

## Chapter 4 The Astronomical Research of Hooke

### The Development of the Galilean Observation Paradigm

At the beginning of the first stage of the Galilean Observation Paradigm, telescopic observations were carried out in order to confirm Galilean discoveries<sup>1</sup>. The capabilities of telescopes finally surpassed those of Galileo's own in about 1640, so that between the late 1630s and the mid-1650s astronomers could progress to observations to refine or advance the Galilean discoveries. Selenography culminated in 1651 with the publication of *Almagestum novum* by Riccioli, and in 1656 Huygens solved the problem raised by Galileo of the strange appearance of Saturn.

Around the mid-1650s, the Galilean Observation Paradigm moved on to its second stage. Astronomers discovered celestial bodies unknown to Galileo. A pointer to the second stage had already appeared in 1646, when Fontana referred to surface markings on Jupiter<sup>2</sup>. But the real shift began in 1655, when Huygens discovered Saturn's satellite, Titan. This was the first major discovery in almost half a century since Galileo<sup>3</sup>. Within a decade, astronomers had begun to consider the rotation of the planets about their own axes, a new subject in astronomy.

New discoveries were now possible only with the most advanced telescopes. We have discussed the emergence of professional optical-instrument makers such as Divini, Campani and Reeve, who supplied long telescopes during this period. Astronomical discoveries continued until about 1685, 'when the limit of usefulness of the long refractor was reached'<sup>4</sup>.

Giovanni Domenico Cassini was a representative figure in the second stage of the Galilean Observation Paradigm. He discovered four new satellites of Saturn between 1670 and the mid-1680s. In 1675, he also discovered that Saturn's ring actually consisted of two rings — Cassini's division.

The second stage also signalled the end of the Galilean Observation Paradigm, or the beginning of the next trend in astronomy. Astronomers began to use tools for precision astronomical measurements in conjunction with telescopes: eyepiece micrometers, telescopic sights and accurate clocks. The accuracy of positional measurements finally surpassed the level of Tycho's observations. Helden wrote:

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<sup>1</sup> The description here essentially repeats that of Chap. 2, especially pp. \*\*ff.

<sup>2</sup> Helden (1974a), pp. 54-55.

<sup>3</sup> Helden (1980), p. 149.

<sup>4</sup> Bonelli & Helden (1981), p. 40; Helden (1980), p. 154. Helden wrote that after 1685 'nothing new was added until William Hershel's discovery of Uranus in 1780 with a reflecting telescope' (*ibid*).

‘The revolution in positional astronomy brought about by the combination of [the] pendulum clock, measuring arcs with telescopic sights, and the micrometer, in the period 1665-1680 was profound’<sup>5</sup>.

Institutional development supported ‘the revolution’. National observatories were established in Paris in 1667, and at Greenwich in 1675, but not until the 1690s did they yield their full harvest. Cassini published a revised table of the movements of the satellites of Jupiter in 1693, which was even more precise than his own excellent table of 1668<sup>6</sup>. John Flamsteed (1646-1719) between 1676 and 1689 made observations with the sextant accurate to 10 seconds, over ten times more precise than Tycho’s<sup>7</sup>. His catalogue of fixed stars was eventually published in *Historia coelestis Britannica* (London, 1725), which was accompanied by *Atlas coelestis* (London, 1729).

Hooke’s astronomical research should be considered in the context of both the second stage of the Galilean Observation Paradigm and the development of accurate positional astronomy, because he began his astronomical study a decade after the beginning of the second stage.

#### Galilean Observation Paradigm in *Philosophical Transactions*

Hooke’s astronomical contributions to *Philosophical Transactions* were made mainly in the 1660s. But as well as articles by or relating to Hooke, which are considered in detail in the next section, articles on astronomy in general held considerable importance in the journal.

Oldenburg started the publication of *Philosophical Transactions* on 6 March 1665. The first volume began with Oldenburg’s editorial dedicatory preface to the Royal Society. This was followed by ‘The Introduction’, which emphasised the importance of communication for ‘the improvement of Philosophical Matters’.

The first article of substance in *Philosophical Transactions*, which appeared immediately after ‘The Introduction’, was entitled ‘An Accompt of the improvement of Optick Glasses’<sup>8</sup>. It introduced an outline of Campani’s treatise, *Ragguaglio di due nuove osservazioni*, which had been published in Rome in July 1664<sup>9</sup>, soon after his triumph over Divini at an open contest (*paragone*, see p.\*\*).

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<sup>5</sup> Helden (1980), pp. 156-157. For the development of the accuracy of angular measurement, see Chapman (1983), especially pp. 134-135.

<sup>6</sup> See *DSB*, ‘G. Cassini’, 3, pp. 100-104 (pp. 101r & 103l).

<sup>7</sup> *DSB*, ‘Flamsteed’, 5, pp. 22-26 (pp 24r-25l); Chapman (1983), p.134.

<sup>8</sup> *Phil. Trans.*, 1 (1665), no. 1, pp. 2-3.

<sup>9</sup> Bonelli & Helden (1981), pp. 25 & 28.

Campani reported that he made lenses for his long telescopes 'with a Turne-tool, without any Mould'. He used 'three Eye-Glasses for his great *Telescopes*, without finding any *Iris*, or such Rain-bow colors, as do usually appear in ordinary Glasses, and prove an impediment to Observations'<sup>10</sup>. The treatise also discussed the 'Circle of Saturn', protuberances and belts on Jupiter, the shadows of its satellites and its rotation about its own axis.

It should be noted that this first article in the first volume of *Philosophical Transactions* was devoted to the advanced long telescopes of Campani. Moreover, the two articles immediately following it were also on observational astronomy. They are supporting evidence that the Galilean Observation Paradigm attracted considerable interest among the members of the Royal Society in its early days.

### Hooke's Early Observations

The articles following that on Campani were entitled 'A Spot in one of the Belts of Jupiter' and 'The Motion of the late Comet prædicted'<sup>11</sup>. The former is especially important for us, because it was a report on Hooke's observation of Jupiter on 19 May 1664. Hooke had already made this known to the Royal Society on 4 January 1665 [1664/5]<sup>12</sup>. The article reports that he saw, with 'an excellent twelve foot Telescope', that 'the said Spot had moved from East to West, about half the length of the Diameter of *Jupiter*' in two hours<sup>13</sup>. The observation could be interpreted in two ways: the discovery of Jupiter's rotation around its own axis, or that of the movement of the shadow of its satellite<sup>14</sup>.

It was Cassini who confirmed the rotation of Jupiter in 1666, and the news was announced in England in an article entitled 'Of a Permanent Spot in Jupiter', which appeared in *Philosophical Transactions*<sup>15</sup>. The rotation was expected, 'yet, till now, it hath not been evinced by Observation': so Cassini's report of 'a permanent Spot

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<sup>10</sup> *Phil. Trans.*, 1 (1665), no. 1, p. 2.

<sup>11</sup> *Ibid.*, p. 3, and pp. 3-8, respectively. The latter article was to introduce a letter from Auzout, which is discussed below.

<sup>12</sup> *Birch*, 2, p. 3.

<sup>13</sup> *Phil. Trans.*, 1 (1665), no. 1, p. 3.

<sup>14</sup> Pugliese mistakenly asserted that Hooke 'noted a moving spot on a belt of Jupiter, indicating its rotation' (*Pugliese*, p. 589). Actually Auzout wrote to Oldenburg that 'I have often praised you, to inform me ye particulars of yt Observation of M. Hook, and of ye motion of this spot, for to conjecture, whether it was a Shadow, or a Spot upon ye Diske of Jupiter, but you never yet gratified this my desire'. See Auzout to Oldenburg, 8 May 1666 (O.S.), *Oldenburg Corresp.*, 3, pp. 110-116 (pp. 110 & 114). The translation above was made by Oldenburg himself.

<sup>15</sup> *Phil. Trans.*, 1 (1666), no. 8, pp. 143-145.

in the Disque of *Jupiter* ' was clearly different from a shadow of its satellite<sup>16</sup>. From its motion, he concluded 'not onely that Jupiter turns about upon his own Axis, but also the Time of such conversion; which he estimates to be, 9 hours and 56 minutes'<sup>17</sup>, almost the value now known. The article also mentioned the possibility of the rotation of other planets, Mars, Venus and Mercury, about their axes. It ended with a description of the rotation and libration of the moon.

In the history of astronomy, the discovery of the rotation of Jupiter has reasonably been ascribed to Cassini<sup>18</sup>. But the author emphasises that Hooke was very close to this discovery, which was at the leading edge of the observational astronomy of that time.

