the comets is again presented, as an exhalation from the upper atmosphere of the earth, reflecting the light of the Sun, similar to the phenomenon of the aurorae. Having the objects of interest reflect the light from the Sun can be used to explain the large parallax distance, since in such an instance the angle between the Sun, the comet and the observer needs to remain constant for the object to be seen (just like for the rainbow). Galileo would later expound on the theory himself in his book *Il Saggiatore*[36]. This was probably the last serious attempt at explaining the cometary observations as a terrestrial phenomenon.

27 Other observers continued to make progress in the observation of comets and proposed yet different explanations for their motion. Johannes Baptista Cysatus (1587-1657), a Swiss jesuit astronomer, made the most precise observations of comets of the early 17th century in his *Mathematica astronomica de loco, motu, magnitudine et causis cometae qui sub finem anni 1618 et initium anni 1619 in cœlo fulsit*[37]. In this book, he described how comets are formed from a nucleus and a tail, and how they revolve around the Sun in circular orbits, and suggested parabolic orbits for some. Even though he could not have detected what is now called the nucleus of a comet, these were very modern insights into the phenomenon for that time. Giovanni Domenico Cassini (1625-1712), an Italian astronomer who became the first director of the Paris Observatory, observed the comet of 1664 and described a theory of its motion in which the comet follows a large circle whose center is in the direction of the star Sirius, with a perigee beyond the orbit of Saturn[38]. These theories of comet motion remained within the Tychonic system framework.

28 Finally, a number of astronomers further developed the program that was prescribed by Seneca to record all possible comet sightings in history. Indeed, only a full set of observations of all those phenomena would certainly help shed light on their origin. This was the goal that

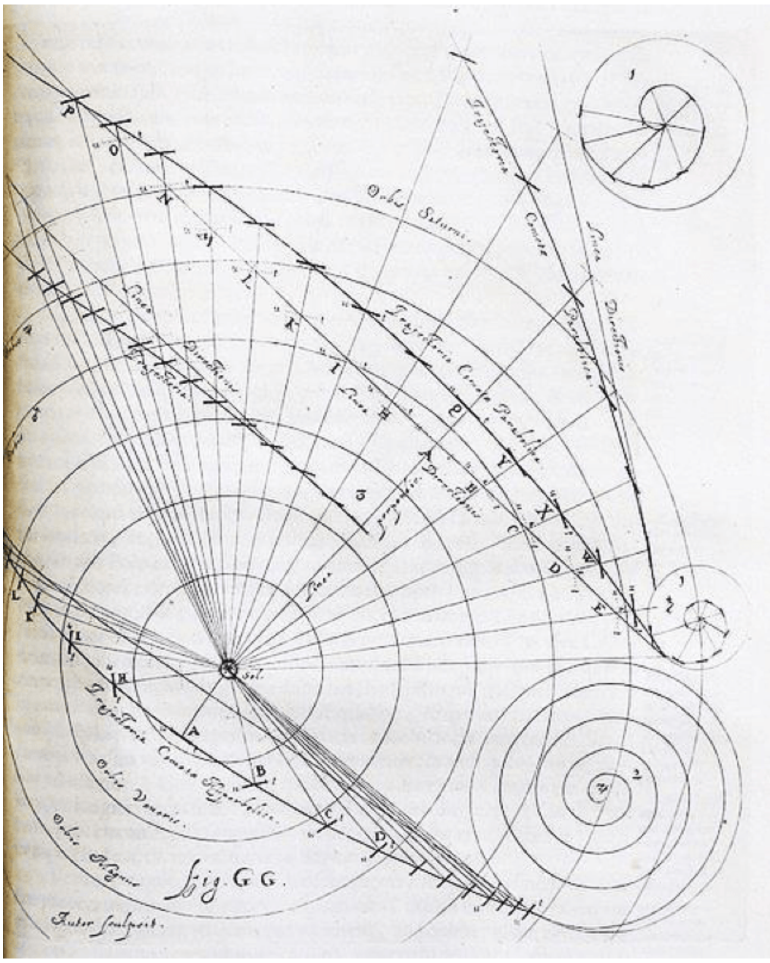
Johannes Hevelius (1611-1687) set for himself when he decided to write the largest compilation of comet observations of the time, his *Cometographia* (1668)[39]. He himself discovered four comets between 1652 and 1677. Hevelius argued that comets were ephemeral objects generated by the upper atmosphere of planets and travelling across the solar system following almost straight-lined orbits deformed by their interaction with the Sun. He argued that the shape of the comet’s head, supposed not to be spherical and assumed to be a disk remaining perpendicular to the solar direction, would induce a significant curvature of the orbit, due to friction with the æther. From astronomical observations, such curves could not be closed ellipses. However, the trajectories of comets were well described by parabolas (and possibly hyperbolas) and this is what Hevelius assumed in his model as illustrated in fig. 5 and in fig. 6. This was the first time that parabolic orbits were considered to explain the movement of celestial objects.

Fig. 5a. Frontispiece of Johannes Hevelius’ *Cometographia*

Representing the competing 3 theories of the origin of comets: Aristotle’s terrestrial theory on the left, Kepler’s linear trajectories and interstellar theory to the right, and Hevelius’ parabolic theory in the centre

Fig. 5b. Plot of the trajectory of the comet of 1665 as recorded by Hevelius [40]

Fig. 6. Hevelius’model for the parabolic trajectories of comets from his *Cometographia*



Note that comets are generated by a spiral linked to a planet, and the disk representing them is constantly perpendicular to the solar direction.
The rectilinear trajectories are deformed into parabolic curves [41]

