

## Chapter 2 The Galilean Observation Paradigm

The past and present fame of *Micrographia* might give the impression that Hooke's activity at the Royal Society was focused mainly on microscopy. But when we see articles relating to Hooke in *Philosophical Transactions*, one of two international scientific journals of that time, a different picture of Hooke emerges. We can identify thirty-six articles relating to Hooke<sup>1</sup>; some were Hooke's own, and others were reports on his research. Their subjects are shown in Table 2 (For the list of articles, see Appendix):

**Table 2: Articles Relating to Hooke in *Philosophical Transactions***

Observations of planets, the moon and the sun	12
Improvement of lens	2
Micrometer	2
Barometer	3
Sounding	3
Microscopy and <i>Micrographia</i>	2
Information on distant places	2
Book review	2
Others	8

The first three subjects above had much to do with telescopes. 'Observations' were certainly performed with telescopes, and 'Improvement of lens' and 'Micrometer' were about the technological improvement of telescopes. In all, sixteen papers out of thirty-six, nearly half of Hooke's articles, were related to astronomical observations. Among them, ten were published in the 1660s, four in the 1670s and two in the 1680s. When we consider that *Philosophical Transactions* began publication only in the mid-1660s, the intensity of Hooke's astronomical research at that time is apparent.

It should be also noted that Hooke's articles on microscopy, the field in which Hooke has enjoyed such acclaim, were published only in the 1690s, three decades after *Micrographia*. They were just two in number, of which one was a short report on a letter to Hooke from Antoni van Leeuwenhoek (1632-1723). Hooke performed

---

<sup>1</sup> While *Philosophical Transactions* was suspended, Hooke edited *Philosophical*

microscopical observations for *Micrographia* between 1661 and 1664, the years before *Philosophical Transactions* was first published. This seems to suggest that Hooke's interest in microscopical observations faded rapidly after the publication of *Micrographia*.

### Huygens and the Royal Society

To comprehend the full significance of Hooke's commitment to telescopes, we need to understand their importance to the Royal Society at large. The contributions of Christiaan Huygens to the Society are instructive for this purpose. Needless to say, Huygens was a great man of science in the middle of the century. He sent many letters to the Royal Society, and attended its meetings in London on several occasions<sup>2</sup>. We may suppose that his communication with the Society reflected the dominant concerns of the scientific community in and outside Britain at that time.

Table 3 reproduces a numerical survey of Huygens's activities made by the author on the basis of the index compiled by G. E. Scala to *The History of the Royal Society of London* by Thomas Birch (4 vols., 1756-57, hereinafter *Birch*), a transcript of the minutes of the Society from 1660 to 1687<sup>3</sup>. According to a full name index by Scala, the name of Huygens appears on 113 pages<sup>4</sup>. In some cases, plural entries were made on the same page, and multiple subjects were discussed under the same entry. Taking this into account, Huygens's name appeared a total of 144 times in *Birch*. Though this includes purely administrative references to Huygens, most entries relate to scientific correspondence between Huygens and the Royal Society, or references by the Society to his scientific achievements.

The Table shows that Huygens's exchanges with the Royal Society can be categorised into six major topics: Telescope & Optics, Astronomy, Air Pump (including the study of air), Mathematics, Motion (of bodies), and Clock. What was included under each topic heading? The entries on 'Motion' were related to Huygens's research on the collision of elastic bodies. This topic was the subject of intense communication after 1668, when Wallis and Wren produced relevant papers<sup>5</sup>. Entries on the 'Air Pump' arose from Huygens's visit to the Royal Society in April 1661, when he had the good fortune to see Boyle's air pump. In the 1660s Huygens was the only natural philosopher who could replicate Boyle's pneumatic engine without the assistance of

---

*Collections* in its place (1679-82). The number includes papers in that publication.

<sup>2</sup> For Huygens's contact with Britain, see M.B. Hall (1980).

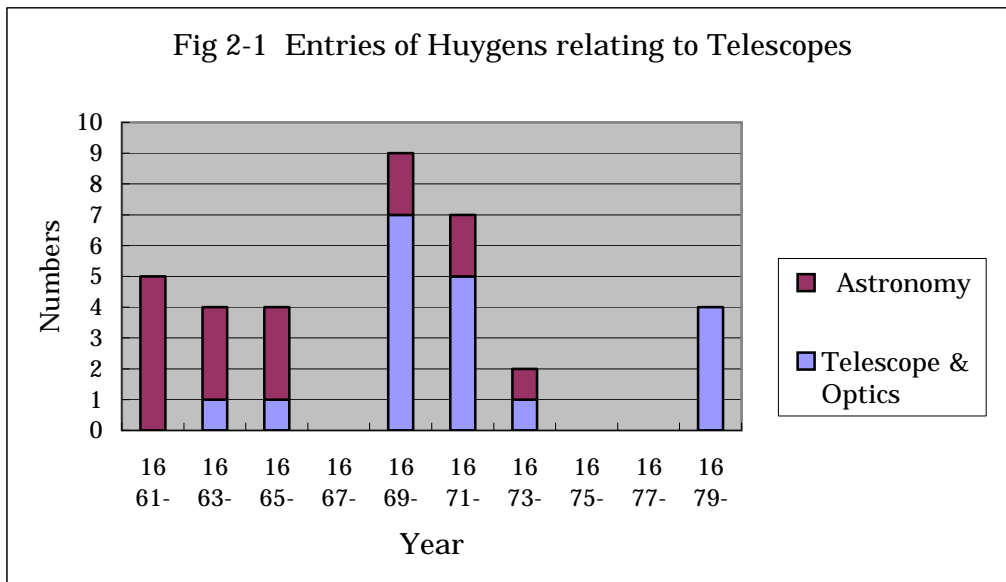
<sup>3</sup> Hunter (1981), p. 205. Huygens was aged 31 in 1660, 58 in 1687.