In the case of the rotation of Mars, Hooke was even more advanced. He observed Mars in February and March 1666, and reported to the meeting of the Royal Society on 28 March. Hooke said that he had observed the motion of several spots on the planet. He concluded that 'Mars as well as Jupiter, the earth, &c. moves about his own axis in about 24 hours'<sup>19</sup>. His report was published in *Philosophical Transactions* in the same year under the title 'Some New observations about the Planet Mars'<sup>20</sup>.

Further details of Hooke's observation were soon published in another article in the journal, 'The Particulars of those Observations of the Planet Mars, formerly intimated to have been made at London in the Months of February and March A. 1665/6'<sup>21</sup>. According to the description, Hooke had already observed some kind of spots in the face of Mars with a 12 foot-long telescope. He directed a longer telescope to the planet in its retrograde. With a 36-foot telescope, it appeared as big as the moon seen with the naked eye. However, because of the instability of the air, he could not obtain a good result at first. Satisfactory observations were made between 3 and 28 March. He drew the appearance of the changing face of Mars, and the illustration was attached to the article (Fig. 4-1, top). At the end of the main text, he estimated

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<sup>16</sup> *Ibid.*, p. 143. The observation in Holland and France of the shadow of Jupiter's satellite was discussed in an article in *Philosophical Transactions* just before that on Cassini's observation. When a satellite came between the Sun and Jupiter, an eclipse occurred and a small round black spot appeared on the body of the planet. See 'Some Observations concerning Jupiter. Of the sh[a]dow of one of his Satellites seen, by a Telescope passing over the Body of Jupiter' (*ibid.*).

<sup>17</sup> *Ibid.*, pp. 143-144.

<sup>18</sup> Bonelli & Helden (1981), p. 39. They listed Cassini's discoveries with Campani's telescopes, including the rotation of Jupiter, in p. 4 note 2.

<sup>19</sup> *Birch*, 2, pp. 74-75 (p. 74).

<sup>20</sup> *Phil. Trans.*, 1 (1666), no. 11, p. 198.

<sup>21</sup> *Ibid.*, no. 14, pp. 239-242. Fontana had already detected a spot on Mars in 1646, but he thought it could be an effect of diffraction. See Helden (1974a), p. 55, note 91.

the period of the rotation: 'from the Observations made *March* 21. 22. and 23. we may guess it to be once or twice in about 24. hours'<sup>22</sup>.

Both in his talk to the Royal Society and in the conclusion of his former article, Hooke had held that the period should be about 24 hours. That he now wrote that it could be 12 or 24 hours was an unfortunate retreat from the correct conclusion.

Following Hooke's second article on Mars's rotation was an article entitled 'Observations Made in Italy, confirming the former, and withall fixing the Period of the Revolution of Mars'<sup>23</sup>. It introduced an outline of 'some printed sheets of Paper'<sup>24</sup> on Cassini's observation. They were sent to the Royal Society by letter from the Venetian Ambassador in Paris.

According to the text, Cassini observed dark spots on Mars from 6 February (N.S.) with a 24-foot telescope made by Campani. Cassini found that the spots gradually moved from east to west, and that they returned eventually to their original positions. He concluded that the period of rotation was 24 hours 40 minutes. However, some astronomers, who made the same observations in March with Divini's telescopes rather than Campani's, claimed it should be about 13 hours<sup>25</sup>. Therefore Cassini continued his observations until 16 April.

'From all which Observations he Judges it to be evident, that the Period of this planets Revolution is not perform'd in the space of 12. hours 20 minutes, but in about 24 hours 40 minutes'<sup>26</sup>.

Again the papers were accompanied by illustrations of the observations, and they were published together with Hooke's (Fig. 4-1, lower right).

The discovery of the rotation of Mars has been ascribed to Cassini<sup>27</sup>. However, his priority is not so clear as in the case of Jupiter's rotation. Hooke had once reached the correct conclusion, shortly before Cassini came to the final verdict.

Another two articles on Hooke's telescopic observations were published in the same part (no. 14) of the first volume of *Philosophical Transactions*. They dealt with Hooke's observations of Jupiter and Saturn. Their accompanying illustrations were published with those referred to above (Fig. 4-1, lower left).

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<sup>22</sup> *Phil. Trans.*, 1 (1666), no. 14, p. 241.

<sup>23</sup> *Ibid.*, pp. 242-245.

<sup>24</sup> *Ibid.*, p. 242.

<sup>25</sup> The text clearly reflected the rivalry between Divini and Campani. Cassini was a leading user of Campani's telescopes.

<sup>26</sup> *Phil. Trans.*, 1 (1666), no. 14, p. 245.

The first of these articles, 'Some Observations Lately made at London concerning the Planet Jupiter', reported Hooke's observation of the planet on 26 June 1666<sup>28</sup>. He saw belts and a shadow of a satellite on the body of Jupiter. The latter article, 'A late Observation about Saturn made by the same', briefly described Hooke's observation of Saturn with its ring on 29 June 1666<sup>29</sup>.

Hooke used a 60-foot telescope for the observations of Jupiter and Saturn. The observations were reported to the Royal Society meetings on 20 June (probably a preliminary observation) and 11 July respectively for Jupiter and Saturn<sup>30</sup>. In the former case, Hooke clearly said that he used 'Mr. Boyle's sixty-foot-glass'.

Along with these observations, Hooke observed an eclipse of the Sun with his colleagues on 22 June 1666. He communicated the result to the Society meeting within a week, and it was included in an article 'Observations made in several places, Of the late Eclipse of the Sun' in *Philosophical Transactions*<sup>31</sup>.

The article compared observations in London, Madrid and Paris. That in London was made by casting the image of the sun onto paper through a 5-foot telescope. During the eclipse, Hooke and his colleagues saw the sun also 'through Mr Boyle's 60. foot-Telescope'. They suggested that there was 'some shining Atmosphere about the Body either of the Sun or Moon'<sup>32</sup>.

We have seen in this section that Hooke performed many detailed observations on the planets in the mid-1660s. The questions of their surface marks and of their rotation about their own axes which interested Hooke were typical subjects of the second stage of the Galilean Observation Paradigm. Hooke's astronomical research was completely in line with the popular astronomical topics of the time. Moreover, the standard of Hooke's observation was comparable with that of Cassini, one of the most eminent astronomers of the latter half of the seventeenth century.

#### Telescopes in *Micrographia*

While Hooke performed astronomical observations in the mid-1660s, he was preparing the publication of *Micrographia*. Naturally, his interest in astronomy was reflected in the book, although little analysis has been done on the astronomical aspects of *Micrographia*.

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<sup>27</sup> Bonelli & Helden (1981), p. 4, note 2.

<sup>28</sup> *Phil. Trans.*, 1, no. 14, pp. 245-246.

<sup>29</sup> *Ibid.*, pp. 246-247.

<sup>30</sup> *Birch*, 2, pp. 98 & 103.

<sup>31</sup> *Ibid.*, p. 100; *Phil. Trans.*, 1 (1666), no. 17, pp. 295-297.

<sup>32</sup> *Ibid.*, p. 295.

On the first page of its Preface, Hooke advocated three approaches for human beings 'to recover some degree of those former perfections': 'rectifying the operations of the *Sense*, the *Memory*, and *Reason*'<sup>33</sup>. For 'infirmities' of human senses he ascribed two causes: 'disproportion of the Object to the Organ' and 'error in the Perception'<sup>34</sup>. The first cause can be covered by the use of instruments, or artificial organs. For example:

'By the means of *Telescopes*, there is nothing so *far distant* but may be represented to our view; and by the help of *Microscopes*, there is nothing so *small*, as to escape our inquiry; hence there is a new visible World discovered to the understanding. By this means the Heavens are open'd and a vast number of new Stars, and new Motions, and new Productions appear in them, to which all the antient [*sic*] Astronomers were utterly Strangers'<sup>35</sup>.

After this, Hooke considers the advantages of mechanical philosophy over those of the Peripatetic, and also methods of improving both the memory and the reason of men. He then discusses mechanical inventions to improve the human senses of hearing, smell, taste and touch, and he describes his wheel-barometer here.

Then he considers recent developments in anatomy, and eventually in astronomical observations, the main subject of the present Chapter. He wrote:

'In *Celestial Observations* we have far exceeded all the Antients, even the *Chaldeans* and *Egyptians* themselves, whose *vast Plains*, *high Towers*, and *clear Air*, did not give them so great advantages over us, as we have over them by our *Glasses* [telescopes]. By the help of which, they have been very much outdone by the famous *Galileo*, *Hevelius*, *Zulichem* [Huygens]; and our own Countrymen, Mr. *Rook*, Doctor *Wren*, and the great Ornament of our Church and Nation, the *Lord Bishop of Exeter* [Seth Ward]'<sup>36</sup>.