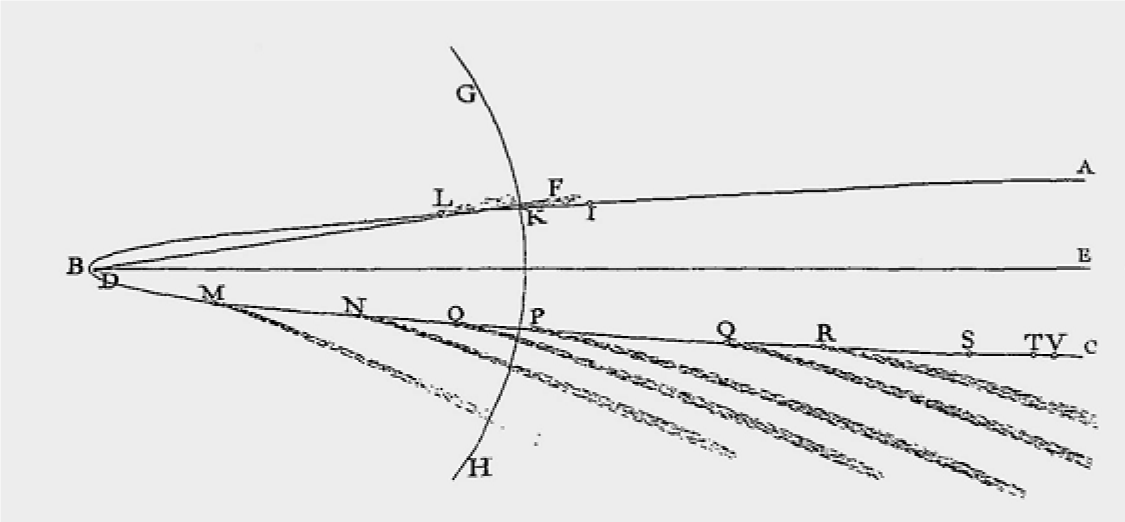
(Public domain image from Wikimedia)

29 At about the same time as the Hevelius publications, a French astronomer, Pierre Petit (1594-1677) remarked the apparent similarity between the orbits of the comets from the years 1618 and 1664 and assumed that it could be the same object orbiting along an elongated orbit with a period of 36 years [42]. He was probably the first astronomer to make the prediction of the return of a comet based on valid observational arguments. The idea of the return of comets as perennial objects orbiting the Sun was ripe for confirmation.

5. Newton’s gravitational theory and the determination of the orbits of comets

30 One of the pressing astronomical problems of the end of the 17th century was to find an explanation for Kepler’s three laws of planetary motion. It is well known that Sir Isaac Newton (1643-1727) revolutionized the physical sciences with the publication of his *Philosophiæ Naturalis Principia Mathematica*[43], which explained the planetary motions by the application of the universal gravitational force binding all massive objects together. It is generally recognized that the demonstration of the gravitational principle relies on the comparison between the force linking terrestrial objects to the Earth, and the force that makes the Moon orbit the Earth. Newton then generalized this principle into a universal gravitational relationship proportional to the masses of the interacting bodies and inversely proportional to their squared distance. Applying this law to the movement of planets, one could directly infer by calculus the three laws of Kepler without further assumptions. All these demonstrations were enough to explain the solar system as it was considered at the time (with planets and satellites), but if Newton’s law was to be truly universal, it should also be able to explain and predict other planetary phenomena, the prime example of which, as we have seen, was the erratic behaviour of comets. This he demonstrated brilliantly by applying his law to the trajectory of the comet of 1680 (C/1680 V1) and calculating for the first time its orbital elements, as illustrated in the graph published in the *Principia* shown in fig. 7.

Fig. 7. Newton’s illustration of the fit of a parabola to the trajectory of the great comet of 1680 published in his *Philosophiæ* Naturalis Principia Mathematica, thus demonstrating the universality of his law to all solar system objects [44]



(Public domain image from Wikimedia)

31 At last, comets were shown to follow regular laws of physics, and to follow conic trajectories, like the planets, stemming from a single physical process, the inverse-square law of gravitation. In fact, Newton goes further than just describing the orbit of comets, as he also tackles their physical properties. Indeed, he notes that comets reflect the sunlight and that they appear visible when they are generally closer than Jupiter to the Sun:

> (Cor 1) Therefore the comets shine by the sun’s light, which they reflect.
> (Cor 2) […] for comets descending into our parts neither emit tails, nor are so well illuminated by the sun, as to discover themselves to our naked eyes, until they are come nearer to us than Jupiter [45].

32 He also noticed that the tail of the comet was much longer after the close passage to perihelion of the body which he interprets as due to the heating from the Sun:

> The greatest and most fulgent tails always arise from comets immediately, after their passing by the neighbourhood of the sun. Therefore the heat received by the comet conduces to the greatness of the

> tail: from whence, I think I may infer, that the tail is nothing else but a very fine vapour, which the head or nucleus of the comet emits by its heat [46].

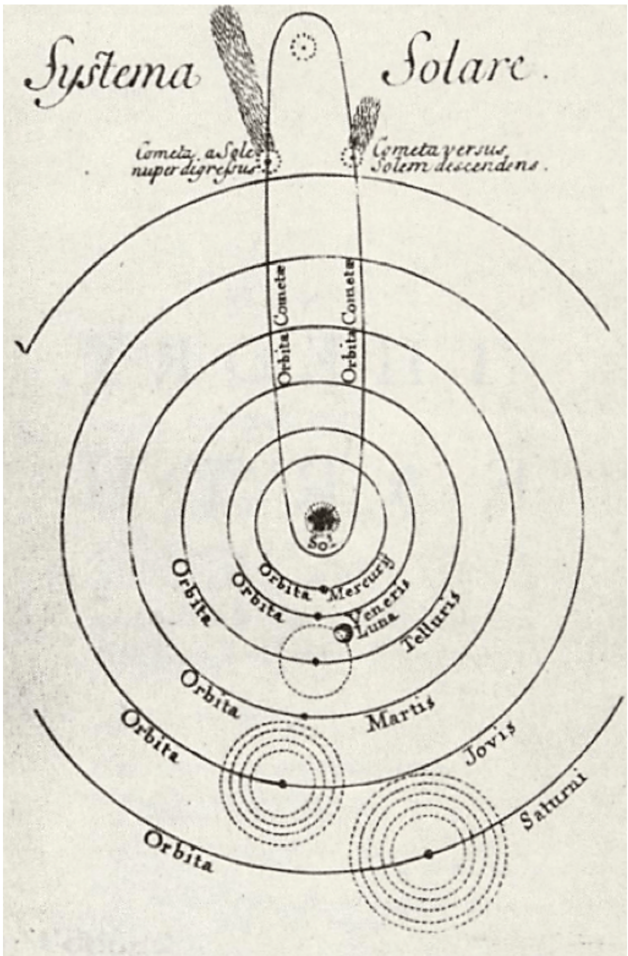
33 Those are very modern considerations and have been corroborated by further studies during the 20th century [47]. Newton then concludes:

> We have said, that comets are a sort of planets revolved in very eccentric orbits about the sun: and as, in the planets which are without tails, those are commonly less which are revolved in lesser orbits, and nearer to the sun, so in comets it is probable that those which in their perihelion approach nearer to the sun are generally of less magnitude, that they may not agitate the sun too much by their attractions. But, as to the transverse diameters of their orbits, and the periodic times of their revolutions, I leave them to be determined by comparing comets together which after long intervals of time return again in the same orbit [48].