<sup>4</sup> Scala (1974), p. 295.

Boyle and Hooke<sup>6</sup>. At first Huygens experienced difficulties in constructing the engine: one problem, the phenomenon of the anomalous suspension of the water<sup>7</sup>, was the main topic of the entries around 1663 in *Birch*. At almost the same time, exchanges on 'Clocks' began. They covered two specific subjects in two separate periods: up to 1670, the pendulum clock was discussed, and, after 1675, the balance spring. In entries on Mathematics, cycloids and calculations of areas were among the subjects.

Table 3: Activities of Christiaan Huygens at the Royal Society

Year	Telescope & Optics	Astronomy	Motion	Air Pump (& Air)	Clock	Maths	Others	Total
1661-	0	5	1	6	1	4	3	20
1663-	1	3	1	14	10	0	11	40
1665-	1	3	1	0	3	0	2	10
1667-	0	0	2	0	0	1	0	3
1669-	7	2	16	0	5	2	7	39
1671-	5	2	0	0	0	0	2	9
1673-	1	1	0	0	0	0	0	2
1675-	0	0	1	3	4	0	1	9
1677-	0	0	0	0	1	0	5	6
1679-87	4	0	0	0	0	0	2	6
Total	19	16	22	23	24	7	33	144



<sup>5</sup> A.R. Hall (1966b), pp. 28ff.

<sup>6</sup> Shapin & Schaffer (1985), Chap 6, especially pp. 235ff.

<sup>7</sup> The water column in the barometer set in the pump did not fall, as it seemed it should, when the receiver was evacuated.

While entries in these categories appeared each in specific periods, entries on 'Telescope & Optics' and 'Astronomy', the two remaining categories, were made comparatively continuously throughout the 1660s until the mid-1670s, when both categories are counted together (Fig. 2-1)<sup>8</sup>. It is justifiable to combine them, because the entries on 'Astronomy' were mainly about telescopic observations of the planets, and the topic had much to do with that of 'Telescope & Optics'. The principal themes from the 1660s to the mid-1670s were lens grinding and Newton's reflector. The peak after 1679 reflects Huygens's publication of the book on the aerial telescope, *Astroscopia compendiaria*, in 1684. Huygens was interested in telescopes throughout his life.

Huygens's contact with the Royal Society clearly corresponded as a whole to the important scientific subjects of the seventeenth century: motion of bodies, air pumps, astronomy, improvement of clocks for navigation, etc. But it should be noted that the number of entries relating to telescopes (*i.e.*, the combined total of the categories 'Telescope & Optics' and 'Astronomy'), thirty-four, was more than on any other subject. This illustrates the importance of the telescope for the scientific community in the mid-seventeenth century.

In this context, it was quite natural that Hooke was led into research on and with telescopes. The telescope attracted much attention among the members of the Royal Society at that time. In fact, the instrument had been a focus of attention among future members of the organisation even in advance of the inauguration of the Society. But before considering their activities in detail, the reader may find a brief history of the telescope helpful.

### Invention of the Telescope

It is not certain who actually invented the telescope. We are often told that it was invented in about 1608 by Hans Lipperhey (*d.* 1619), a Dutch spectacle maker, at Middelburg in Zeeland<sup>9</sup>. This story is based on his patent application, which appears in the minutes of the States-General in The Hague<sup>10</sup>. Even before then, devices with lenses to correct visual defects had been known in the Netherlands. But the news of Lipperhey's development spread knowledge of the telescope across Europe, through

---

<sup>8</sup> Note that in 1667-68, Huygens's name was mentioned only three times in total in *Birch*. The anomalous lack of entries here applies to all categories, not just the combined category of 'Astronomy' with 'Telescope & Optics'.

<sup>9</sup> For example, King (1955), p. 34; Helden (1975), p. 252.

diplomatic channels<sup>11</sup>.

Galileo first heard the news in Venice in July 1609, and he constructed a telescope himself<sup>12</sup>. His telescope used a convex and a concave lens, a type known as the 'Galilean telescope'. Galileo returned to Venice the following month with his eight-power telescope. By the end of the year, he could make a twenty-power telescope, which he used for astronomical observations<sup>13</sup>.

The results of Galileo's observations were published in *Sidereus nuncius* (Starry Messenger) in March 1610. He revealed observations that supported the Copernican heliocentric system: the earth-like irregular surface of the moon, the satellites of Jupiter, the difficulty of magnifying fixed stars, and the fact that the Milky Way and nebulas are made up of innumerable tiny stars.

In July, in a letter about his observations, Galileo mentioned that the body of Saturn seemed to be comprised of three parts: a large dish with two smaller companions. At the end of 1610, he saw the phases of Venus, which he regarded as decisive evidence for the Copernican system. In early 1611, Galileo became interested in sunspots, and he published letters about them in 1613<sup>14</sup>.

In the history of science, Galileo's telescopic observations have been discussed mainly in two contexts: one in considering the course of the astronomical revolution from the geocentric to the heliocentric system<sup>15</sup>, and the other in the context of the development of optics and the theory of colours from Kepler through Descartes to Newton<sup>16</sup>. Indeed, Galileo's discoveries triggered an enthusiasm for telescopes in Europe, and many natural philosophers set out to devise optical improvements to them.