All these names are already familiar as those of astronomers in the Galilean Observation Paradigm.

Next Hooke praises the aeromechanical discoveries represented by 'the *Noble Engine of the most Illustrious Mr. Boyle*', and he proceeds to promote experimental

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<sup>33</sup> *Micrographia*, sig. a1r.

<sup>34</sup> *Ibid.*, sig. a1v.

<sup>35</sup> *Ibid.*, sig. a2v.

<sup>36</sup> *Ibid.*, sig. d1v.

philosophy in general, writing:

'I do not only propose this kind of *Experimental Philosophy* as a matter of high *rapture* and *delight* of the mind, but as a *material* and *sensible Pleasure*'<sup>37</sup>.

For the sake of the argument in the Conclusion of this paper, the author restates the fact that astronomical observations were regarded by Hooke as a representative realm of experimental philosophy, on a par with anatomy, aeromechanical studies, and microscopical observations.

In the latter half of the Preface, Hooke discussed the improvement of lenses for optical instruments. He wrote:

'The Glasses I used were of our English make, but though very good of the kind, yet far short of what might be expected, could we once find a way of making Glasses Elliptical, or of some more true shape'<sup>38</sup>.

It is apparent that Hooke was not completely free of the false belief that aspheric lenses were the way to improve optical instruments. Nevertheless, he knew that:

'As for *Telescopes*, the only improvement they seem capable of, is the increasing of their length; for the Object being remote, there is no thought of giving it a greater light than it has; and therefore to augment the Aperture, the Glass must be ground of a very large sphere; for, by that means, the longer the Glass be, the bigger aperture will it bear, if the Glasses be of an equal goodness in their kind...and a sixty foot Glass will proportionably bear a greater Aperture than a thirty, and will as much excel it also as a six foot does a three foot, as I have experimentally observ'd in one of that length made by Mr. *Richard Reives* here at *London*, which will bear an Aperture above three inches over'<sup>39</sup>.

Even though Hooke mistakenly thought that the advantage of long focal lenses lay in their bigger apertures to collect more light, he certainly knew that the

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<sup>37</sup> *Ibid.*, sig. d2r.

<sup>38</sup> *Ibid.*, sig. d2v.

<sup>39</sup> *Ibid.*, sig. e1r-e1v.



only possible method for improving telescopes was to make them longer. And, of course, he also knew that longer focal length was a necessary condition for higher magnification power<sup>40</sup>.

In the Preface of *Micrographia*, Hooke proposed an Engine for the manufacture of lenses with longer focal lengths (Fig. 4-2)<sup>41</sup>. It was a lens-grinding lathe with two crossing mandrels EF and OP. Both rotated at high speed, and a lens Q, fastened to the bottom N of the upper mandrel, was ground by a bit or hollow cylinder K set upon the lower mandrel. Hooke claimed of the machine that 'I see no reason, but that a Glass of a thousand, nay of ten thousand foot long, may be as well made as one of ten', though 'it will be exceeding *difficult* to make and *manage* a Tube [of a telescope] above *an hundred foot long*'<sup>42</sup>.

#### *Micrographia* and Astronomical Observations

In Observ. LVIII, near the end of *Micrographia*, Hooke discussed a problem relevant to astronomical observations: inflection of light in air or transparent mediums<sup>43</sup>. He introduced the problem with the phenomenon that 'the Sun and Moon near the Horizon, are disfigur'd'<sup>44</sup>. Hooke also wrote that astronomers had observed that 'all the Luminous bodies appear above the Horizon, when they really are below it'<sup>45</sup>. He argued that:

'the true cause of all these *Phænomena* is from the *inflection*, or *multiply* *refraction* of those Rays of light within the body of the *Atmosphere*, and that it does not proceed from a *refraction* caus'd by any terminating *superficies* of the Air above, nor from any such exactly defin'd *superficies* within the body of the *Atmosphere*'<sup>46</sup>.

Refraction by dense air near the surface of the earth is greater than that by the thinner air higher in the atmosphere, and the difference causes inflection of the light reaching the earth. To elucidate the principle, Hooke first referred to his

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<sup>40</sup> *Ibid.*, sig. e1v. Magnification power is calculated as the ratio of the focal lengths of the object and ocular lenses.

<sup>41</sup> *Ibid.*, sig. e1v-e2r.

<sup>42</sup> *Ibid.*, sig. e2r & e2v.

<sup>43</sup> *Ibid.*, pp. 217ff.

<sup>44</sup> *Ibid.*, p. 217.

<sup>45</sup> *Ibid.*, p. 218.

<sup>46</sup> *Ibid.*, p. 219.

paradoxical experiment at the Royal Society<sup>47</sup>. This demonstrated that refraction in water is greater than in ice, which despite our instincts has the lower density. Then Hooke described an experiment with brine and fresh water to represent ‘*multiplicate refraction*’ caused by the gradual change of density in the atmosphere (Fig. 4-3, fig 1 therein)<sup>48</sup>. He prepared a box ADGE with the two long sides made of flat glass. He filled it half full with strong salt water, and the rest with fresh water. When sunlight was cast on the opaque side DHGC, it was inflected along the line PNOM toward the denser medium.

Hooke introduced here his own experiments and data that supported ‘Boyle’s Law’<sup>49</sup>. On the basis of the Law, Hooke calculated the gradual change of the density of an air column or cylinder extending from the surface of the earth to the sky<sup>50</sup>. He wrote that:

‘it being more likely, that there is a continual increase of rarity in the parts of the Air, the further they are removed from the surface of the Earth: It will hence necessarily follow, that...the ray of Light passing obliquely through the Air...will be continually, and infinitely inflected, or bended, from a straight, or direct motion’<sup>51</sup>.

He also argued that local and incidental changes of the density of the air near the surface of the earth could cause inflection. This was the reason ‘why the body of the Starrs appear to tremulate or twinkle’<sup>52</sup>.

Observ. LIX and LX, the last two parts of *Micrographia*, were dedicated to astronomical observations of the stars. The former was ‘Of multitudes of small Stars discoverable by the Telescope’<sup>53</sup>. When Galileo turned his telescope on the Pleiades, or ‘seven stars’ to the naked eye, he discovered that it consisted of thirty-six stars: an example of the multitude of stars<sup>54</sup>. When Hooke repeated the observation with a good 12-foot telescope, he could see seventy-eight stars. He drew them in an

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<sup>47</sup> *Ibid.*, p. 220. Hooke made the experiment on 11 February 1663 (*Birch*, 1, p. 193). Its details were printed later in *Philosophical Experiments*, pp. 24-26.

<sup>48</sup> *Micrographia*, p. 220.

<sup>49</sup> *Ibid.*, pp. 222ff.

<sup>50</sup> For a further study of Hooke’s analysis of the air column, see *Pugliese*, pp. 170ff.

<sup>51</sup> *Micrographia*, p. 228.

<sup>52</sup> *Ibid.*, p. 231.

<sup>53</sup> *Ibid.*, pp. 241-242. This was based upon Hooke’s report to the Royal Society meeting on 26 August 1663. See *Birch*, 1, p. 297.

<sup>54</sup> See, Galileo, *Sidereus nuncius*, English translation by Helden in 1989, pp. 61-62.

illustration in *Micrographia* (Fig. 4-4, right). With a 36-foot telescope, he discovered still more stars in the Pleiades. He had ‘produced a s[c]heme of pleiades’ to the Royal Society on 26 August 1663<sup>55</sup>, though it is not certain whether the schema was the one printed in *Micrographia*. Hooke also observed ‘the Sword of *Orion*, where the ingenious Monsieur *Hugens van Zulichem* has discovered only three little Stars in a cluster’. With a 36-foot telescope he discovered five stars there<sup>56</sup>. The discovery had been reported to the Royal Society meeting on 7 September 1664<sup>57</sup>.

*Micrographia* ended with ‘Observ. LX. Of the Moon’. Hooke carried out the observation of the surface of the moon in October 1664. He drew an illustration of the area Hevelius named ‘Mons Olympus’, and Riccioli ‘Hippurchus’ (Fig. 4-4, left)<sup>58</sup>. He wrote that he used ‘a thirty foot Glass’, though this seems to be a simple misprint for ‘thirty-six foot’<sup>59</sup>.

Here he considered how the ‘pits’ (craters) were shaped. He argued that the cause seemed ‘to me to have been the effects of some motions within the body of the Moon, *analogus [sic]* to our Earthquakes’. Terrestrial earthquakes were generated ‘from some subterraneous fires, or heat, great quantities of vapours’. Hooke supposed a similar mechanism for the moon, and wrote that ‘it is not improbable, but that there may be generated, within the body of the Moon, divers such kind of internal fires and heats, as may produce such Exhalations’<sup>60</sup>.