34 This definitely places comets amongst planetary objects of the solar system and indicates the line of research for further cometary studies.

35 Indeed, all known comets of the time presented orbits too elongated to determine whether their trajectory was a closed curve or not and the parabolic fit to the trajectories of comets would lead the objects to remain transient events and never to be seen again. However, the idea that some comets at least could be on such elongated elliptical orbits that they may be able to return was starting to be taken seriously. William Whiston (1667-1752) published in his *New Theory of the Earth* [49] the hypothesis that planetary objects orbiting the Sun constituted a system, that is a set of celestial bodies interacting with the gravitational forces and excluding the fixed stars [50]. He also tentatively explained the biblical deluge by the forces exerted by comets on the Earth as illustrated prominently in his Solar System shown in fig. 8. However, Whiston theories remained speculative.

Fig. 8. Whiston’s illustration of the Solar System appearing in his *New Theory of the Earth*

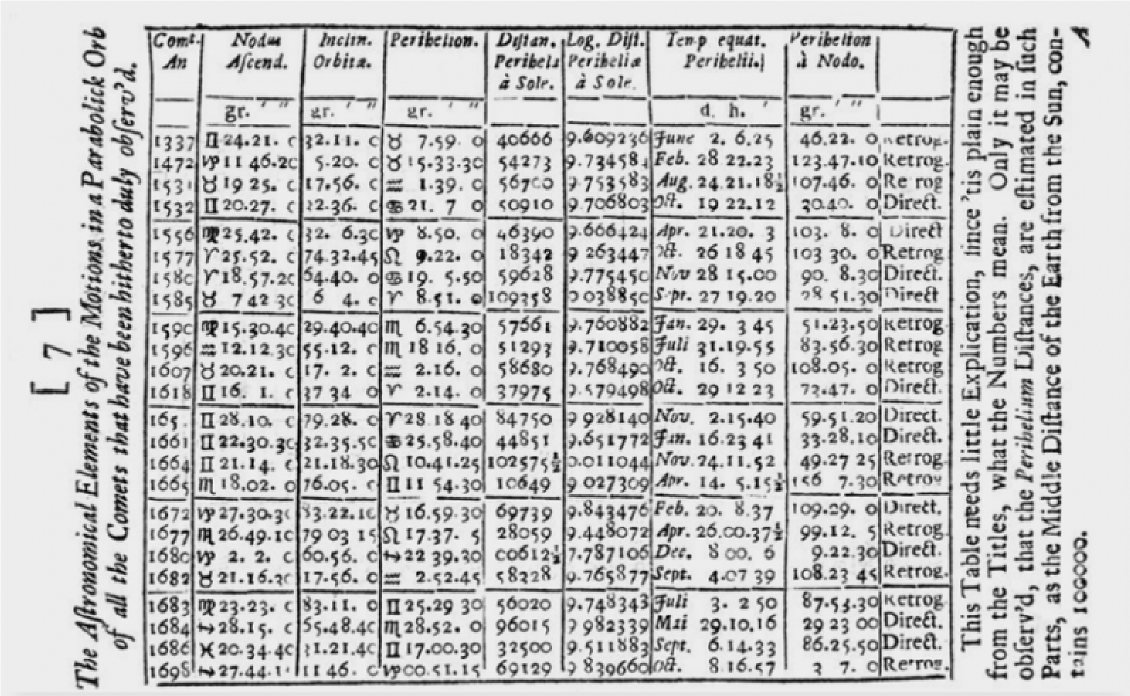


This is one of the first times where the planetary objects orbiting the Sun were illustrated as a system, and the first illustration of a closed elongated cometary orbit.

(Public domain image from Wikimedia)

36 Equipped with the mathematical tools devised by Newton, Sir Edmond Halley (1656-1742) tackled the task to determine as precisely as possible the orbital parameters of the recorded historical comets. This work took some time, and his results were published in the book *A Synopsis of the Astronomy of Comets*[51], in which he presented the estimated orbital parameters for 24 historical comets. He noticed that three sets of parameters appeared very similar, those for the comet of 1531, 1607 and 1682 as can be seen in fig. 9 and fig. 10.

Fig. 9. Halley’s cometary orbital parameters table published in his *Synopsis of the Astronomy of Comets*



[7]

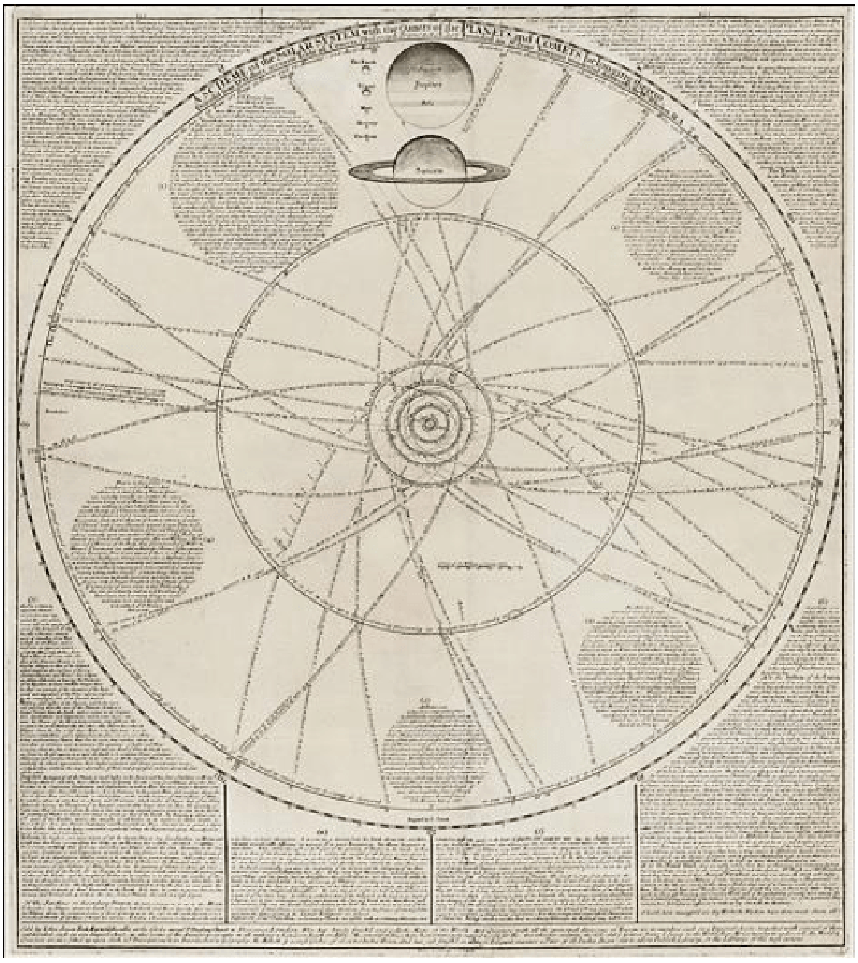
The Astronomical Elements of the Motions in a Parabolick Orb of all the Comets that have been hitherto duly observ'd.