### The Development of Optics

Kepler began his optical research earlier than Galileo<sup>17</sup>. He published *Ad Vitellionem paralipomena* (Frankfurt, 1604), which included studies on the refraction

---

<sup>10</sup> Helden (1977a), pp. 20-25 & 35ff.

<sup>11</sup> Helden (1976), pp. 13-14; Helden (1977a), pp. 25-26.

<sup>12</sup> For Galileo's telescopes and his astronomical observations, see Drake (1978), Chap. 8-10.

<sup>13</sup> For the assessment of the magnifying power, see *ibid.*, pp. 147-148.

<sup>14</sup> *Istoria e Dimostrazioni intorno alle macchie solari e loro accidenti* (Rome, 1613).

<sup>15</sup> For example, Kuhn (1957), pp. 219-228.

<sup>16</sup> Ronchi (1970), Chap. 3-4; Sabra (1967). A similar historiography can also be found in Sec. III of Joseph Priestley, *The History and the Present State of Discoveries Relating to Vision, Light, and Colours* (London, 1772).

<sup>17</sup> For the description in this paragraph, see Mory (1971); Lindberg (1976), Chap. 9; Helden (1974a), pp. 40-43.

and reflection of light, the *camera obscura*, the inverted retinal image of the object, and so on. After Kepler read Galileo's *Sidereus nuncius*, he wrote *Dioptrice* (Augsburg, 1611), in which he analysed the production of images with lenses. In this, he applied an approximate relation that the angle of incidence of light was nearly proportional to that of refraction at small angles. He established the theoretical basis for the 'Keplerian telescope', which uses two convex lenses. He revealed that the spherical lens could not refract parallel incident rays to a focal point — the spherical aberration — and he showed that a lens of hyperbolic section could avoid this defect<sup>18</sup>.

Descartes learned of Kepler's optics in the Netherlands in the early 1620s, and developed it further in Paris through his contact with Claude Mydorge (1585-1647), Marin Mersenne (1588-1648), Jacques Alleaume and others, who were interested not only in geometry but also in optics and astronomy<sup>19</sup>. Descartes discovered the law of refraction in about 1626, probably independently from Willebrord Snel (1580-1626)<sup>20</sup>. He published the law in his *Dioptrique* (Paris, 1637). He demonstrated that a lens of elliptical or hyperbolic section was free from spherical aberration. Descartes recommended the use of the hyperbolic lens, because it would be easier to grind, and in the book he proposed machines for grinding them.

Newton hit upon the idea of his reflector while grinding a hyperbolic lens following Descartes's idea in the mid-1660s<sup>21</sup>. He recognised an intrinsic defect of refractors when he performed prismatic experiments, making 'at first a very pleasing divertissement'. When he saw an oblong shape for the spectrum of the sun, he deduced that white light consisted of rays of light of differing refrangibility. He concluded that the effect of chromatic aberration of lenses, caused by the differing refrangibility, was greater than that of spherical aberration. To avoid chromatic aberration, he decided to abandon the improvement of glass lenses and instead turned to the use of reflection.

### Galilean Observation Paradigm

The historiography above is certainly valid as a history of optics itself. However, Albert van Helden pointed out that optics alone is not enough to understand the development of the telescope and its role in the seventeenth century. He wrote

---

<sup>18</sup> M. Caspar and F. Hammer (eds.), *Gesammelte Werke*, 19 vols. (München, 1937-83), 4, pp. 371-372 & 387-389.

<sup>19</sup> For Descartes optics, see Sabra (1967), Chap. 1-4; Schuster (1977), Chap. 4.

<sup>20</sup> Sabra (1967), pp. 99-103. Cf. Schuster (1977), pp. 303ff.

<sup>21</sup> Newton's theory of colours and its formation will be discussed in detail in Chap. 6, Part A.

‘The traditional treatment of the telescope is replete with optical diagrams, explanations of spherical and chromatic aberration, and references to the theoretical investigations of Galileo, Kepler, Descartes, Huygens, and Newton, with the result that one is left with the impression that the telescope was an instrument which, if not invented through science, was at any rate turned into the sophisticated instrument it became by science — the science of optics’<sup>22</sup>.

As a result, the traditional historiography deflects our attention from the ‘real’ development of telescopes through practical trial and error, as we shall see below.

Another defect of the historiography above is that it does not include observational activities with telescopes. What did astronomers observe in the heavens after Galileo? What were the purposes of their observations? What practical difficulties had they to overcome? Were there not improvements in attachments to telescopes for advanced observations? Indeed, the telescope was not a contrivance for itself, but a ‘tool’ to be applied to astronomical activities. Unless we consider, for example, the target stars of observations, the history must be incomplete.

To overcome these difficulties, the author introduces the term ‘Galilean Observation Paradigm’<sup>23</sup>. This includes in its scope both the actual improvements to telescopes, and post-Galilean observational practices.

The Paradigm began with Galileo, and it developed throughout the seventeenth century. It was based on the technology of ‘long telescopes’, the only available method to achieve useful telescopes at that time. In the seventeenth century, telescopes were improved solely by making better and longer refractors, not by reflectors (which were known but impracticable) or by achromatic lenses (which were to be invented in the next century). The main target stars of Galilean Observation Paradigm were celestial bodies within the solar system<sup>24</sup>, the intention being to answer a series of questions identified by Galileo: selenography, the surface

---

<sup>22</sup> Helden (1974a), p. 38.

