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Unveiling the size of the Universe: the first accurate measurement of the Earth-Sun distance by Giovanni Domenico Cassini*

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Abstract: This master's degree thesis sheds new light on the history of a peculiar scientific expedition: the two-year (1672-73) voyage to Cayenne (French Guiana) supervised by the Italian astronomer Giovanni Domenico Cassini and led by the *élève astronome* of the *Académie Royale des Sciences* Jean Richer. The observations carried out simultaneously in Cayenne and in Paris enabled Cassini to obtain the first remarkably accurate measurement of the Earth-Sun distance, but not only that. A careful check and inspection of the original documents kept in the Archives of the *Académie* in Paris allowed to reconstruct the history of the expedition. This essay highlights the key findings and contributions of the thesis.

Keywords: History of Astronomy, Scientific Expeditions, Cayenne expedition, Jean Richer, Giovanni Domenico Cassini, Earth-Sun Distance, Parallax, Latitude, *Académie des Sciences*.

1. Introduction: the birth of scientific expeditions in France under Louis XIV

In the ambitious plan of King Louis XIV (1638-1715), better known as the Sun King, France should have become culturally dominant in Europe and extend its influence in art, literature, and science all over the world. To create this 'golden age' for the country, the King thought that he should have conquered and annexed as many key territories as possible. The first Minister of State Jean-Baptiste Colbert (1619-1683) suggested him that to prove the political dominance of France, he should have financed (alongside military campaigns) scientific expeditions aimed to determine the extent of French colonial possessions with the highest possible accuracy. Following Colbert's advice, the newborn *Académie Royale des Sciences* (1666), an institution which expressed both the *grandeur* of the monarchy and of the King himself and provided state-funded researchers, organized scientific expeditions to Denmark, Canada, French Guiana, Cape Verde Islands, Martinique, Senegal, Egypt, Siam, etc. These voyages took advantage of the French overseas trading companies: the new expeditions' project had great repercussions for France that both enforced its commercial strength and gave a strong impulse to nautical science.

Fig. 1. Jean Dominique Cassini, Tirage photographique, auteur inconnu, titre forgé. Bibliothèque de l'Observatoire de Paris, Inv.I.211.

2. Giovanni Domenico Cassini's role

The astronomers of the *Académie*, being also geographers and cartographers, were chosen as 'leading actors' of these expeditions, as measuring the terrestrial coordinates (latitude and longitude) strongly required their skills. All the French expeditions organized in those years were under Giovanni Domenico Cassini's (1625-1712) supervision: the Italian astronomer left Bologna (where he was holding a

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university chair in Astronomy) in 1669 and was warmly welcomed at the King's court in Paris (Fig. 1).[1] He also became director of the magnificent new place for astronomical observations and geographical studies: the *Observatoire Royal de Paris*, founded by Louis XIV at Colbert's instigation.

Cassini was used to coordinate from Paris the astronomers' work by instructing them, testing the instruments, and receiving the results to be compared with the measurements personally made from his station at the *Observatoire*.[2] Thanks to his temper and authority, he coordinated research which were taking place thousands of kilometers apart. In the second important period of his life, he could see for the first time his aspiration to work with colleagues for a common scientific purpose materialized: the term "*observer de concert*" occurred frequently in Cassini's writings and was precisely referred to a working group resulting from the astronomers' collaboration. The academicians remained in Paris, and Cassini above all, were always informed about what was happening abroad through private correspondence with the scholars who were travelling overseas.

3. The two-year scientific expedition to Cayenne (French Guiana)

The two-year expedition (1672-73) to French Guiana is particularly valuable from a historical and astronomical point of view, as specific observations carried out simultaneously from there and from Paris allowed to obtain a new level of knowledge in the astronomical field; the desire for glory of the *Roi Soleil* began with an aggressive military expansion and turned out into an improvement of astronomy. The complete account of the Cayenne expedition appeared in 1679, [3] at a time when the reliability of documentation was the key factor for the credibility of an institutional oversea trip.