Comet. An.	Nodus Ascend.	Inclin. Orbitæ.	Perihelion.	Distan. Perihelii à Sole.	Log. Dist. Perihelii à Sole.	Temp. equat. Perihelii.	Perihelion à Nodo.	
	gr. ′ ″	gr. ′ ″	gr. ′ ″			d. h. ′	gr. ′ ″	
1337	♊ 24.21. 0	32.11. 0	♉ 7.59. 0	40666	9.609236	June 2. 6.25	46.22. 0	Retrog.
1472	♑ 11 46.20	5.20. 0	♉ 15.33.30	54273	9.734584	Feb. 28 22.23	123.47.10	Retrog.
1531	♉ 19 25. 0	17.56. 0	♒ 1.39. 0	56700	9.753583	Aug. 24.21.18½	107.46. 0	Retrog.
1532	♊ 20.27. 0	32.36. 0	♋ 21. 7 0	50910	9.706803	Oct. 19 22.12	30.40. 0	Direct.
1556	♍ 25.42. 0	32. 6.30	♑ 8.50. 0	46390	9.666424	Apr. 21.20. 3	103. 8. 0	Direct.
1577	♈ 25.52. 0	74.32.45	♌ 9.22. 0	18342	9 263447	Oct. 26 18 45	103 30. 0	Retrog.
1580	♈ 18.57.20	64.40. 0	♋ 19. 5.50	59628	9.775450	Nov 28 15.00	90. 8.30	Direct.
1585	♉ 7 42 30	6 4. 0	♈ 8.51. 0	109358	0.038850	Sept. 27 19.20	28 51.30	Direct.
1590	♍ 15.30.40	29.40.40	♏ 6.54.30	57661	9.760882	Jan. 29. 3 45	51.23.50	Retrog.
1596	♒ 12.12.30	55.12. 0	♏ 18 16. 0	51293	9.710058	Juli 31.19.55	83.56.30	Retrog.
1607	♉ 20.21. 0	17. 2. 0	♒ 2.16. 0	58680	9.768490	Oct. 16. 3 50	108.05. 0	Retrog.
1618	♊ 16. 1. 0	37 34 0	♈ 2.14. 0	37975	9.579498	Oct. 29 12 23	73.47. 0	Direct.
1652	♊ 28.10. 0	79.28. 0	♈ 28 18 40	84750	9 928140	Nov. 2.15.40	59.51.20	Direct.
1661	♊ 22.30.30	32.35.50	♋ 25.58.40	44851	9.651772	Jan. 16.23 41	33.28.10	Direct.
1664	♊ 21.14. 0	21.18.30	♌ 10.41.25	102575½	0.011044	Nov. 24.11.52	49.27 25	Retrog.
1665	♏ 18.02. 0	76.05. 0	♊ 11 54.30	10649	9 027309	Apr. 14. 5.15½	156 7.30	Retrog.
1672	♑ 27.30.30	83.22.10	♉ 16.59.30	69739	9.843476	Feb. 20. 8.37	109.29. 0	Direct.
1677	♏ 26.49.10	79 03 15	♌ 17.37. 5	28059	9.448072	Apr. 26.00.37½	99.12. 5	Retrog.
1680	♑ 2. 2. 0	60.56. 0	♐ 22 39.30	00612½	7.787106	Dec. 8 00. 6	9.22.30	Direct.
1682	♉ 21.16.30	17.56. 0	♒ 2.52.45	58328	9.765877	Sept. 4.07 39	108.23 45	Retrog.
1683	♍ 23.23. 0	83.11. 0	♊ 25.29 30	56020	9.748343	Juli 3. 2 50	87.53.30	Retrog.
1684	♐ 28.15. 0	65.48.40	♏ 28.52. 0	96015	9 982339	Mai 29.10.16	29 23 00	Direct.
1686	♓ 20.34.40	31.21.40	♊ 17.00.30	32500	9.511883	Sept. 6.14.33	86.25.50	Direct.
1698	♐ 27.44.15	11 46. 0	♑ 00.51.15	69129	9 839660	Oct. 8.16.57	3 7. 0	Retrog.

This Table needs little Explication, since 'tis plain enough from the Titles, what the Numbers mean. Only it may be observ'd, that the *Perihelium* Distances, are estimated in such Parts, as the Middle Distance of the Earth from the Sun, contains 100000.