<sup>23</sup> The author would like to thank Dr. Jim Bennett for his suggestions regarding the observations Galileo initiated. In our discussion, he used the expression ‘Galilean tradition’, from which my term ‘Galilean Observation Paradigm’ was coined.

<sup>24</sup> Because the term ‘solar system’ seems to have evolved only at the beginning of the eighteenth century (Helden, 1974a, p. 56, note 96), the author’s definition of the Galilean Observation Paradigm can be applied only as a matter of hindsight. Nevertheless, the term is useful to characterise the historical development of observational astronomy.

marking of the planets, the periods of their revolution around their axes, the exact numbers of satellites of Jupiter and Saturn, the ring shape of Saturn, &c. These were popular topics among natural philosophers in the mid-seventeenth century, including Huygens, Hevelius, and members of the Royal Society.

#### Incremental Improvements to Telescopes

The telescope was first used to magnify terrestrial objects, for the identification of ships, military observation, and similar purposes. Even when celestial observations were made, they were mainly to confirm those of Galileo and not in search of new discoveries. Galilean-type telescopes were used for all these purposes. But in the late 1630s, the design of telescopes for terrestrial and celestial uses finally began to diverge<sup>25</sup>.

The principle of the Keplerian telescope was described in 1611, but it was not used widely until the 1640s. Helden found some records that Francesco Fontana (c. 1590-1656) made a 'Keplerian telescope' as early as 1608, before Kepler set the theoretical basis for it. Antonius Maria Schyrllaenus de Rheita, a Capuchin monk, discussed its technical aspects in his book of 1645<sup>26</sup>. The Keplerian telescope has a 30-40 times wider field of view than the Galilean. This is an advantage for telescopes with high magnification power, which in principle have a narrow field of view. Another advantage of the Keplerian telescope is its positive focus, which allows astronomers to mount measuring devices<sup>27</sup>. However, it produces an inverted image of the observed objects. This was regarded as a serious defect, especially by rich patrons who, although they loaned their telescopes to astronomers, also used them for their own amusement. As a result, the Keplerian telescope spread through Europe only slowly<sup>28</sup>.

Though the history of optics usually concentrates on the improvement of telescopes by means of aspheric lenses, real history did not follow this course. The fact that Newton was engaged in grinding hyperbolic lenses in the 1660s tells us both that natural philosophers were still trying to do this themselves, and that they could not yet achieve satisfactory lenses.

Helden pointed out that between 1610 and 1660, considerable improvements

---

<sup>25</sup> Helden (1974a), pp. 42-44.

<sup>26</sup> *Ibid.*, p. 41; Helden (1976), pp. 19ff.

<sup>27</sup> Helden (1974a), pp. 41-42.

<sup>28</sup> Helden (1976), p. 19, note 30.



were made in techniques for grinding spherical lenses<sup>29</sup>. He demonstrates this by reference to scientific tests of two lenses produced in the seventeenth century. Both used Venetian glass of similar quality. One is an early telescopic lens ascribed to Galileo, which is preserved in Florence. It has a useful aperture of 38 millimetres and an actual resolving power of 10 seconds at best. Another lens, made in 1660 and tested at Utrecht, has an aperture of 42 millimetres and was found to have a resolving power of 3.7 seconds, a value near the theoretical limit<sup>30</sup>.

Another way to improve telescopes was to construct long telescopes with lenses of long focal length. This method was probably developed through practical experience. With hindsight, we can understand that it achieved high magnification comparatively free from both chromatic and spherical aberrations: colour dispersion of light is smaller for longer focal lengths, and the effect of spherical aberration is inversely proportional to the square of focal length<sup>31</sup>.

Telescopes started to increase in length after 1645. From about 1645 to 1650 the length of good telescopes increased from 6-8 feet to 10-15 feet. Magnification power increased from 30 to 40 diameters. By 1660 the average length of good telescopes was about 25 feet, and by 1670 it had increased to 40-50 feet. Before the end of the seventeenth century, extraordinarily long telescopes of over 200 feet were made<sup>32</sup>.

### The Emergence of Telescope Makers

As the telescope developed into a sophisticated instrument, it became harder for spectacle makers to achieve the required quality. It was not easy to grind long focal-length lenses of very slight curvature. Therefore, astronomers usually worked with particular skilled craftsmen, who were to become specialist professional telescope makers, with higher social status<sup>33</sup>.

Until the 1630s, Galileo's telescopes were regarded as the best in Europe. For example, Galileo sent a telescope to Pierre Gassendi (1592-1655) and Nicolas Peiresc (1580-1637) in about 1635, and they acclaimed it as the best telescope they had ever used. Galileo employed an artisan, Ippolito Franchini (1593-1653), to supply

---

<sup>29</sup> Helden (1974a), p. 45.

<sup>30</sup> *Ibid.*, pp. 45-46. The lens at Utrecht was made by Campani, whose activities are discussed later.

<sup>31</sup> King (1955), p. 49. Though Inwood recognised that greater focal length diminishes spherical aberrations, he did not mention its advantage of reducing chromatic dispersion (Inwood, 2002, p. 53).

<sup>32</sup> Helden (1974a), pp. 46-47.

telescopes to his clients<sup>34</sup>.

New developments began to appear in about 1640. Fontana, of Naples, was the first to surpass Galileo's telescopes. His telescopes were of the Keplerian type, and had much higher power of magnification and greater field of view than Galileo's. Evangelista Torricelli (1608-1647), a successor to Galileo, endeavoured to restore the pre-eminence of Florence in telescope making. By 1646 his telescopes had become the most renowned in Italy, but it is not known whether his telescopes were really better than Fontana's<sup>35</sup>.