3.1 The main purposes of the expedition and the choice of the destination

The main purposes of the expedition concerned the verification of some celestial observations which Cassini had already studied while he was in Bologna. An astronomical calendar was established to derive the following quantities (Richer 1679, p. 2):

a. The ecliptic obliquity (the angle between the Earth orbit and the equator plane).
b. The Equinoxes times.
c. Sun, Venus, and Mars parallaxes.
d. The movements, phases, and parallax of the Moon.
e. The movements of Mercury (a planet that had been rarely observed from Europe).
f. The main characteristics of the Southern Stars (which were only partially or not at all visible from Paris).
g. The effect of refraction of light.
h. A study on the barometer.
i. The length of the pendulum.
j. Some measurements of the tides' amplitude.

The detailed and strict plan of investigation decided long before the departure is one of the reasons to recognize the two years in Cayenne as the prototype of early-modern scientific expeditions.

To carry out this astronomical project, the academicians chose the main French settlement in

[1] In 1673 Cassini obtained the *act de naturalisation* for his marriage with the French noblewoman Geneviève de Laistre, becoming a French citizen and changing is name into Jean-Dominique. For Cassini's biography, refer to: Cassini (2003). See also the archival source: Cassini (no date). His autobiography has been published in: Cassini (2020).

[2] Cassini compiled a practical reminder entitled "Instructions générales pour les observations géographique à faire dans les voyages" which later became the introduction to: Cassini (1693).

[3] Richer (1679). The work was later republished in: *Mémoires de l'Académie Royale des Sciences* (1666-1699), VIII[1], pp. 233-326. Refer to: Olmsted (1942).

Madagascar, Fort Dauphin, at the Southeast tip of the island, as the original destination.[4] Unfortunately, only places laying within the two tropics (with a latitude |φ| ≤23°27') have the Sun at the zenith, where refraction is negligible, twice a year: being Fort Dauphin at a latitude of 25°, the place did not fulfil the request. This is exactly the reason why the astronomers changed the destination from Madagascar to French Guiana:[5] the latitude (4°56' North) of the French port of Cayenne ensured the achievability of the astronomical project. In addition, communications from Paris to French Guiana were faster than those to Madagascar. The change of the destination and the choice of the best period of the year to carry out the astronomical observations lead to the success of the expedition, which enabled the first determination of longitude on land and the first accurate measurement of the Earth-Sun distance.

3.2 The choice of the 'leading actor': Jean Richer

The scholar chosen for the expedition was Jean Richer (1630-1696):[6] the only likely representation of the astronomer is a drawing (Fig. 2) done by the illustrator Sébastien Leclerc (1637-1714) that may be intended as a portrait of Richer with some important astronomical instruments such as a telescope, a quadrant, a pendulum clock, and an armillary sphere.

Fig. 2. Richer, J. (1679). *Observations astronomiques et physiques faites en l'isle de Caïenne.* Paris: Imprimerie Royale, Bibliothèque nationale de France (BnF), detail, p.1.

Richer's life is partially unknown: it is almost certain that he was born in France likely around the 1630s, but the place is not known. He received a good education, worked as an engineer, and entered the *Académie* as a junior astronomer in 1666; four years later he was awarded with the title of *mathématicien de l'Académie*, a term which was regularly used to describe persons skilled in astronomical observations. Richer perfectly embodied the figure of scientific development in the modern era: he went through training process on the purpose of the trip, followed accurately instructions compiled by Cassini and brought back to his homeland essential measurements.[7] The accomplishments of the voyage were linked not only to his skills, but also to the employment of the most suitable and advanced instruments and tools, which allowed important scientific achievements.

In Cayenne, Richer brought with him a 20-foot and a 5-foot telescopes, a quadrant with a 2.5-foot radius and an octant with a 10-foot radius. Both the latter instruments were made of well-beaten iron with the graduated limb of copper. The objective glass had been made by Jacques Borelly (1623-1689), an optical glass manufacturer who entered the *Académie* in 1674. Before leaving for French Guiana, Richer made a measurement test with both the quadrant and the octant from Paris, and then repeated the same procedure once he arrived in Cayenne (Richer, 1679, pp. 3-5). Thus, he verified that his instrumentation had not been damaged during the transatlantic travel. For measuring the time, he took with him two pendulum clocks, one marking the seconds and the other marking the half-second, made by the King's watchmaker Isaac II Thuret (1630-1706).