(Royal Astronomical Society, Public domain image from Wikimedia)

Fig. 10. Solar system chart by William Whiston showing the orbits of the planets and cometary paths calculated by Halley



(Royal Astronomical Society, Public domain image from Wikimedia)

37 He then made the connection with a prior observation of a retrograde comet observed in the year 1456, assuming it could be the same returning comet. Based on this set of values, and especially the inclination of their orbits and their perihelion distances, he predicted the return of the comet for the year 1758. Note that he already noticed this similarity during a public presentation of this work he presented at the Royal Society in 1696 [52]:

> The principal use therefore of this Table of the Elements of their Motions, and that which induced me to construct it, is, That whenever a new Comet shall appear, we may be able to know, by comparing together the Elements, whether it be any of those which has appear'd before, and consequently to determine its Period, and the Axis of its

> Orbit, and to foretell its Return. And, indeed, there are many Things which make me believe that the Comet which Apian observ’d in the Year 1531. was the same with that which Kepler and Longomontanus took Notice of and describ’d in the Year 1607. and which I myself have seen return, and obferv’d in the Year 1682. […] This, moreover, confirms me in my Opinion of its being the same; that in the Year 1456. in the Summer time, a Comet was seen passing Retrograde between the Earth and the Sun, much after the same Manner: Which, tho’ no Body made Observations upon it, yet from its Period, and the Manner of its Transit, I cannot think different from those I have just now mention’d. Hence I dare venture to foretell, That it will return again in the Year 1758. And, if it should then return, we shall have no Reason to doubt but the rest must return too: Therefore Astronomers have a large Field to exercise themselves in for many Ages, before they will be able to know the Number of these many and great Bodies revolving about the common Center of the Sun and reduce their Motions to certain Rules [53].

38 More precisely, he predicted the comet to return “about the end of the year 1758, or beginning of the next” [54].

39 Unfortunately, Halley died before the return of this comet, but his prediction was seriously followed by astronomers (Alexis Clairaut, Joseph Jérôme Lalande and Nicole-Reine Lepaute) who dedicated time to predict more precisely the orbit of the comet taking into account the perturbations induced by the giant planets, Jupiter and Saturn. They predicted a perihelion passage in mid-April 1759 with an error of about a month [55]. Charles Messier (1730-1817) was the first to re-observe the comet in January 1759 and its orbital characteristics were consistent with the ones of the previous apparitions of the comet. This prediction confirmed the validity of Newtonian mechanics and firmly located the comets as planetary bodies within the solar system. Since then about 375 periodic comets have been discovered and they are conventionally named after their discoverer [56]. The successful prediction of the return of comet 1P/Halley spectacularly demonstrated the validity of the Newtonian physics and the law of gravitation to explain planetary motion.

6. The 18th and 19th centuries: comets and asteroids as Solar System objects and their interactions with the Earth

40 With the successful prediction of the return of Halley’s comet, science entered definitively in the era of Newtonian physics, and comets found their place amongst the planetary bodies of the solar system. The successful theories explaining cometary phenomena and motions were compiled in the books of the enlightenment, such as in the article “comètes” of the *Encyclopédie*[57] of Denis Diderot (1713-1784) and Jean Le Rond d’Alembert (1717-1783) or the exhaustive *cométographie*[58] published by the astronomer Alexandre Pingré (1711-1796).

41 Successive studies of comets were dedicated to understanding their origin and properties. A large panel of possible theories were discussed at that time, ranging from the mechanistic theory of the origin of comets from planets and influencing planets by Whiston[59], to theories related to the recently discovered field of electricity and magnetism, where cometary tails are compared to the aurorae and explained by electric discharges in the work of Hugh Hamilton (1729-1805)[60], for example. Perhaps the theory of formation of the tails of comets that resembles most closely the modern ones was the discussion by Leonard Euler (1707-1783) of the phenomenon as a refraction effect of the light through particles emitted by the comet’s head[61]. Most cometary theories of the 18th century are described exhaustively in Heidarzade, 2008.

42 Pierre Simon Laplace (1749-1827) was the first one to estimate the mass of comets in his *Traité de mécanique céleste* using the close encounter of the comet D/1770 L1 (Lexell’s comet) with the Earth. He writes:

> Si l’on suppose que la masse m de la comète, égale à la masse m’ de la terre, on trouve pour l’augmentation [delta]T’ de l’année sydérale, [delta]T’=0’.11612.
> Nous sommes bien certains par toutes les observations, et surtout

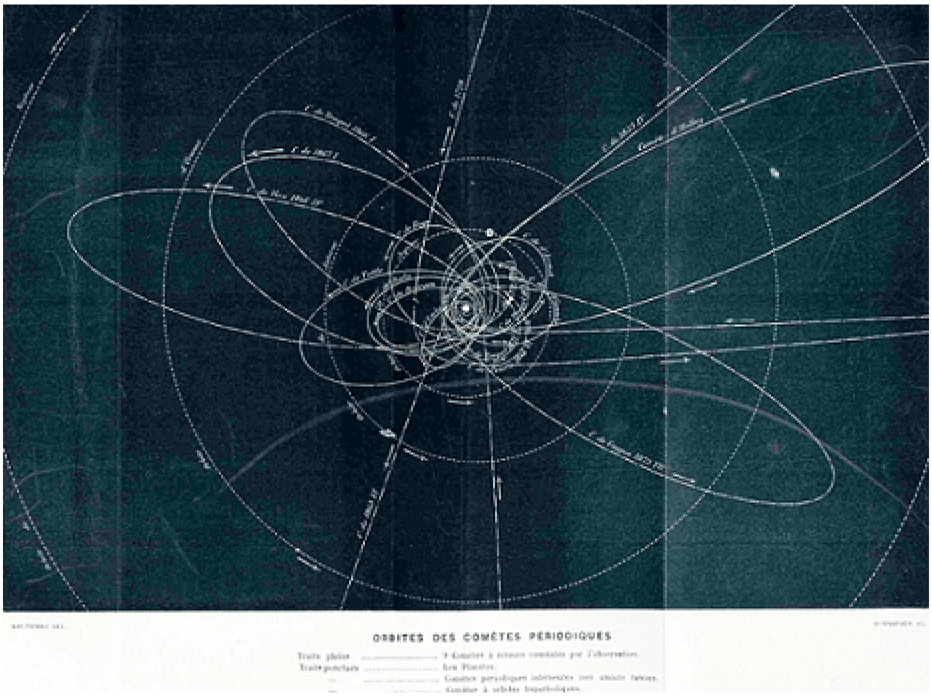
> par les nombreuses comparaisons des observations de Maskeline, que Delambre vient de faire pour construire ses tables du soleil, que la comète de 1770 n’a pas altéré de 2”.8, l’année sydérale ainsi nous pouvons être sûrs que sa masse n’est pas 1/5000 de celle de la terre [62].