In this period, Johannes Wiesel of Augsburg was a popular telescope maker in northern Europe. Rheita claimed that he had taught Wiesel a great deal<sup>36</sup>. Charles Cavendish (1591-1654), who left England for Hamburg after the battle of Marston Moor, was interested in telescopes and made inquiries about Wiesel's in 1644. In England, Johannes Morian, a member of the 'Hartlib circle' which gathered around Samuel Hartlib (*d.* 1670?), exchanged letters with Wiesel. A description in a letter of 1649 confirms that Wiesel had supplied at least two telescopes to members of the Hartlib circle. It is known that Wiesel's telescope used a compound eyepiece, which enlarged the narrow field of view thus alleviating a serious defect of long telescopes<sup>37</sup>.

In about 1650, a brilliant telescope maker in Rome, Eustachio Divini (1610-1685), acquired a high reputation. He began his career as a clockmaker, and turned to making telescopes in 1646. He produced high quality telescopes about 40 feet long with strong magnification power. Fontana and Divini belonged to a new generation of telescope makers, who could also perform astronomical observations and publish their results themselves<sup>38</sup>. Divini proposed a theory about Saturn, and entered into controversy with Huygens<sup>39</sup>.

A young craftsman in Rome, Giuseppe Campani (1635-1715), eventually bettered Divini in an open contest (*paragone*) of telescopes in April 1664<sup>40</sup>. Campani

---

<sup>33</sup> *Ibid.*, p. 49; Helden (1976), p. 26.

<sup>34</sup> Bonelli & Helden (1981), pp. 4-5.

<sup>35</sup> *Ibid.*, pp. 5-6.

<sup>36</sup> Helden (1976), pp. 31-32.

<sup>37</sup> *Ibid.*, pp. 32-33; Helden (1977b), pp. 27-29. Later, Huygens invented another system for the compound eyepiece, which is used widely even now (Helden, 1981, p. 17).

<sup>38</sup> Bonelli & Helden (1981), pp. 8-11.

<sup>39</sup> Helden (1970). Huygens won the controversy, and consequently it was believed that his telescopes were better than Divini's. In the paper, Helden casts doubt on this supposition.

<sup>40</sup> Bonelli & Helden (1981), pp. 14ff. They showed that Campani's victory was not decisive, but he could nevertheless use it to boost his public image.

was influenced by his two elder brothers: one a clockmaker in the Vatican who probably taught him the craft, and the other a church rector who had a deep interest in science. Campani embarked upon telescope-making in about 1660. One secret of his telescopes lay in the arrangement of lenses in the eyepiece, which produced better and more-highly magnified images even with shorter tube lengths<sup>41</sup>. Other advantages were the careful selection of the glass for the lenses, and Campani's technique for grinding and polishing them. He invented a comparatively sophisticated lathe, and used a specially printed sheet to test the resolution of his telescopes<sup>42</sup>.

With these improvements, Campani challenged Divini at the first open contest in 1663, and finally beat him the next year. Campani composed a tract *Ragguaglio di due nuove osservazioni* in 1664 on his improvements, and copies were sent to Florence, France and Holland<sup>43</sup>. News of the book spread even as far as London, via Paris in 1665<sup>44</sup>.

Giovanni Domenico Cassini, professor of astronomy at Bologna University, who attended the first open contest, became a leading user of Campani's telescopes (Fig. 2-2). In 1669, Cassini went to France at the request of Louis XIV, and in 1671 he was asked to superintend the newly built observatory in Paris. He had made a series of important discoveries since 1664 with Campani's telescopes, both in Italy and in France, including four new satellites of Saturn and the division in Saturn's ring. The excellence of Campani's telescope impressed astronomers of the French Academy. As a consequence Jean-Baptiste Colbert (1619-83), the King's influential minister ordered a 34-foot telescope from Campani and set it up in the observatory<sup>45</sup>.

## Selenography

What did astronomers see with their telescopes in the early half of the

---

<sup>41</sup> *Ibid.*, pp. 16-18.

<sup>42</sup> Simpson (1981), p. 17. Campani claimed that he did not use any mould, and that he ground lenses directly with a precision lathe. But this was doubted by Bonelli & Helden (1981), pp. 26-27.

<sup>43</sup> *Ibid.*, p. 25.

<sup>44</sup> 'An Account of the improvement of Optick Glasses', *Phil. Trans.*, 1 (1665), no. 1, pp. 2-3; Bonelli & Helden (1981), p. 28. Bonelli & Helden supposed that 'Auzout's and Huygens's curiosity about Campani's lens-making method occasioned Robert Hooke to imagine a lens-grinding machine' in *Micrographia*. But this is very doubtful, because the printing of the book started in the summer of 1664, about six months before the news arrived.

<sup>45</sup> King (1955), pp. 58-59; Bonelli & Helden (1981), p. 39 & p. 42, note 103; *Phil. Trans.*, 8 (1673), no. 92, pp. 5178-5185 (p. 5180); *ibid.*, 16 (1686), no. 181, pp. 79-84 (p. 81).

seventeenth century? They observed Mars, Jupiter, Saturn, satellites of the planets, the moon and the sun, *i.e.* celestial bodies in the solar system. Mapping of the fixed stars was done to some extent for the purpose of preparing a background reference frame<sup>46</sup>, but otherwise it was overshadowed until the latter half of the seventeenth century by the observational pattern Galileo had triggered.