Hooke proceeded to discuss the earth-like surface of the moon, and went on to consider the similarities between the earth and the moon and their probable cause. He wrote that ‘there is in the Moon a principle of gravitation, such as in the Earth’<sup>61</sup>. He concluded:

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<sup>55</sup> *Birch*, 1, p. 297.

<sup>56</sup> *Micrographia*, p. 242. Huygens actually wrote in *Systema Saturnium (Oeuvres, 15, pp. 236-237)* that he saw twelve stars in the sword of Orion. The description in *Micrographia* could be Hooke’s false impression.

<sup>57</sup> *Birch*, 1, p. 465. Harwood (1989), p. 125 misprinted the date of the meeting.

<sup>58</sup> *Micrographia*, p. 242.

<sup>59</sup> Simpson (1989), p. 38, note 16. Indeed, in a letter to Boyle on 15 September 1664, just before the observation of the moon, Hooke wrote ‘I begin now to make use of a 36 feet glass, and hopes shortly to make some observations’, *Boyle Corresp.*, 2, pp. 324-326 (p. 326). In the same letter, Hooke acknowledged the generosity of the Royal Society in furnishing him ‘with tubes, according to my directions’ and ‘with an exact time-keeper’ (*ibid.*).

<sup>60</sup> *Micrographia*, pp. 243-244.

<sup>61</sup> *Ibid.*, p. 245. As another comparison between the earth and the moon, Hooke argued that ‘the Vale [of the moon] may have Vegetables *analogus* to our Grass, Shrubs, and Tree (*ibid.*, pp. 242-243). In Hooke’s time, there was a ‘controversie, whether the

‘it affords an excellent distinguishing Instance in the search after the cause of gravitation, or attraction, to hint, that it does not depend upon the diurnal or turbinated motion of the Earth, as some have somewhat inconsiderately supposed and affirmed it to do’<sup>62</sup>.

This was a clear criticism of the Cartesian vortex theory. Thus *Micrographia* ended, not with discussion of the microscopical world, but with consideration of the cause of gravitation.

Hooke’s astronomical descriptions in *Micrographia* bore the hallmarks of the Galilean Observation Paradigm. In the Preface, he discussed the improvement of telescopes with long focal lenses. Towards the end of the book, he presented his observations on the problems raised by Galileo: the multitude of stars, selenography, and the earth-like nature of the surface of the moon.

The improvement of telescopes and astronomical observation were of profound importance to Hooke, as he wrote in *Micrographia*:

‘that the meliorating of *Telescopes* will afford as great a variety of new Discoveries in the Heavens, as better *Microscopes* would among small terrestrial Bodies, and both would give us infinite cause, more and more to admire the omnipotence of the Creator’<sup>63</sup>.

#### Hooke and Long Telescopes

As we saw in the previous Chapter, the improvement of telescopes attracted the interest of the future members of the Royal Society before the founding of the institution, as the cases of Goddard and Neile illustrate. This interest was smoothly absorbed into the early Royal Society. For example, on 10 April 1661, the President of the Society:

‘appointed of a committee with Sir ROBERT MORAY, Sir PAUL NIELE, Dr. WALLIS[,] Dr. GODDARD, and Mr. WREN, to consider all sorts of tools and instruments for making glasses proper for perspectives, for the use of the society’<sup>64</sup>

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*Moon* have an atmosphere or not, like the *Earth*’ (*Gunther*, **8**, p. 145).

<sup>62</sup> *Micrographia*, p. 246.

<sup>63</sup> *Ibid.*, p. 242.

<sup>64</sup> *Birch*, **1**, p. 20.

The improvement of telescopes was achieved by the manufacture in England of better spherical lenses with long focal lengths, though the theoretical advantage of aspheric lenses was known.

Hooke himself used long telescopes, as Table 4 clearly shows. This is a list of Hooke's telescopes referred to in this paper. Hooke repeatedly mentioned telescopes of 12, 36 and 60 feet length.

Table 4: Telescopes Used by Hooke

Length	Where it appears	Observational Object	Remarks
5 feet	PT, 1, p.296	Eclipse (22 June 1666)	
12	MG, p.218	Twinkling of Stars	
	MG, p.241	Pleiades (26 Aug. 1663)	
	PT, 1, p. 3	Spot of Jupiter ( 9 May 1664 )	
	PT, 1, p.240	Spot of Mars (before Feb. 1666)	
36	MG, p.241	Pleiades	
	MG, p.242	Belt of Orion (7 Sept 1664)	Ap. above 3.5 inch
	BC, 2, p.326	Began to use 36ft ( 15 Sept 1664 )	A letter to Boyle
		Belt of Jupiter	
	MG, p.24	Moon (Oct 1664)	Misprinted
	PT, 1, p.239	Spot of Mars (3 Feb. 1666)	
60	MG, sig.e1v		Made by Reeve Ap. Above 3 inch
	BC, 2, p.326	Belt of Jupiter (before 15 Sept 1664)	Mention in a letter
	PT, 1, p.245	Belts & Satellites of Jupiter (26 June 1666)	Boyle's TS
	PT, 1, p.246	Saturn (29 June 1666)	
	PT, 1, p.295	Edge of the Sun in Eclipse (22 June 1666)	

(Abbreviations)

MG: *Micrographia* (London, 1665)    PT: *Philosophical Transactions*    BC=*Boyle Corresp.*

Ap.: Aperture    TS: Telescope

The 60-foot telescope was made by Reeve in 1664, and was bought by Boyle in 1666 (see Chapter 3, p. \*\*). It is very probable that Hooke used more than one 36-foot telescope. He wrote to Boyle in September 1664 that 'I begin now to make use of a 36

feet glass<sup>65</sup>, and the observations referred to in Table 4 were made from about that date. But it is known that there had been another 36-foot telescope at Gresham College, donated by Neile in 1658. It was hoisted on the obelisk in the courtyard, which was surmounted by Wren's metal model of Saturn<sup>66</sup>.

Hooke left a record and illustration of the 36-foot telescope in his manuscript now stored at the Royal Society (Fig. 4-5)<sup>67</sup>. Its tube 'was about 40 foot long and served to make use of an object glass of 36 foot'<sup>68</sup>. The pole of fir from which the telescope was suspended was 'about 50 foot long and 14 inches in Diameter at the lower end'<sup>69</sup>.

In the manuscript Hooke described Wren's and Rooke's observation with the telescope as follows:

'With this and w<sup>th</sup> another [telescope] of 28 foot in length a great number of astronomical observations were made both by Sr. Christopher Wren about the figure of Saturn and adjusting its theory which you will finde afterwards more at large explained by himself. And Describing the figure of the phases of the moon, from which he composed a Globe of the Body of the moon...The globe has ever since been kept in his Majestys closet of Rarities at white hall...Multitudes of other were made by Mr Laurence [*sic*] Rooke, both of these and the other planets for the Rectifying their theories by accurate & pertinent observations Most of which have been since his death lost to the great detriment of that since<sup>70</sup>.

The description suggests that the telescope was shared by natural philosophers, and it is reasonable to assume that Hooke was among them.

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<sup>65</sup> Hooke to Boyle, 15 September 1664, *Boyle Corresp.*, 2, pp. 324-326 (p. 326).

<sup>66</sup> *Birch*, 1, p. 48. The author has already mentioned the telescope on p. \*\*.

<sup>67</sup> Royal Society Classified Papers, vol. 20 (Hooke Papers), no. 61, ff. 129r-136v. It is not certain when the manuscript was written. While the event referred to took place around 1660, the manuscript calls Wren 'Sir Christopher' although he was not knighted until 1673. See *Pugliese*, pp. 570-571.

<sup>68</sup> Royal Society Classified Papers, vol. 20, no. 61, f. 129r.

<sup>69</sup> *Ibid.*

<sup>70</sup> *Ibid.*, ff. 130r-131r. It is known that Rooke observed eclipses of Jupiter's satellites before his death in 1662. On 18 February 1663, Oldenburg wrote to Hevelius that 'Various Fellows of the Royal Society have lately been asked to undertake the responsibility of continuing here the observations of the eclipses of the satellites of Jupiter begun by Rooke' (*Oldenburg Corresp.*, 2, pp. 25-30, especially pp.27-28). See also *Birch*, 1, p. 109; Sprat (1667), pp. 183-192.

## Christopher Cock: A New Optical Instrument-Maker

We saw in the last Chapter that Richard Reeve, an able optical instrument-maker, was at the peak of his activity when Hooke joined the Royal Society at the beginning of the 1660s. Reeve made a good 60-foot telescope with which Hooke performed several observations listed in Table 4, and he collaborated more generally with Hooke. But he lost his reputation suddenly when he killed his wife at the end of 1664, two years before his death.