43 With their small masses, comets are thereafter considered not to be able to perturb significantly the planetary motions of the solar system. Another major concept that emerged from Laplace’s study of cometary orbits was the nebular hypothesis for the origin of the solar system, which he described in his *Exposition du système du monde* [63]. In this model, the comets are the unagglomerated remnants of the material that formed the planets around the Sun, that he considered to be the initial atmosphere of the Sun. This model of formation of comets from the primordial protosolar nebula is still valid and explains why comets remain highly studied to this day.

44 Further work of the 19th century allowed significant advances in our understanding of the material constituting the comets. François Arago (1786-1853) was the first one to observe and detect polarization from a cometary atmosphere (C/1819 N1) demonstrating that refracted light is part of the luminosity of comets [64]. The Italian astronomer Giovanni Battista Donati (1826-1873) pioneered the use of spectroscopy to study celestial objects and stars and was the first one to observe the light spectrum of a comet (C/1864 N1 Tempel). He noticed that the cometary light presented emission lines indicating that part of the light was being emitted by the comet itself [65]. Spectroscopic studies of comets and other celestial objects would then go on to dominate the field of astronomical studies.

45 To add to the studies of comets, it is important to remember that the scientific studies of the 19th century have seen the discovery of many small bodies of the solar system in addition to the cometary objects that were known at the time (illustrated in fig. 11).

Fig. 11. Representation of the orbits of known for the planets and the known periodic comets at the end of the 19th century [66]



(Public domain image from BnF, https://gallica.bnf.fr)

46 Indeed, the first asteroid, 1 Ceres, was discovered by Giuseppe Piazzi (1746-1826) in 1801 [67]. This demonstrated the occurrence of small planetary remnants located in a main belt of objects between the orbits of Mars and Jupiter. They were named asteroids as they were so small, their appearance was similar to the point source of stars seen in the telescopes. The number of known asteroids increased exponentially with time and we now know more than 1 million asteroids larger than 1km in size orbiting the Sun. The concept of a solar system linking all planetary bodies gravitationally to the Sun strengthened as the types and the numbers of planetary objects, all orbiting the Sun, increased with time.

47 The last evolution in the ideas concerning the link between the small bodies and the solar system are still being explored today, but started to be mentioned in the 19th century as well. It concerns the fact that when so many small objects orbit the Sun, some of them may pass so close to the Earth as to interact with it, or fall on it. The probability of such an event was estimated to be negligibly small by Laplace [68]. However, two lines of evidence of interactions between the small

bodies (comets and asteroids) and the Earth were discussed during the 19th century. The first one was the discovery that meteorites were extra-terrestrial stones, as suggested by Ernst Chladni (1756-1827)[69] and demonstrated by Jean-Baptiste Biot (1774-1862), who studied the strewn field of the fall of the Aigle meteorite in 1803[70]. This discovery gave strength to the possibility that samples of extra-terrestrial bodies of the solar system may be found on Earth after their impact, and that small bodies regularly fall on Earth. The second one was the discovery that the regular apparition of meteor showers could be linked to the proximity of passages from comets. This would mean that the particles ejected from the comets would fall on the Earth as it crosses the cloud of dust left over by the cometary activity. Giovanni Schiaparelli (1835-1910) presented the results of his studies and was able to link the occurrence of the Leonids with the trajectory of comet 3D/Biela, and also the Perseid meteor shower with the trajectory of comet 109P/Swift-Tuttle[71].Since then, it has been shown that most meteor showers are associated with the activity of comets[72].

48 These last studies confirmed that solar system members interact not only gravitationally but also by encountering one another over long time scales.

7. Conclusions

49 In this essay, we have attempted to demonstrate that understanding the origin of comets and their peculiar behaviours has been a major motivation that shaped the early astronomical studies and our models of the planetary system through time. Indeed, any improvement of an astronomical model on the previous ones had to take into account these celestial transient phenomena, or remove them from consideration, either by rejecting them to the world of terrestrial phenomena, like Aristotle did, or by moving them outside of the realm of the planetary motion, like Kepler assumed. In the end, their various trajectories and the predicted return of Halley’s comet validated brilliantly the advent of Newtonian mechanics in the 18th century, and were even a strong statistical argument in favour of the nebular origin of the Solar System as imagined by Laplace.

50 Finally it was admitted that celestial objects such as comets and asteroids could affect the Earth, by impacting it. The concept of objects

orbiting the Sun as forming a single consistent system, named the Solar System, was therefore a consequence of the link the comets played in space by orbiting far and close to Sun, but also in time as they are the most primitive remnants we know today of the initial matter that condensed to form the planets from the protosolar nebula 4.5 billion years ago. This fact motivates further detailed studies of these objects in order to decipher the origin of the Solar System and the Earth, such as was performed by the Rosetta space mission at comet 67P/Churyumov-Gerasimenko as illustrated in fig. 12.

Fig. 12. Illustration of the exploration of comet 67P/Churyumov-Gerasimenko by the Rosetta space mission and the lander Philae in 2014-2016

(European Space Agency)

51 In the end, astronomical studies of comets and asteroids through time have demonstrated the close interactions that the members of the Solar System may have and remind us, if it was at all necessary, that the Earth remains a planetary body of the system, subject to the same laws and vicissitudes as any other member of the Solar System.

NOTES

1 The author wishes to acknowledge Ujjaini Alam for proofreading the text of the manuscript and two anonymous referees for their constructive comments.

2 A. Le Boeuffle, "La comète de Halley à l'époque romaine", In: *Bulletin de l'Association Guillaume Budé: Lettres d'humanité*, n° 44, décembre 1985. pp. 385-389.

3 E. Sherburne, "The sphere of Marcus Manilius made an English poem: with annotations and an astronomical appendix", *London: Nathanael Brooke*, 1675, p. 63.

4 Cf. J. T. Ramsey, A. L. Licht, *The comet of 44 BC and Caesar's funeral games* (Atlanta: Scholars Press, 1997).

5 W. S. Tsu, "The observations of Halley's comet in Chinese history", *Popular Astronomy*, n° 42, 1934, p. 192.

6 *Ibidem*, p. 197.

7 C. Songchang, "Three Research Notes on the Silk Manuscript *Tianwen qixiang zazhanb* 天文氣象雜占", *Bamboo and Silk*, vol. 2, 2019, n° 2, pp. 274-289.

8 F. R. Stephenson, K. K. C. Yau, H. Hunger, "Records of Halley's comet on Babylonian tablets", *Nature*, 1985, vol. 314, nº 6012, pp. 587-592.