Bonelli and Helden traced the history of the astronomy of the time, and wrote that 'discoveries came in two great waves, the first from 1609 to 1612, and the second from 1655 to 1685'. Galileo's telescope and his own observations (the irregular surface of the moon, the satellites of Jupiter, &c.) dominated the first period, and the second was related to the activities of Divini and Campani<sup>47</sup>. Helden also argued in his earlier paper, with slight contradiction, that some revision took place in the late 1630s, but that new discoveries began only after 1646<sup>48</sup>. In fact observations from the late 1630s to the mid-1650s refined the earlier discoveries from the first wave; weak signs of the second wave gradually emerged in about 1646, as we see below. So we may set the end of the first stage of observational astronomy or of the Galilean Observation Paradigm around the mid-1650s.

The first stage of the Observation Paradigm was opened by Galileo's own observation, and it drew to an end through a refinement process after the late 1630s, in the particular cases of the observation of the moon and Saturn. Selenography was one of the most important topics of the period. Galileo had shown that the moon had an irregular surface, like the earth. After Galileo, telescopic observation of the moon sought to confirm his discovery, which contradicted the Peripatetic belief in a perfectly spherical and smooth surface of the moon. This opened the way to mapping the moon<sup>49</sup>.

At first, astronomers were content with drawing rough sketches. But toward the end of the 1630s another group of astronomers appeared who 'intended to reproduce the Moon's surface as accurately as possible, with the various formations they saw on it, in order to facilitate more accurate observations of star occultations

---

Cassini's discoveries are discussed again in Chapter 4.

<sup>46</sup> Bonelli & Helden (1981), p. 39. The number of identified comets was only seven in 1609, and had risen to sixteen by 1684.

<sup>47</sup> *Ibid.*, pp. 39-40. Here they argued the reason why telescopic discoveries came in two waves: the discriminating power of the telescope 'remained constant until about 1640, when it began to increase. The quickest increase came between 1650 and 1670' (*ibid.*, p. 40).

<sup>48</sup> Helden (1974a), p. 54.

<sup>49</sup> For the development of the tradition of selenography, see Vyver (1971a); Vyver (1971b); Whitaker (1989) \*\*. Vyver and Whitaker's papers contain many illustrations

and lunar eclipses<sup>50</sup>.

Gassendi, Langren, Hevelius, and Riccioli were among the important figures in selenography<sup>51</sup> (Fig. 2-3). Gassendi had the idea of drawing a coloured map of the moon, applying a nomenclature to the lunar topography. He had the support of his close friend, Peiresc. They used a skilled engraver, Claude Mellan (1598-1688), to prepare the picture of the moon in the 1630s, and three engravings were made in 1637<sup>52</sup>.

Michel Florent van Langren (1600-1675), cosmographer at Brussels to King Philip IV of Spain, was interested in selenography for the purpose of determining longitude. He compiled several maps of the moon in 1644 and 1645. He named 325 lunar formations, though only three of his names survive today. His map seems to have been popular; a printed counterfeit copy was discovered in Strasbourg at the beginning of the last century<sup>53</sup>.

Johannes Hevelius (1611-1687) took up selenography under the influence of Gassendi and Peiresc<sup>54</sup>. He published his first work *Selenographia* (Gdansk, 1647), the product of four years of conscientious observations, containing more than 500 pages with numerous illustrations<sup>55</sup>. Hevelius named 274 lunar formations, and the book made him the 'founder of lunar topography'<sup>56</sup>.

However, most of Hevelius's names were replaced under a modern system of nomenclature by a listing in *Almagestum novum* (Bologna, 1651), which was published by Giovanni Baptista Riccioli (1618-1663). He was a Jesuit astronomer, and believed in a modified version of the geocentric Tychonic system. *Almagestum novum* was a comprehensive review of astronomy up to 1650<sup>57</sup>. It contained two lunar maps, which

---

of the moon, identifying the natural philosophers who drew them.

<sup>50</sup> Vyver (1971a), p. 69. An exception was Thomas Harriot (1560-1621), who drew maps of the moon earlier than the second group (*ibid.*, p. 71). He also observed sunspots a year earlier than Galileo. But his observations were not published, so they were not known until the end of the eighteenth century. See North (1974).

<sup>51</sup> Helden (1974a), p. 42.

<sup>52</sup> Vyver (1971a), pp. 71-72.

<sup>53</sup> *Ibid.*, pp. 72-74. At almost the same time, Rheita and Fontana, who promoted the Keplerian telescope, published maps of the moon. But their maps were primitive as selenographs (*ibid.*, pp. 74-75).

<sup>54</sup> *Ibid.*, p. 76.

<sup>55</sup> King (1955), p. 51. Though Hevelius used Galilean telescopes in the 1640s for his observations for the book, the 'old-fashioned' instrument satisfied the purpose (Helden, 1976, p. 35). For the role of 'visual language' (*i.e.*, illustrations) in *Selenographia*, see Winkler & Helden (1993).

<sup>56</sup> Vyver (1971a), p. 76.

<sup>57</sup> Helden (1974a), p. 53, especially note 82. As Helden wrote here, 'Some of the best observational astronomy in the seventeenth century was, in fact, done by astronomers

were drawn by Riccioli's Jesuit friend, Francesco Maria Grimaldi (1618-1663). It was said that when he made observations, Grimaldi always had at hand the maps of Langren and Hevelius<sup>58</sup>. Astronomers did not attempt to start again from the beginning in the study of selenography. The tradition of selenography was of cumulative research building on previous work, the first stage of which finally closed at the end of the seventeenth century<sup>59</sup>.