Hooke then began to work with Christopher Cock (often Cocks or Cox, *d.* 1697), who was probably trained by Reeve. Cock completed his apprenticeship in 1666, just after Reeve's death. He decided to set up on his own, rather than continue to work under Reeve's son, also named Richard<sup>71</sup>.

Cock's reputation gradually rose at the end of the 1660s. For example in 1668, Newton, who was still unknown to the academic world, purchased objective lenses for himself and his university from Cock<sup>72</sup>. On 11 February 1669, the 'operator' of the Royal Society 'was ordered to speak to Mr. HOOKE, that the new great microscope of Mr. CHRISTOPHER COCK's making be brought to the society at the next meeting'<sup>73</sup>. The microscope was produced at the meeting, and the Society paid Cock eight pounds<sup>74</sup>. In August of the same year a telescope made by Cock was shipped to Hevelius, who praised it highly.

In 1664, Campani's telescope won over Divini's at a contest in Italy. Cassini made several discoveries with Campani's telescopes. It seems an interesting coincidence that Cock took over from Reeve at almost the same time.

English telescopes had achieved comparable performance to those made in Italy, and gained even more as Cock emerged. Hooke wrote that Reeve's 60-foot telescope of 1664 'was full as good, if not better' than those of Italy<sup>75</sup>. But in 1669, Oldenburg could write to Cassini as follows:

'A certain English craftsman compared a telescope of his own with another of Campani's, which was made available by His Highness the Duke of Tuscany, and so far as I can learn his had the edge over Campani's in the combined

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<sup>71</sup> Simpson (1985), pp. 360-364. Simpson wrote that Cock 'was the son of a Freeman of the City of London, a Cordwainer' (p. 360). In another paper, Simpson wrote 'I believe [Christopher] was John Cock's son' (Simpson, 1989), p. 47. Cf. Taylor (1954), pp. 248 & 283.

<sup>72</sup> Simpson (1989), pp. 51-52; Bennett (1983), item 117.

<sup>73</sup> *Birch*, **2**, p. 346.

<sup>74</sup> *Ibid.*, pp. 348-349.

<sup>75</sup> *Philosophical Experiments*, p. 390.

judgement of all those present, even the Prince himself'<sup>76</sup>.

It is highly probable that the craftsman mentioned here was Cock.

Hooke's close collaboration with Cock stands out in Hooke's diary which began in August 1672. Cock's name appears on many pages, showing the frequency of his interaction with Hooke<sup>77</sup>. This is explored in more detail later, but it is important to note that Hooke was able quickly to acquire a good optical instrument maker after the death of Reeve.

### Controversy with Auzout

We have seen that in *Micrographia* Hooke described an engine to grind long focus lenses. Though the astronomical aspects of *Micrographia* have largely escaped the attentions of historians of science, this was not so for the contemporary natural philosophers of Hooke's time. For example, Adrien Auzout (1622-1691) wrote a treatise criticising the engine and a controversy broke out between him and Hooke. Their exchanges were published in *Philosophical Transactions*.

Adrien Auzout was a French natural philosopher, born in Rouen<sup>78</sup>. He is known as one of those who contrived the experiment of the 'vacuum within a vacuum' (1647). He was a member of the Montmor Academy (Académie Montmor), a group of natural philosophers in Paris who gathered around Henri Louis Habert de Montmor (c.1600-1679) between 1657 and 1664. The Academy included Jacques Rohault (1620-1675), Gilles Personne Roberval (1602-1675), Ismael Boulliau (1605-1694), Huygens and Auzout. Auzout was interested in astronomy, and he tried a telescope longer than 300 feet. He joined negotiations to invite Cassini to Paris<sup>79</sup>.

Auzout's name appeared even in the first part of the first volume of *Philosophical Transactions*. A synopsis of a paper he sent to the Royal Society was introduced in an article 'The Motion of the late Comet prædicted'<sup>80</sup>, saying that Auzout was critical of the widespread opinion that 'the motions of *Comets* were so irregular, that they could not be reduced to any Laws'<sup>81</sup>. He argued that he had predicted the movement of the comet which had recently appeared.

The controversy between Auzout and Hooke was triggered by his *Lettre à*

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<sup>76</sup> Oldenburg to Cassini, 4 May 1669, *Oldenburg Corresp.*, **5**, pp. 510-511.

<sup>77</sup> *Diary 1672-1680*, Index (p. 483); Simpson (1989), p. 52.

<sup>78</sup> For the description below, see *DSB*, 'Auzout', **1**, pp. 341-342 & 'Montmor', **9**, pp. 497-499.

<sup>79</sup> See *DSB*, 'G. Cassini', **3**, pp. 100-104 (p. 102l).

<sup>80</sup> *Phil. Trans.*, **1** (1665), no. 1, pp. 3-8.



*monsieur l'Abbé Charles* (Paris, 1665b). It was again summarised in *Philosophical Transactions*, in this case in two successive articles. The first article was entitled 'Monsieur Auzout's Judgment touching the Apertures of Object-Glasses...', in which Auzout claimed that 'the *Apertures*, which *Optick-Glasses* can bear with distinctness, are in about a *subduplicate* proportion to their [focal] *Length*'<sup>82</sup>. He offered no proof of this claim. Instead, he relied on his experience, and presented 'A *TABLE* of the *Apertures of Object-Glasses*' which listed lenses he had probably seen or heard of, with their apertures.

The claim was an implicit criticism of Hooke, who in the Preface of *Micrographia* dared to write of his lens-grinding machine that 'I see no reason, but that a Glass of a thousand, nay of ten thousand foot long, may be as well made as one of ten'<sup>83</sup>. The more the lens magnifies the object, the darker its image becomes, so long focal length lenses must have large apertures. But Auzout did not believe that the apertures needed to collect the required light would be achieved, because 'great *Optick-Glasses* have almost never as great an *Aperture* as the small ones, in proportion to what they Magnifie, and that therefore they must be more dim'.

The second article contained much more direct criticism of Hooke's lens-grinding engine (Fig. 4-1). Indeed, it had the title 'Considerations of Monsieur Auzout upon Mr. Hook's New Instrument for Grinding of Optick-Glasses'<sup>84</sup>. Auzout pointed out that, first of all, it was not easy 'to procure *Great* pieces of Glass without *Veins*, and other faults, nor to get such, as are thick enough without *Blebbs*'<sup>85</sup>. Next, he raised practical objections to Hooke's lens-grinding engine: the difficulty of keeping a lens of slight curvature exactly at the centre of the cutting tool, the problem of maintaining the small angle between the two mandrels and keeping them in the same plane, detrition of the cutting edge, unequal pressure over the surface of the lens, and the thickness of the sand and putty layer. Lens grinding demands that 'the preciseness and delicateness is greater than can easily be imagined', so that 'his [Hooke's] Engine was published upon a meer Theory, without having made any Experiment'<sup>86</sup>. Hooke had claimed that lenses of a thousand and ten thousand feet focal length were possible. In that case, the angle between the two mandrels should be only 6 or 7 minutes, too small an inclination to sustain. Auzout wrote that a lens

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<sup>81</sup> *Ibid.*, p. 4.

<sup>82</sup> *Ibid.*, 1, no. 4, pp. 55-56 (p. 57).

<sup>83</sup> *Micrographia*, sig. e2r.

<sup>84</sup> *Phil. Trans.*, 1 (1665), no. 4, pp. 57-63.

<sup>85</sup> *Ibid.*, p. 57.

<sup>86</sup> *Ibid.*, pp. 57-58.

with 300-foot focal length was not easy to make, and if used to magnify the object one thousand times the image would be dark because of its small aperture. He showed some cynical generosity in writing that Hooke's engine could be an advertisement or promotion for a future version of the engine. So he proposed several things 'which he thinks may remedy some inconveniencies of Mr. *Hook* his *Turn*':

'The *first* is, to invert the Glass, and to put it under the *Ring*, that so not only the Glass may be placed more *Horizontally*, and not slide upon the *Cement*, but that *Sand* also, and the *Putty* may stay upon the Glass.

The *other* is, that there must be two *Poppetheads*, into which the *Mandril* must pass, where the *Ring* is to be fastened'<sup>87</sup>.

But still he emphasised that he thought it more important to make lenses of large aperture. He also exhorted the use of 'deep Eye-glasses; seeing it is not the length that gives esteem to *Telescopes*'. He went so far as to attack even Campani because his lenses did not have large apertures.