9 Aristotle, *Meteorology*; Translated by E.W. Webster, *In The Works of Aristotle* (edited by J.A. Smith and W. D. Ross, Oxford University Press, 1931), §7.

10 Cf. T. Heidarzadeh, *A History of Physical Theories of Comets, from Aristotle to Whipple* (Berlin: Springer Science & Business Media, 2008), p. 21-51.

11 L. A. Seneca, "The Natural Questions…, Book VII. Which treats of Comets", § II; in J. Clarke, *Physical Science in the Time of Nero: Being a Translation of the* Quæstiones Naturales *of Seneca* (London: Macmillan and Company, Limited, 1910), p. 273.

12 B. R. Goldstein, *The Astronomy of Levi ben Gerson (1288–1344): A Critical Edition of Chapters 1–20 With Translation and Commentary* (Berlin: Springer Science & Business Media, 2012), p. 107; cf. also T. Heidarzadeh, *op. cit.*

13 J. L. Jervis, *Cometary Theory in Fifteenth-Century Europe*, Berlin, Studia Copernicana, vol. 26, Springer Science & Business Media, 1985.

14 *Ibidem*.

15 J. Regiomontanus, *Ioannis De Monteregio Germani, Viri Vndecunq [ue] doctissimi, de Cometæ magnitudine, longitudineq[ue] ac de loco eius uero, problemata* XVI, (Norimbergae, Fr. Peypus, 1531).

16 The style and the quality of the observations is not reminiscent of Regiomontanus and the treatise *De Cometis* may have been written by someone from Peurbach’s school as argued by J. L. Jervis (*op. cit.*, p. 117).

17 T. Hagecius ab Hayek, C. Gemma, J. Voegelin, J. Regiomontanus, *Dialexis de novæ et prius incognitæ stellæ inusitatæ magnitudinis & splendidissimi luminis apparitione, & de eiusdem stellæ vero loco constituendo*, (Frankfurti ad Moenum, 1574).

18 *Ibidem*, translated by J. L. Jervis, *op. cit.*, p. 119.

19 G. Fracastoro, *Homocentricorum sive de Stellis, de Causis Criticorum Dierum Libellus*, (Venezia: Giunti, 1535); cf. J. L. Jervis, *op. cit.*, p. 121.

20 P. Apian, *Astronomicum Cæsareum*, (Ingolstadt, Apianus 1540).

21 J. L. Jervis, *op. cit.*, p. 122-123

22 W. G. Wesley, “The Accuracy of Tycho Brahe’s Instruments”. *Journal for the History of Astronomy*, 1978, vol. 9, n°1, p. 42-53.

23 T. Brahe, *De nova et nullius ævi memoria prius visa Stella* (Copenhague: Hafniæ, Laurentius, 1573).

24 T. Brahe, *De mundi ætherei recentioribus phænomenis*, liber secundus (Francofurti: G. Tampachium, 1610); cf. J. L. E. Dreyer, Tycho Brahe, *A Picture of Scientific Life and Work in the Sixteenth Century* (Edinburgh: Adam and Charles Black, 1890).

25 M. Maestlin, *Observatio et Demonstratio Cometæ Ætherei, qui Anno* 1577. *et* 1578. *constitutus in sphæra* Veneris, *apparuit*,… (Tübingen, 1578).

26 T. Hagecius ab Hayek, *Descriptio Cometæ, qui apparuit Anno Domini* M. D. LXXVII. A IX. *Die Nouembris usque ad* XIII. *diem Ianuarij, Anni &c.* LXXVIII. (Pragæ, 1578).

27 T. Hagecius ab Hayek, *Apodixis physica et mathematica de cometis tvm in genere, tvm in primis de eo: qui proximè elapso anno* LXXX. *in confinio ferè Mercurij et Veneris effulsit: & plus minus* LXXVI. *dies durauit. Ad generosum*

& ampliss. virum Dn. Andream Dvditivm Cæsaris consiliarum (Dresden: Görlitz, 1581).

28 C. D. Hellmann, *The Comet of 1577* (New York: AMS Press, 1971), 488.

29 T. Brahe, *De mundi ætherei…*, *op. cit.*, p. 191.

30 P. Baker, “The Optical Theory of Comets from Apian to Kepler”, *Physis-Firenze*, 1993, vol. 30, n° 1, p. 1-26.

31 J. Kepler, *De cometis. Libelli tres.* Augustæ Vindelicorum (Augsbourg), A. Apergeri, 1619; translated by James Alan Ruffner, “The Curved and the Straight: Cometary Theory from Kepler to Hevelius”, *Journal for the History of Astronomy*, 1971, vol. 2, n° 3, p. 181.

32 J. A. Ruffner, *op. cit.*

33 This statement comes from the fact that, if an observer does not want to consider comets as planetary objects, only two possibilities remain: either they are terrestrial phenomena, or they belong to the realm of the fixed stars. That Kepler was able to make this hypothesis shows at the same time how considerations of the fixed stars evolved after the Tycho Brahe observations of the 1572 Supernova but also how counterintuitive cometary trajectories remained compared to the ones of
planets.
One can also note that two interstellar objects crossing the Solar System have been discovered in recent years: 1I/2017 U1 Oumuamua and comet 2I/Borisov.

34 T. Heidarzadeh, *A History of Physical Theories of Comets, from Aristotle to Whipple* (Berlin: Springer Science & Business Media, 2008), p. 21-51.
R. Descartes, *Principia philosophiæ*, Amsterdam 1644.

35 M. Guiducci, G. Galilei, *Discorso delle comete di Mario Gvidvcci fatto da lui nell’Accademia fiorentina* (Firenze: Pietro Cecconcelli, 1619).

36 G. Galilei, *Il Saggiatore* (Roma: G. Marcardi, 1623).

37 J. B. C. Cysatus, *Mathematica astronomica de loco, motu, magnitudine et causis cometæ qui sub finem anni 1618 et initium anni 1619 in cœlo fulsit. Ingolstadt Ex Typographeo Ederiano*, 1619.