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[4] Paris, Archives de l'Académie des Sciences, *Régistres de l'Académie des Sciences, II (Mathématiques, 1666-68),* p. 155. This is a speech given by one of the founders of the *Académie*, Adrien Auzout (1622-1691), who presented the first known proposal for a scientific expedition to the institution only three weeks after its first formal meeting, on December 22nd, 1666.

[5] Christiaan Huygens (1629-1695) first specifically mentioned Cayenne as the destination of the observers in a letter to Henry Oldenburg (1618-1677) dating September 4th, 1669 (see: Huygens 1888, p. 486).

[6] Two letters written by Richer to Cassini survive: Richer, J. (1672). *Lettre de Richer à Cassini I,* Cayenne le 4 mai 1672. Bibliothèque numérique, Observatoire de Paris, B4/11 bis (70). Richer, J. (1672). *Lettre de Richer à Cassini I,* Cayenne le 20 juillet 1672. Bibliothèque numérique, Observatoire de Paris, B4/11 bis (71).

[7] Richer had also led another previous (1670) expedition to Acadia. See: Olmsted (1960).

Once Richer came back to Paris, his notes were published with a little delay for unknown causes, but his enterprise reached an earlier popularization among the contemporaries with his accounts discussed in several Paris salons. Richer was then given the title of *ingénieur du Roi* and he was assigned to an engineering project in Germany. In 1679, he was elected to full membership of the *Académie*; no other information exists except the place – Paris – and the year – 1696 – of his death.

4. The first accurate longitude determination on land

Since the European powers engaged in the conquer of colonies, navigators strongly needed detailed maps and nautical charts to determine a vessel position in the oceans and have a safe and efficient navigation. New astronomical procedures to find the exact location on land and sea~~s~~ were developed: navigation projects proceeded thus side by side with a cartography improvement.

The determination of latitude was quite an easy task in the seventeenth century: it was not difficult for sailors located in the Northern Hemisphere to find out their ship latitude with an accuracy of about 1°, by the height of the Polar Star (which equals the latitude), using instruments such as the astrolabe and the quadrant. Determining the longitude, instead, required simultaneous observation of astronomical phenomena from a ship and from another (reference) place on land: the time difference between the two locations corresponded to the longitude difference (since one-hour difference in local times corresponds to 15° of Earth rotation around its axis and consequently in longitude). The quest for longitude became a matter of national interest: the Spanish monarchy turned to experts in navigation and cosmography to address the problem and instituted the so called ‘longitude prize’ in the hope of a solution. The initiative was followed by French, Dutch, and English governments.

4.1 The eclipses of Jupiter’s satellites

At the time of the Cayenne expedition, astronomers made use of lunar eclipses (a practice described in detail in Richer’s 1679 report) to measure the longitude of a place. However, Cassini strongly believed that a new method involving simultaneous measurements of the eclipses of Jupiter’s satellites (Io, Europa, Ganymede, and Callisto) obtained from different places on Earth, could have led to remarkable achievements in the longitude quest. When Galileo Galilei (1564-1642) discovered the satellites, he suggested that they could be used to determine the longitude of a place thanks to their very quick motion and their regular occurring: the local time difference of the starting (and/or ending) of the eclipse between the unknown longitude place and reference place (of known longitude) would have equalled the longitude difference. Galileo vainly investigated for a long time this practice to correct, renew and refine the geographical knowledge of the time, but he faced many issues: first, since the method required high precision pendulum clocks, it could not be performed on boats. What is more, even if placed on ground, pendulum clocks precision was not very high, and most astronomers thought that it would have been too difficult to get accurate results out of it. Finally, by Galileo’s death in 1642, the only published tables on Jupiter’s satellites motions were too inaccurate.