### The Puzzle of Saturn

In July 1610, Galileo first observed Saturn with a telescope. At the end of the month he wrote letters to Belesario Vinta (1542-1613), the secretary to the Grand Duke of Tuscany, and mentioned his discovery that the body of Saturn appeared as if it consisted of three stars. They almost touched each other in a straight row, and the middle star was about three times bigger than the other two<sup>60</sup>. When he observed Saturn again late in 1612, he was surprised to see that the two small stars had disappeared. He guessed that they were hidden for the present, and would show themselves again around the summer of 1613. They did reappear in July, fulfilling Galileo's prediction<sup>61</sup>. In the summer of 1616, when Galileo observed Saturn again, he now saw the middle body with two round handles<sup>62</sup>. Galileo suggested in *Dialogo* (Firenze, 1632) that the change of appearance may have been caused by the rotation of Saturn around its own centre<sup>63</sup>. But even in 1640, he was not sure of the true reason for the changing appearance, and sought much more information<sup>64</sup>.

We now know that the changing appearance of Saturn is caused by its ring being observed from different angles. The ring is only about a thousand feet thick, and when it lies edge-on to the earth even modern telescopes cannot detect it. In some other orientations, Saturn seems as if it were made of three parts.

It was not until the middle of the 1630s that astronomers began observing

---

who either rigidly adhered to a geocentric system or never came out publicly with their opinion'. He also wrote that 'In a way the telescope was a blessing to conservative astronomers, because it established an area of research within astronomy in which one's religious and astronomical convictions did not particularly matter'. Indeed, Riccioli's belief in the Tychonic system is made graphic in the frontispiece of *Almagestum novum*. The frontispiece is reprinted in Cohen (1980), p. 45, fig. 59.

<sup>58</sup> Vyver (1971a), pp. 77-78. The maps were printed in Book 4, Chapter 7 of the work.

<sup>59</sup> *Ibid.*, p. 69.

<sup>60</sup> Drake (1978), p. 161; Helden (1974b), p. 105. Galileo suggested that using less powerful telescopes, Saturn would appear as a single oval body (*ibid.*, p.105-106).

<sup>61</sup> Drake (1978), p. 198; Helden (1974b), p. 107.

<sup>62</sup> *Ibid.*, pp. 109-110.

<sup>63</sup> The second day of *Dialogo* (English translation by Drake, p. 263).

Saturn and advancing hypotheses to explain its strange appearance. Gassendi started systematic observation of Saturn in the summer of 1633. He left illustrations, one of which showed the shape of a 'silk-egg'<sup>65</sup>. Fontana in Naples drew Saturn with a handled appearance in 1638, but he did not publish this until 1646. Illustrations and descriptions of Saturn proliferated after 1642, when it showed a round appearance. In this year Hevelius, and in the next year Riccioli and Grimaldi, started their observations. Hevelius published his results in *Selenographia* in 1647. Gassendi discussed all of his observations in his *Animadversiones* of 1649<sup>66</sup>. Also in that year, Divini showed a handled oblong Saturn in his printed advertising pamphlet<sup>67</sup>.

Theoretical consideration developed alongside the increasing number of observations. In 1651, Riccioli reviewed the appearances of Saturn since 1610 and classified their shapes in his *Almagestum novum*<sup>68</sup>. Hevelius presented in his *De Native Saturni Facie* (Danzig, 1656) his idea that the body of Saturn could be ellipsoidal with two sickle-shaped appendages<sup>69</sup>.

The ring hypothesis was eventually made public by Huygens in his *Systema Saturnium* (The Hague, 1659)<sup>70</sup>. At the beginning of the book, Huygens briefly summarises studies of the appearance of Saturn since Galileo. He continues with descriptions of telescopes he had made, and details of his observations of Saturn with them. He then introduces the illustrations of preceding observations by Galileo, Scheiner (Christoph, 1573-1650), Riccioli, Hevelius, Divini, Fontana, Gassendi &c, and analyses them critically (Fig. 2-4). Then Huygens announces his ring hypothesis: that the spherical body of Saturn is surrounded by a ring plate oblique to its ecliptic.

#### An Iconology of Telescopes at the Royal Society

Galileo's telescopic observation initiated a research tradition, in which selenography and the problem of Saturn assumed considerable importance. In addition, Galileo emphasised the importance of observing the satellites of Jupiter. He proposed a means of using them to determine longitude. His basic idea was to regard the four satellites as the hands of a clock in the sky<sup>71</sup>.

The use of observation to answer the questions raised by Galileo constituted,

---

<sup>64</sup> Helden (1974b), p. 111.

<sup>65</sup> *Ibid.*, pp. 111-112.

<sup>66</sup> *Ibid.*, pp. 112-115.

<sup>67</sup> Helden (1970), p. 37.

<sup>68</sup> Helden (1974b), p. 115.

<sup>69</sup> Helden (1968), p. 214.

<sup>70</sup> The book is reprinted in *Oeuvres*, **15**, pp. 209-353.

in the phrase of Thomas Kuhn, the 'normal science' of astronomy in the seventeenth century. This research tradition has been given the name 'Galilean Observation Paradigm' in the present paper. The development of the Paradigm relied on the incremental development of long telescopes, with which astronomers observed celestial bodies in the solar system.

What of the Paradigm in England, the country of Robert Hooke? John Wallis left a very informative record at the end of the seventeenth century. He had reached his eightieth year, and responding to repeated requests from his friend he produced an autobiography which was written by an amanuensis and corrected by himself<sup>72</sup>.