Hooke's counterargument followed Auzout's second article. It was titled 'Mr. Hook's Answer to Monsieur Auzout's Considerations, in a Letter to the Publisher of these Transactions'<sup>88</sup>. Hooke argued that his engine

'was not meer *Theory* I propounded, but somewhat of *History* and *matter of Fact* : For, I had made trials, as many as my leisure would permit, not without some good success; but not having time and opportunity enough to prosecute them, I thought it would not be unacceptable to such, as enjoyed both, to have a description of a way altogether *New*, and *Geometrically* true, and seemingly, not unpracticable'<sup>89</sup>.

It was true that Hooke's grinding engine had been discussed at Royal Society meetings in 1664, a year before their exchange<sup>90</sup>. He then attacked Auzout's assertions of the

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<sup>87</sup> *Ibid.*, p. 61.

<sup>88</sup> *Ibid.*, pp. 64-69.

<sup>89</sup> *Ibid.*, p. 64. Hooke argued that what he had written was certain and 'philosophical matter of Fact', because the publication of *Micrographia* was made under the licence of the Royal Society' (*ibid.*, p. 65). Cf. Shapin & Schaffer (1985), Chap. 2, 'Seeing and Believing: The Experimental Production of Pneumatic Facts'.

<sup>90</sup> *Birch*, 1, pp. 417, 477 & 483. Hooke continued his study of the engine at least until 1669 (*ibid.*, 2, pp. 56 & 385). When Wren proposed 'his engine for grinding hyperbolic glasses' at the meeting of the Society on 10 June 1669, Hooke also began

difficulty of obtaining good glass and of keeping the centre of lenses while grinding:

'I think *that* not now so difficult here in *England*, where I believe is made as good, if not much better Glass for *Optical Experiments*, than ever I saw come from *Venice*. Next though it were better that the thickest part of a long *Object-Glass* were exactly in the middle, yet I can assure Monsieur *Auzout*, that it may be a very good one, when it is an Inch or two out of it. And I have a good one by me at present of 36. foot, that bear an *Aperture...*of 3 1/2 Inches over, and yet thickest part of the Glass is a great way out of the middle'<sup>91</sup>.

Hooke emphasised that it was rather difficult to grind long focal lenses by hand:

'I know very well, that in making a 60. foot Glass by the strength of the hand, in the common way, not one of ten that are wrought, will happen to be good, as I have been assured by Mr. *Reeves*; who, I am apt to think, was the first that made any good of that length'<sup>92</sup>.

The problem is:

'that the Tool does only touch the Glass in a *Mathematical Circle*; that is true, perhaps, at first, but before the Glass is wrought down to its true *Figure*, the *Edge* of the *Tool* will be worn or grownd away, so that a Ring of an inch broad may be made to touch the *Spherical Surface* of the Glass'<sup>93</sup>.

Hooke argued that 'The giving the *Inclination* to the *Mandrils*, is not at all difficult...Nor it is so very difficult to lay them both in the same Plain. And keep them *steddy*, when once fix'd, is most easy'<sup>94</sup>. He stressed that even a 1000-foot lens was possible. Hooke rejected Auzout's 'remedy' for his machine:

'And as to that of 2 *Poppet-heads*, I do not well understand it, if differing from

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his study on an engine for elliptical and hyperbolic lenses. At the beginning of the next year Hooke 'declared his opinion, that Dr. WREN's engine for grinding hyperbolic glasses would not be practicable' and argued that his engine for elliptical and hyperbolic lenses was feasible (*ibid.*, pp. 379, 388, 399 & 416).

<sup>91</sup> *Phil. Trans.*, 1 (1665), no. 4, pp. 65-66.

<sup>92</sup> *Ibid.*, p. 66.

<sup>93</sup> *Ibid.*, pp. 66-67.

<sup>94</sup> *Ibid.*, p. 67.

mine; and the keeping of the Tool upon the Glass with a spring or weight, must spoyle the whole; since if either of the *Mandrils* will easily yield backwards, the *regularity of all* will be spoiled'<sup>95</sup>.

He ended his counterargument with criticism of Auzout's preoccupation with large apertures:

'His *Theory of Apertures*, though he seems to think it very authentick, yet to me it seems not so cleer. For the same Glass will endure greater or lesser *Apertures*, according to the lesser or greater Light of the Object'<sup>96</sup>.

Auzout sent two letters to Oldenburg arguing back against Hooke. Between the two, Oldenburg sent a summary of Hooke's objections<sup>97</sup>. These exchanges basically repeated the arguments above, though Auzout accepted Hooke's claim that good glass was now available in England<sup>98</sup>. Some new points were whether Auzout or Reeve had been the first to achieve a 60-foot telescope<sup>99</sup>, and Auzout's request to reveal the secret of a method Hooke had devised to increase the focal length of lenses without lengthening the telescope tube<sup>100</sup>.

There was also an exchange on the subject of observing living creatures on other celestial bodies, which is relevant to the next Chapter of this paper. Both Auzout and Hooke had considered whether it was possible to 'see *Plants* or *Animals* in the *Moon*'<sup>101</sup> in their articles in *Philosophical Transactions* referred to above. According to Auzout, it was what '*Des Cartes* gave hope, and Mr *Hook* despairs not of'<sup>102</sup>. Auzout was very doubtful, and wrote in his letter as follows:

'But until we have terrestrial animals more than eighteen feet in diameter, I

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<sup>95</sup> *Ibid.*, p. 68.

<sup>96</sup> *Ibid.*, p. 69.

<sup>97</sup> Auzout to Oldenburg, 22 June 1665 (O.S.), *Oldenburg Corresp.*, **2**, pp. 410-427; Oldenburg to Auzout, 23 July 1665, *ibid.*, pp. 439-443; Auzout to Oldenburg, 12 August 1665 (O.S.), *ibid.*, pp. 461-475. Hooke intended to write further counterargument, but there appears to be no record of it. See Hooke to Oldenburg, February 1666, *ibid.*, **3**, pp. 43-44 (p. 43).

<sup>98</sup> *Ibid.*, **2**, pp. 412 & 420.

<sup>99</sup> *Ibid.*, pp. 413 & 421, 440 & 442. For the method of extending the focal length, Hooke had announced in 'Mr. Hook's Answer' above that he would soon disclose it (*Phil. Trans.*, 1, 1665, no. 4. p. 67).

<sup>100</sup> *Oldenburg Corresp.*, **2**, pp. 467 & 473. Hooke's method is explained below.

<sup>101</sup> *Phil. Trans.*, **1** (1665), no. 4, p.68.

<sup>102</sup> *Ibid.*, p. 60.

must beg Mr. Hooke to take the trouble to try whether he can distinguish animals one foot tall at a distance of 60,000 feet or of 20,000 yards and whether he thinks after this that he should hope to see living creatures even on the moon...and finally in a word to try whether he can see anything on the Earth subtended by an angle of 35 or 36 seconds'<sup>103</sup>.

Oldenburg suggested to Auzout the background of Hooke's claim:

'As for what you say about the smallness of the visible angle, I know that some time ago Mr. Hooke made it plain, while explaining some mathematical instruments, that very few persons can distinguish an angle less than one minute, although some by practice can train themselves to see a lesser one'<sup>104</sup>.

We shall return to the point of the resolving power of the human eye when we consider the controversy between Hooke and Hevelius on precision measurement instruments.

Extracts from Auzout's second letter were published in *Philosophical Transactions* in two successive articles. They were titled 'Monsieur Auzout's Speculations of the Changes, likely to be discovered in the Earth and Moon, by their respective Inhabitants' and 'The Instance of the same Person to Mr. Hook, for communicating his Contrivance of making, with a Glass of a Sphere of 20 or 40 foot diameter, a Telescope drawing several hundred foot...'<sup>105</sup>.

The whole exchange of four letters after 'Mr. Hook's Answer' was published by Auzout in a French tract entitled *Réponse de Monsieur Hook aux considerations de M. Auzout* (Paris, 1665a)<sup>106</sup>.

### Johannes Hevelius

Auzout was not the only natural philosopher who was interested in Hooke's telescopic studies. Johannes Hevelius, a leading astronomer of the seventeenth

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<sup>103</sup> *Oldenburg Corresp.*, **2**, pp. 417 & 424.

<sup>104</sup> *Ibid.*, pp. 441 & 443.

<sup>105</sup> *Phil. Trans.*, **1** (1665), no. 7, pp. 120-123 & 123-125.

<sup>106</sup> The copy stored at the British Library (shelf mark, c.125 d.17) is bound with an English translation of Auzout's letter of 12 August 1665. Though the editor wrote 'The translation is Oldenburg's, evidently made for Hooke's use' (*Oldenburg Corresp.*, **2**, p. 474), it could also be for the preparation of two successive articles in *Philosophical Transactions*. Later, Auzout had to apologise for publishing the letter from England without the permission of the author. See, Auzout to Oldenburg, 23 September 1665 (O. S.), *Oldenburg Corresp.*, **2**, pp. 515-521 (pp. 515 & 518).

century, also paid attention to Hooke's research.