Despite this, in Cassini’s opinion the low frequency of lunar eclipses made such method less useful than Galileo’s one. Moreover, he had already compiled the ephemerides of Jupiter’s moons while he was in Bologna. Once in Paris, he got the support from his colleagues and managed to collect data of eclipses taken by astronomers from very different and distant places on Earth: simultaneous astronomical observations represent an important trace of the collaboration between scholars in the modern era. The effort in determining longitude and latitude were part of the larger French scheme, driven by the *Académie*, to combine scientific practices and explorations with the King’s practical need of corrected geographical maps.

During 1667 and 1668, the *Académie* was planning the new important program of astronomical observations to be carried out overseas. One of the first destinations chosen was Denmark, and more precisely the Hven island, where Tycho Brahe (1546-1601) had established the Uraniborg Observatory one century before. This travel led by the Abbot Jean Picard (1620-1682), together with the voyages of several other German scholars in France, promoted the establishment of strong scientific relations between the Northern regions and France. In 1671-72, Picard and Cassini were able to establish together the longitude difference between Paris and the island of Hven, which resulted (10°32’30”) only 12 arc minutes larger than the true value (10°20’33”) that can be derived by subtracting Hven longitude (12°41’28”) from Paris one (2°20’55”).[8]

Shortly after, Cassini asked Richer’s help to estimate another longitude difference: due to bad weather and adverse atmospheric conditions, the *élève astronome* could observe Jupiter’s satellites only during the second part of his stay in Cayenne. The motion of the moons on April 1st, 1672, together with the comparison of the meridian altitude of the Sun at the Equinoxes and the lunar eclipse on November 7th, 1672, provided three longitude differences: 3h 26m 33s (corresponding to 51° 38’ 15”), 3h 42m (corresponding to 55° 30’) and 3h 28m 28s (corresponding to 52° 7’ 0”) respectively (Cassini 1684, pp. 37-39).[9] The real longitude difference between Paris and Cayenne is 3h39m22s in time units (corresponding to 54°50’30”). Thus, the estimates were in this case not as accurate as they were for Hven, which is not unexpected due to the much larger distance between France and its overseas colony. Although the new method involving Jupiter’s satellites turned out to be not feasible to apply on a ship, it gave rather accurate longitude measurements on land: for geography, cartography and astronomy that was an epoch-making accomplishment.

5. The first accurate AU measurement

The Cayenne expedition deserves particular attention also because it enabled the experimental determination of the Earth-Sun distance, also called Astronomical Unit (AU). This value has been sought after since ancient times and its first estimate was made by the Greek astronomer Aristarchus of Samos (c. 310-230 BC), who largely underestimated it, finding that the Sun should have been only 19 times farther from the Earth than the Moon. Subsequent estimations of the AU remained limited within one twentieth and one tenth of its real value.

5.1 Sun and Mars parallaxes

The angular measure ($\pi_\odot$) of the Earth-Sun distance is called solar parallax: it is simply seen as the difference in the Sun position in the sky, but it cannot be directly determined because there is no fixed system to refer to during the day. What is more, there is a high difficulty in identifying with accuracy the Sun centre. Aware of these problems, Cassini devised an alternative and innovative solution by asking Richer to measure Mars parallax (π_M) from Cayenne. The smaller is the Earth-Mars distance, the larger is Mars parallax: the most favourable observational condition were at the time in which the planet was in opposition and hence close to the Earth. Not by chance, the commission of the *Académie* sent Richer to Cayenne in the fall of 1672, when the planet was expected to be at the point in its orbit closest to the Earth, after a period which lasted for about fifteen years. Clearly, the intuitions of an expert like Cassini and the reliability of his Ephemerides were key elements in achieving the epoch-making milestone for the new science: the first experimental accurate measurement of the Earth-Sun distance.

Following Cassini’s request, Richer recorded the meridian height of Mars and of a few close stars almost every day from the end of July to the end of November, but his measurements were reliable only for three September nights because of unfavourable weather conditions. Cassini did the same from Paris, with better weather conditions. The astronomers used the orbits of Jupiter’s moons to synchronize the clocks in the two locations. Comparison of the angular displacement of Mars from the stars allowed Cassini to derive that the planet was lower in Paris than in Cayenne of 12’’, 13’’ and 17’’ (Cassini 1684,

[8] Jean Picard suggested to send a commission to Uraniborg to determine the exact position of the observatory and to allow the comparison with the astronomical results obtained in Paris; the request was immediately approved by Colbert, and Picard himself left for Denmark on July 21st, 1671. See: Bertrand (1869, pp. 27-36). For the complete account of the expedition, see: Picard (1680).