38 G. D. Cassini, *Theoria motus Cometæ Anni 1664* (Roma 1665).

39 J. Hevelius, *Cometographia*, Gedani (Gdansk), S. Reiniger, 1668; cf. J. A. Ruffner, *op. cit.*

40 J. Hevelius, *Descriptio cometæ* (Gdansk: Gedani, 1666), 188 pages.

41 J. Hevelius, *Cometographia*, *op. cit.*

42 J. C. Sturm, *Cometarum natura motus et origo: Secundum duas hodie celebriores Joh. Hevelii et P. Petiti* (Altdorfi: J. H. Schönnerstaedt, 1681).

43 I. Newton, *The Mathematical Principles of Natural Philosophy* [*Philosophiæ naturalis principia mathematica*, 1687], translated by Andrew Motte (New York: Danniel Adee, 1846), Book 3, p. 490 *sq*.

44 *Ibidem*, p. 484.

45 *Ibidem*, p. 464.

46 *Ibidem*, p. 486.

47 D. W. Hughes, “The Principia and Comets”, *Notes and Records of the Royal Society of London*, 1988, vol. 42, n° 1, p. 53-74.

48 I. Newton, *op. cit.*, p. 495.

49 W. Whiston, *A New Theory of the Earth* (London: Roberts, 1696).

50 D. Foucault, “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”, *Nacelles*, vol. 4, 2018.

51 E. Halley, *A Synopsis of the Astronomy of Comets* (Oxford: John Senex, 1705).

52 P. Broughton, “The First Predicted return of Comet Halley”, *Journal for the History of Astronomy*, 1985, vol. 16, n° 2, p. 123-133.

53 E. Halley, *op. cit.*, p. 21-22.

54 *Ibidem*, p. 22.

55 P. Broughton, *op. cit.*

56 https://pdssbn.astro.umd.edu/data_sb/resources/periodic_comets.shtml (accessed on 10/01/2020).

57 D. Diderot, J. D’Alembert, *Encyclopédie ou dictionnaire raisonné des sciences, des arts et des métiers*, t. 3 (Paris, 1753).

58 A. G. Pingré, *Cométographie ou traité historique et théorique des comètes* (Paris: Imprimerie Royale, 1783).

59 W. Whiston, *op. cit.*

60 H. Hamilton, *Philosophical Essays on the Following Subjects. I. On the Ascent of Vapours, the Formation of Clouds, Rain and Dew, and on several other*

Phœnomena of Air and Waters. II. Observations and Conjectures on the Nature of the Aurora Borealis, and the Tails of Comets. III. On the Principles of Mechanicks (London: J. Nourse, 1767, 2nd ed.).

61 L. Euler, “Recherches physiques sur la cause des queues des comètes, de la lumière boréale et de la lumière zodiacale”, *Mémoires de l’Académie des sciences de Berlin*, 2 (1746) 1748, p. 117-140.

62 P. S. Laplace, *Traité de mécanique céleste* (Paris: Courcier, 1805), t. 4, p. 230.

63 P. S. Laplace, *Exposition du système du monde* (Paris: Bachelier, 6e édition, 1835).

64 F. J. D. Arago, « Quelques nouveaux détails sur le passage de la comète découverte dans le mois de Juillet 1819, devant le disque du soleil », *Annales de chimie et de physique*, 1820. p. 104-110.

65 B. Hetherington, “Giovanni Battista Donati, 1826-1873”, *Journal of the British Astronomical Association*, 1973, vol. 83, p. 461-462.

66 A. Guillemin, *Les Comètes* (Paris:Hachette, 1875).

67 G. Foderà Serio, A. Manara, P. Sicoli, “Giuseppe Piazzi and the discovery of Ceres”, In Jr. W. F. Bottke, A. Cellino, P. Paolicchi, and R. P. Binzel (eds), *Asteroids III* (University of Arizona Press, 2002), p. 17-24.

68 P. S. Laplace, *Traité de mécanique céleste, op. cit.*, p. 230.

69 E. F. F. Chladni, *Über den Ursprung der von Pallas gefundenen und anderer ihr ähnlicher Eisenmassen und über einige damit in Verbindung stehende Naturerscheinungen* (Riga: Johann Friedrich Hartknoch, 1794).

70 J.-B. Biot, *Relation d’un voyage fait dans le département de l’Orne, pour constater la réalité d’un météore observé à l’Aigle, le 6 floréal, an* XI (Paris: Baudouin, 1803).

71 G. V.Schiaparelli, *Le Stelle cadenti* (Milano: Fratelli Treves, 1873).

72 P. Jennisken, *Meteor showers and their parent comets* (Cambridge University Press, 2006).

RÉSUMÉS

English

This essay describes how the study of comets and asteroids through time motivated the emergence of the concept of Solar System to describe all the bodies orbiting the Sun as a single consistent ensemble. Comets present apparently unpredictable orbits with variations in brightness that lead ancient observers to consider them as meteorological rather than celestial phenomena. As observations became more regular and more precise, especially with Tycho Brahe, astronomers realized comets moved amongst the other planets around the Sun. As a consequence, cometary orbits needed to be explained within a single framework encompassing the movements of all planets and satellites around the Sun. This was achieved with the Newtonian mechanics and the successful prediction of the return of a comet by Edmund Halley. The discovery of the asteroids in the 19th century further strengthened the concept of “planetary system”, which has become a major paradigm of modern planetary science.

Français

Cet essai décrit comment l’étude des comètes et des astéroïdes au cours du temps a motivé l’émergence du concept de Système Solaire pour décrire l’ensemble des corps orbitant le Soleil au sein d’une unique entité. Les comètes présentent des trajectoires apparemment imprévisibles avec des variations en forme et en intensité qui ont amené les anciens observateurs du ciel à les considérer comme des phénomènes météorologiques plutôt que célestes. Au fur et à mesure que les observations se sont faites plus régulières et plus précises, notamment avec celles de Tycho Brahe, les astronomes ont réalisé que les comètes se déplaçaient parmi les planètes autour du Soleil. En conséquence, les orbites cométaires avaient besoin d’être explicables dans un système de pensée comprenant également les mouvements des planètes et de leurs satellites autour du Soleil. Cela fut achevé grâce à l’avènement de la mécanique newtonienne et la prédiction avec succès du retour d’une comète par Edmond Halley. La découverte de l’ensemble des astéroïdes au XIX^{e} siècle renforcera cette notion de « système planétaire » qui est devenue de nos jours un paradigme majeur des sciences planétaires.

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Mots-clés

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