Hevelius was born at Danzig in 1611 as one of at least ten children of a very prosperous brewer<sup>107</sup>. His family name was written in many ways: Hevel, Hövel, Höfelcke, Hewelcke, Höwelcke, Höfelius, Hövelius, Höwellus. He himself introduced the Latin form Hevelius. His early education was mainly at a Gymnasium at Danzig, where he was given private lessons on astronomy and astronomical instruments by a teacher of mathematics, Peter Krüger. In 1630 Hevelius left for Leiden to study jurisprudence. On his journey, he made observations of a solar eclipse. From Holland, he went to London in 1631, and visited Paris between 1632 and 1634. Hevelius met Gassendi and Boulliau in Paris, and Athanasius Kircher (1601/2-1680) at Avignon. After his return to Danzig he was busy with official life, being elected honorary magistrate in 1641 and a decade later to the city council (*Rathsherr*). In addition, he had to run the family brewery after the death of his father in 1649. But these constraints rather intensified his passion for astronomy. In 1644 he built a small tower onto his house, and later he added a platform for observation. It was the best observatory in Europe until those of Paris and Greenwich were established, and the King of Poland visited it in 1660 (Fig. 4-6). Hevelius lost his first wife in 1662, and the next year he married Catherina Elisabetha Koopman who helped him greatly with his observations. After his death, she published his compendium of observations, *Prodromus astronomiae* (Danzig, 1690), a catalogue of more than 1500 stars.

Hevelius's first book was *Selenographia*, published in 1647. As we saw in Chapter 2, it contained four years of his observations. Though he named almost 300 lunar formations, his nomenclature system was rewritten by Riccioli. Hevelius's second great work was the observation of a comet in 1652, published more than a decade later in *Cometographia* (Danzig, 1668).

Hevelius's reputation had been established by the 1650s. For example, Huygens mentioned Hevelius's *Dissertatio de nativa Saturni facie* (Danzig, 1656) in his *Systema Saturnium* in 1659<sup>108</sup>. Hevelius's correspondence with future fellows of the Royal Society can be traced back earlier, to 1647<sup>109</sup>. Though it was not until 1664 that he was elected a fellow of the Royal Society, once Moray proposed him on 30 March Hevelius was elected immediately 'because a stranger of eminent worth'<sup>110</sup>.

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<sup>107</sup> The description in this section follows MacPike (1937), Chap. 1 and *DSB*, 'Hevelius', **6**, pp. 360-364.

<sup>108</sup> *Oeuvres*, **15**, pp. 284ff.

<sup>109</sup> Turnbull (1952-3), pp. 111.

<sup>110</sup> *Birch*, **1**, p. 404.

## Hevelius and Long Telescopes

Hevelius was interested in the improvement of telescopes. Of course, he knew of the theoretical possibility of avoiding spherical aberration with aspheric lenses<sup>111</sup>. But he pursued the practical improvement of telescopes by making them longer, as other natural philosophers did. While the longest telescope recorded in his first work *Selenographia* was only 12 feet long<sup>112</sup>, he used longer and longer telescopes as time went on.

In 1666, Hevelius was impressed by Hooke's observations of Jupiter and Mars with long telescopes. He wanted a telescope by Reeve, and wrote in October 1666 to Oldenburg that 'If I could get a good one of those of 60. foot you mention, at a reasonable rate, you would oblige me in sending me one' <sup>113</sup>. In the same letter Hevelius asked questions about the structure of the telescopes, how they were made, and the way they were mounted<sup>114</sup>.

Hooke answered the enquiry via Oldenburg, and described the details of the telescope with an illustration (Fig. 4-7). He wrote:

'The longest glasse I have severall times made use of is a sphaericall lens convex on both sides of a sphaere whose radius is 60 foot and the focus or length of the glasse is neer about the same length...The method by which that I have was made Was by the ordinary way in a very large Dish and wrought upon the tool by the hand wthout any kind of engine...The tube I make use of is about 66 or 68 foot in length & consists only of two long square boxes or tubes made of very thin & light slit Deale here and there bound together wth very thin plates of iron...'<sup>115</sup>

The whole tube weighed about 200 lb and was hoisted on a mast as Fig. 4-7 shows. When we compare the figure with the frontispiece of Sprat's *History* (Fig. 2-5b), it is

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<sup>111</sup> Hevelius to Oldenburg, 22 May 1665 (O. S.), *Oldenburg Corresp.*, **2**, pp. 329-399 (pp. 393 & 396). Here Hevelius claimed that ten years previously he had invented a method to grind 'lenses of any conic section'. But there is no evidence that he could make aspheric lenses (Simpson, 1981, p. 24).

<sup>112</sup> King (1955), p. 51; Bendini (1967), p. 398. The telescope magnified about fifty times.

<sup>113</sup> Hevelius to Oldenburg, 19 October 1667, *Oldenburg Corresp.*, **3**, pp. 248-259 (pp. 250 & 256-257).

<sup>114</sup> *Ibid.*

<sup>115</sup> Hooke to Oldenburg, c. 20 February 1667, *ibid.*, pp. 347-349 (p. 348). Oldenburg inserted Hooke's explanation in a letter in Latin sent to Hevelius on 27 February (*ibid.*, pp. 350-355).

clear the frontispiece incorporated Hooke's illustration of the telescope for Hevelius.

In October 1667, Hevelius thanked Oldenburg for Hooke's answer, and asked him to procure 'a very excellent telescope sixty or more feet long'<sup>116</sup>. Hevelius did not have enough money at the time, so he decided to send several copies of his *Cometographia* &c. to Oldenburg expecting him sell them for the payment<sup>117</sup>. Hevelius wrote to Oldenburg that 'I ask you in choosing the telescope to make use of the knowledge and advice of the famous Mr. Hooke, who is so very experienced in that art'<sup>118</sup>. In August 1669, the telescope was finally sent to Hevelius, together with a Hooke-type microscope he had ordered later<sup>119</sup>. They were made by Cock<sup>120</sup>. Oldenburg and Hooke did not want to order them from the younger Reeve, 'whose labours we have been reluctant to employ for more than one reason'<sup>121</sup>. The telescope sent to Hevelius was 50 feet long, shorter than it should have been<sup>122</sup>.

In June 1670, Hevelius thanked Oldenburg and Hooke for sending him 'along with a splendid microscope, the lenses for a fifty-foot telescope which were the notable provision of Mr. Hooke'<sup>123</sup>. He continued:

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<sup>116</sup> Hevelius to Oldenburg, 11 October 1667 (O. S.), *ibid.*, pp. 517-520 (pp. 517 & 519).

<sup>117</sup> *Ibid.*, pp 517-519. Hevelius sent several copies of *Cometographia* and other writings to Oldenburg in about June 1668. See Hevelius to Oldenburg, 3 June 1668 (O. S.), *ibid.*, 4, pp. 443-449 (pp. 444 & 447).

<sup>118</sup> *Ibid.*

<sup>119</sup> Oldenburg to Hevelius, 2, August 1669, *ibid.*, 6, pp. 165-171 (pp. 165 & 168-169). At the beginning of the letter, Oldenburg apologised for the delay caused by the technical problems of grinding a good lens. For the order for the microscope, see Hevelius to Oldenburg, 11 March 1669 (O. S), *ibid.*, 5, pp. 440-443 (pp. 441-443).

<sup>120</sup> Cock's Receipt', *ibid.*, p.172. The total price was 40 pounds. Cock expected an additional payment of ten pounds (*ibid.*, pp. 166 & 169), but this was not agreed (*ibid.*, 7, pp. 45 & 48).

<sup>121</sup> Oldenburg to Hevelius, 28 October 1668, *ibid.*, 5, pp. 112-117 (pp. 114 & 116). Reeve wrote directly to Hevelius on 24 July 1668 hoping to obtain his order for the telescope, but in vain (*ibid.*, 4, p. pp. 581-582).

<sup>122</sup> Oldenburg to Hevelius, 2 August 1669, *ibid.*, 6, pp. 165-171 (pp. 167 & 170). Oldenburg wrote that 'We do not send you a telescope tube appropriate to the focal length of the objective both because our makers demanded a very unreasonable price for making it (namely £15 sterling) and we thought you could buy such a tube at a much less price from your craftsmen' (*ibid.*).