[9] Cassini presented his calculations in: Cassini (1684).

p. 39). The third and last measurement resulted larger than the previous two, whereas, as Cassini stated, should have been smaller because the planet was a little farther from the Earth at the end of September, while at the beginning of the month it was closer to the opposition. Thus, the observed increase in the angular difference had to be attributed to an imperceptible defect in the observations and Cassini was totally aware of that.

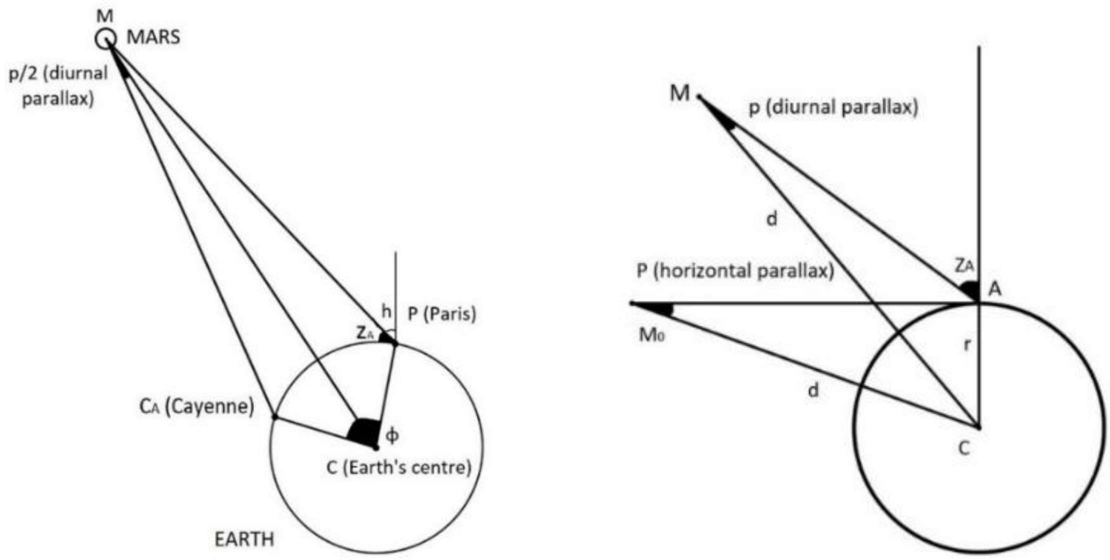

Fig. 3, left: Geometry for the calculation of Mars diurnal parallax; **right:** Geometry for the calculation of Mars horizontal parallax.

5.2 Cassini's calculations

Cassini adopted a mean value of 15" for the angular difference in Mars meridian height; from this, he derived the horizontal parallax of Mars that resulted π_M = 25,3" (Cassini 1684, p. 40). The calculations are only partially discussed in Cassini's 1684 *Elémens*: the following mathematical-geometrical procedure is the focus of my thesis work.

Referring to Fig.3 (left), knowing the distance between Paris and Cayenne and the length of the Earth's circumference, the angle at the center φ can be obtained through proportionality with the 360-degree angle. Cassini in Paris and simultaneously Richer in Cayenne measured Mars height (h) from which they obtained the zenith distance z_A= 90°- h (complementary to the height above the horizon). The two triangles MC_AC (Mars-Cayenne-center of the Earth) and MPC (Mars-Paris-center of the Earth) are similar: φ/2 and the angle at the base (which is given by 90° + z) are known. The only undetermined angle is p/2 and it equals the half of the diurnal parallax.