The autobiography contains an account of the activities of natural philosophers in London in about 1645, the time leading up to the formation of the Royal Society. As Parliament became dominant in the Civil War, some of the members left for Oxford in 1648 or 1649. Before that, philosophers in London held meetings, sometimes at Goddard's lodgings in Wood Street, sometimes at Gresham College. Wallis relates:

'Our business was (precluding matters of Theology and State Affairs) to discourse and consider of Philosophical Enquires, and such as related thereunto; as Physick, Anatomy, Geometry, Astronomy, Navigation, Staticks, Magneticks, Chymicks, Mechanicks, and Natural Experiments; with the State of these Studies, as then cultivated, at home and abroad. We there discoursed of the Circulation of the Blood, the Valves in the Veins, the Copernican Hypothesis, the Nature of Comets, and New Stars, the Satellites of Jupiter, the Oval Shape (as it then appeared) of Saturn, the spots in the Sun, and its Turning on its own Axis, the Inequalities and Selenography of the moon, the several Phases of Venus and Mercury, the Improvement of Telescopes, and grinding of Glasses for that purpose, the Weight of Air, the Possibility or Impossibility of Vacuities, and Natures Abhorrence thereof: the Torricellian Experiment in Quicksilver, the Descent of heavy Bodies, and the degrees of Acceleration therein; and divers other things of like nature'<sup>73</sup>.

---

<sup>71</sup> Drake (1978), p. 193.

<sup>72</sup> Scriba (1970), p. 17. The paper includes transcriptions of both the first draft and the final version of the autobiography. Part of the description overlaps with John Wallis, *A Defence of the Royal Society* (London, 1678), pp. 7-8.

<sup>73</sup> Scriba (1970), p. 40. Here, contractions are expanded and italics are neglected, for the convenience of readers.



The description clearly illustrates that they were interested in almost all the major topics at the forefront of contemporary natural philosophy, from the Torricellian vacuum through the Copernican system to the circulation of blood.

But the author would draw the reader's attention to the astronomical topics they discussed: 'the Satellites of Jupiter, the Oval Shape (as it then appeared) of Saturn, the spots in the Sun, and its Turning on its own Axis, the Inequalities and Selenography of the moon, the several Phases of Venus and Mercury, the Improvement of Telescopes, and grinding of Glasses for that purpose'. This clearly corresponds to Galilean Observation Paradigm the author has defined. Natural philosophers in London around 1645 were interested in the observation of celestial bodies in the solar system with improved telescopes.

Had their interest been lost by the time they reconvened in London and organised the Royal Society about fifteen years later? The details are discussed in the next Chapter, but in fact they had never lost the curiosity expressed in the Paradigm. In support of this claim, the author here briefly introduces an illustration and its iconographical analysis.

Fig. 2-5a is the frontispiece of Sprat's *History of the Royal Society*<sup>74</sup>. The book was produced to protect the Royal Society against its critics. John Evelyn (1620-1706), who drew the plate, placed a bust of King Charles II, the patron of the Society, at the centre, and located Francis Bacon, its ideological mentor, to the right, and Lord Brouncker, the first President, to the left.

Steven Shapin and Simon Schaffer gave an intriguing iconographical analysis of the picture in their *Leviathan and the Air-pump*. They called attention to a scientific instrument behind the three persons: Boyle's air pump with a round glass receiver, in the centre-left background. They argued that it was drawn here because of the 'powerfully emblematic status of the air-pump' for the Royal Society's experimental programme<sup>75</sup>.

If their interpretation is valid, it seems that telescopes must have had a similar emblematic status at the Royal Society. If we examine an enlargement of the part of the picture near the air pump (Fig. 2-5b), we can identify a very long telescope just behind the pump. It is hoisted on a tower surmounted by a flag, and a person is

---

<sup>74</sup> The plate was not originally prepared for Sprat's book, but for another book which had similar aims. For the process by which it was finally adopted for Sprat's, see Hunter (1981), pp. 194-197.

<sup>75</sup> Shapin & Schaffer (1985), pp. 30-35, especially p. 32.

looking through the tube.

We see in the next Chapter that the original picture of the telescope was drawn by Hooke for Hevelius. The frontispiece suggests not only that telescopic observation played an important role at the beginning of the Royal Society, but also that Hooke's astronomical activities attracted considerable attention from the members. Therefore, we are obliged to devote as much analysis to Hooke's astronomy as we have to Boyle's air pump, the importance of which has been regarded as almost self-evident.

In *Leviathan and the Air-pump*, Shapin and Schaffer pointed out that 'the air-pump was seventeenth century "Big Science"'<sup>76</sup>. They estimated the price of Boyle's pump at 25 pounds — more than the annual salary of Hooke as Curator. But the author would emphasise that the price of a long telescope surpassed that of the air pump. In the 1660s, 36-foot telescopes cost 30 pounds. For a 100-foot telescope, the price reached as much as 100 pounds<sup>77</sup>. Only the wealthy, or groups of natural philosophers, could have afforded them. Therefore, long telescopes were 'Big Science' too, and 'represented the aspirations and achievements of the new science of the mid century, and inevitably became a focus of interest and a source of national pride in philosophical circles'<sup>78</sup>.

---

<sup>76</sup> *Ibid.*, p. 38.

<sup>77</sup> Richard Reeve, who worked with Hooke, compiled a price list of telescopes. It is printed in Court and Rohr (1930-1), p. 121. See also Simpson (1989), p. 39, note 20. For comparison, a college education at Oxford seems to have cost about 50 pounds a year (Stone, 1974, p. 43).

<sup>78</sup> Simpson (1989), p. 34.