The next step was to obtain Mars horizontal parallax, which is referred to the Earth's equatorial radius, so it is always bigger than the diurnal parallax. In Fig. 3 (right) the letter r stands for the Earth radius and d is the Mars (M or M_0) distance from the Earth's centre (C). Considering the MAC triangle: for the law of sines and since the sine of the zenith distance angle is equal to the sine of the supplementary MÂC, it is possible to write the following equation:

$$\frac{r}{sen\,p} = \frac{d}{sen\,z_A} \tag{1}$$

Hence,

$$sen\,p = \frac{r}{d}\,sen\,z_A = sen\,P\,sen\,z_A \tag{2}$$

In the small angles approximation *sen p* ≈ *p* and *sen P* ≈ P. Thus, the horizontal parallax is:

$$P \approx \frac{p}{sen\, z_A} \tag{3}$$

Since $p \approx 15''$ and $z_A = 90° - h_{Paris} = 41°$, in first approximation we get Mars horizontal parallax as $P \approx 25''$. In fact, Cassini derived *P* = 25 1/3'' and concluded that the distance between Earth and Mars with the planet in opposition had to be about 8100 Earth radii (R_T), with a possible error of ±1000 R_T, due to the parallax measurement accuracy estimated by Cassini to amount to 3" (Cassini 1684, p. 47).

5.3 Kepler's third law of planetary motion

Cassini's method required at this point a parallelism between the Earth-Mars distance and the Earth-Sun one: the Copernican revolution brought new ideas about the Solar System and astronomers became interested in deriving the AU through Johannes Kepler (1571-1630)'s third law of planetary motions, which is an empirical mathematical relation stating that the square of the orbital period of a planet is proportional to the cube of the semi-major axis of the orbital ellipse. Planets orbital periods could be easily measured and planets distances from the Sun (in AU) could also be derived using triangulation methods.[10] The only undetermined value was the AU.

Combining the parallax principle and Kepler's third law, and since the distance between Earth and Mars related to the average Earth-Sun distance as 1': 2' 2/3, the same relation had to occur between solar and Mars parallaxes (given that the parallax is inversely proportional to the distance). Cassini derived $\pi_\odot = 9{,}5''$ for the Sun parallax and calculated the Earth-Sun distance as 21.600 R_T with an error of ±2000 R_T, up to ±3000 R_T (Cassini 1684, p. 46). The true, nowadays value for the solar parallax is $\pi_\odot = 8{,}8''$, so he slightly underestimated the real value of the AU (23.485 R_T).

Cassini's remarkably accurate calculations resulted in a huge and unexpected enlargement of the Solar System, which was believed at that time to coincide with the entire Universe (hence the title of my work). The greatest legacy of such a determination was that astronomers sought of the most important and fundamental of all galactic measurements, and the knowledge of the first method of the cosmic distance ladder (or distance scale).

6. Conclusions

Despite the increased quality of astronomical instrumentation in the subsequent century, new determinations of the AU were very similar to Cassini's one.[11] As a matter of fact, the Cayenne expedition, performed almost one century before, remains a milestone in the determination of the long searched for Earth-Sun distance value, thanks to that practicable method of investigating solar parallax through Mars. For Cassini's contemporaries, the revelation of the true size of the Solar System represented a shocking hint of how small humans were in front of a Universe that turned out to be much wider than anyone ever believed. Cassini himself was surprised, as he stated: "Voila de grandes distances que nous venons de conclure de trois petites parallaxes" (Cassini 1684, p. 47). His result could have never been achieved without the innovative method of investigation born in France under Louis XIV: the scientific expedition.

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[10] The method of triangulation was used to calculate the distances of planets from the Sun, and it is similar to the method used by Aristarchus to measure the distance of the Moon: he observed the satellite when it was in quadrature, which is close to, but not exactly equal to, the Moon first quarter and last quarter phases. The same concept was used for the inner planets: observations were made when Venus and Mercury were at their maximum elongation, i.e., with a phase of half illumination, and the Sun-Earth-planet system formed a right triangle. The tangent of the angle under which the Sun-planet distance is seen, is given by the ratio of the two cathetus (Sun-planet distance and Earth-Sun distance), so all distances were calculated as multiples or submultiples of the AU. External planets, instead, were observed in quadrature.

[11] See: Débarbat (2013).

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