<sup>123</sup> Hevelius to Oldenburg, 25 June 1670, *ibid.*, 7, pp. 44-50 (pp. 44 & 47). In April 1666, Oldenburg made enquiry to Hevelius about the rumour that one Burattini, Master of the Mint to the King of Poland, was polishing lenses for a telescope of 120 feet. Hevelius answered that 'Mr. Burattini is still busy finishing his long telescope; certainly he has not yet completed that task...I have been friendly with him for a long time; he is indeed a remarkably skilled mechanic and an Italian by birth'. See Oldenburg to Hevelius, 30 March, 1666, *ibid.*, 3, pp. 72-79 (pp. 73 & 76); Hevelius to Oldenburg, 23 June 1666 (O. S.), *ibid.*, pp. 167-172 (pp. 169-170 & 172).



'So far as I can judge of the microscope it satisfies my expectations very well; I am reluctant to seem doubtful concerning the telescope too, and as soon as I can direct it to a star I shall be able to tell you something about it more certainly. Especially as I shall direct the similar lenses of the illustrious Mr. Burattini (for a telescope of 62 feet which is to be constructed) to the same object; he is sending them to me as a gift at the first opportunity. I already possess some of his lenses of sixteen, twenty, and thirty feet, which I have found to be absolutely outstanding. Next autumn, God willing, I shall disclose to you the results furnished by each telescope'<sup>124</sup>.

The same summer, Hevelius informed Boulliau that he greatly commended the telescope lenses he had received from England. He asserted them 'to be the best hee ever yet used'<sup>125</sup>.

In *Machina coelestis, pars prior* (Danzig, 1673)<sup>126</sup>, published three years later, Hevelius mentioned these lenses. Chapter 20 of the book was devoted to the construction and setting-up of a 60-foot telescope<sup>127</sup>. Hevelius referred to good lenses of 50, 60 and 70 feet<sup>128</sup>, among which the 50-foot was probably that sent from England and the 60- and 70-foot from Burattini<sup>129</sup>. He clearly stated that the tube for the 60-foot lens was made 'according as the English'<sup>130</sup>. Indeed, Hevelius joined two 30 feet long square boxes of fir, and suspended them from the mast at the joint with a rope as Hooke had suggested (Fig. 4-8). The rope could be winched from the bottom of the mast. When we compare this illustration with the one Hooke sent to Hevelius (Fig. 4-7), their similarity is clear.

In Chapter 21 of the book, Hevelius also discussed his great telescope of 150 feet. At first, he had planned to construct it by connecting four square boxes of 40 feet length, each made of four planks. But the total of sixteen wooden planks would have been very heavy. Instead he made each section with only two planks, joining them in

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<sup>124</sup> *Ibid.*, 7, pp. 44 & 47-48.

<sup>125</sup> Vernon to Oldenburg, 25 August 1670, *ibid.*, 7, pp. 139-142 (p. 140). Boulliau communicated the commendation to Vernon, then in Paris.

<sup>126</sup> Hevelius began to write the work as early as 1663. See Hevelius to Oldenburg, 25 December 1663 (O. S.), *ibid.*, 2, pp. 136-140 (pp. 137 & 139).

<sup>127</sup> Hevelius (1673), pp. 391ff.

<sup>128</sup> *Ibid.*, p. 392.

<sup>129</sup> Hevelius wrote to Oldenburg that 'The very illustrious Mr. Burattini recently sent me as a gift a variety of lenses for very long telescopes, among which I found one of seventy feet eight inches in diameter'. See Hevelius to Oldenburg, 17 August 1670 (O. S.), *Oldenburg Corresp.*, 7, pp. 123-130 (pp. 126 & 129).

<sup>130</sup> Hevelius (1673), p. 392.

an inverted T-shape and supporting the upright plank with numerous wooden brackets on both sides. The brackets on one side were square plates having large holes at the centre<sup>131</sup>. The four sections were then joined together lengthwise as Fig. 4-9 shows. Lenses were fitted at each end of the telescope, and light from the object lens passed through the holes in the brackets to the eyeglass. The object lens was made by Burattini<sup>132</sup>. The telescope was a form of 'aerial telescope', in which the light path from the object lens to the eyeglass was not covered by a tube. Hevelius maintained that the telescope worked as if it was covered in on every side<sup>133</sup>. It had the problem that it was too liable to lateral curvature, and to correct this he attached a well-stretched cord along the plane of the horizontal planks<sup>134</sup>. Hevelius erected a pole of about 90 feet in a suburb of the city of Danzig, and suspended the telescope in essentially the same way as had been used for the 60-foot telescope<sup>135</sup>.

#### Hooke's Methods for Contracting Telescopes

Very long telescopes like Hevelius's were not popular in England<sup>136</sup>, but in continental Europe we can find several instances of very long telescopes. For example, Cassini was using 100- and 136-foot telescopes when he discovered two satellites of Jupiter in 1684. Auzout claimed that he succeeded in grinding lenses of 300 and 600 feet focal length<sup>137</sup>. But 'very few, if any, astronomical discoveries were made with telescopes which, by contemporary standards, were very long'<sup>138</sup>, and even moderately long telescopes were not easy to handle.

Hooke proposed two ways to shorten telescopes of long focal length. In the controversy with Auzout in 1665, he alluded to one of these methods<sup>139</sup>. He soon published an article about it in *Philosophical Transactions*, entitled 'A Method, by which a Glass of a small Plano-convex Sphere may be made to refract the Rayes of light to a Focus of a far greater distance, than is usual'<sup>140</sup>. The device used two glasses: a

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<sup>131</sup> *Ibid.*, pp. 405-406.

<sup>132</sup> *Ibid.*, p. 404. The lens is probably Burattini's 140-foot lens which Hevelius mentioned in his letter in 1672, a year before the publication of *Machina coelestis, pars prior*. See Hevelius to Oldenburg, 31 May 1672 (O. S.), *Oldenburg Corresp.*, **9**, pp. 83-86 (pp. 83 & 85).

<sup>133</sup> Hevelius (1673), p. 417.

<sup>134</sup> *Ibid.*, p. 413.

<sup>135</sup> *Ibid.*, pp. 411 & 415.

<sup>136</sup> King (1955), p. 62.

<sup>137</sup> Bendini (1967), p. 399.

<sup>138</sup> Helden (1974a), p. 47.

<sup>139</sup> *Phil. Trans.*, **1** (1665), no. 4, p. 67. He also mentioned the invention at the meeting of the Royal Society on 29 May 1665, *Birch*, **2**, p. 52.

<sup>140</sup> *Phil. Trans.*, **1** (1666), no. 12, pp. 202-203.

flat glass and a plano-convex lens. They were sealed with cement to each end of a brass tube. The space between the two glasses was filled with water, oil of turpentine, spirit of wine, or other clear fluid. Then 'according to the differing refraction of the interposed Liquors, so shall the *Focus* of this compound Glass be longer or shorter'<sup>141</sup>. In *Micrographia* the same principle was adapted to the microscope, in this case filling the intervening space with clear water<sup>142</sup>.

Another method was to fold the light path of the refracting telescope by means of reflection from internal mirrors (Fig. 4-10). The light entering through the object lens was reflected several times before it reached the eyeglass at the opposite end.

Hooke first mentioned this method at a Society meeting on 28 February 1667<sup>143</sup>. On 21 March, 'Mr. HOOKE produced again his new kind of contracted telescope of two foot long, performing the part of a six foot glass by the means of two reflexions'<sup>144</sup>. At the meeting of 6 June, 'He intimated, that this sort of telescopes would serve for a very convenient helioscope'<sup>145</sup>. If the reflecting power of the mirror was weakened, sunlight could be attenuated to the level of brightness suitable for the observer.

Hooke read a discourse on the idea at the meeting on 28 January 1675<sup>146</sup>. In the following year, it was published in a treatise entitled '*A Description of Helioscopes*' (hereinafter *Helioscope*)<sup>147</sup>. Hooke wrote that his helioscope:

'By often reflecting the Rayes from the surfaces of *black Glasses*, which are grownd very exactly, flat, and very well polished, so to diminish the Radiations, that at length they become as weak and faint as those of the Moon in the twilight, so that one may with ease, and very much pleasure, view, examine and describe the phase of the Sun, and the *maculæ* and *faculæ* thereof'<sup>148</sup>.

Hooke stressed the advantages of this method of viewing the sun compared

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<sup>141</sup> *Ibid.*, p. 203.

<sup>142</sup> *Micrographia*, sig. f2r.

<sup>143</sup> *Birch*, 2, p. 152. Waller mistakenly wrote 'Feb. the 28th. He [Hooke] first produc'd his *Reflecting Telescope*' (*Posthumous*, xiii).\*\*

<sup>144</sup> *Birch*, 2, p. 158.

<sup>145</sup> *Ibid.*, p. 180.

<sup>146</sup> *Ibid.*, 3, p. 179.

<sup>147</sup> *Gunther*, 8, pp. 121-152.

<sup>148</sup> *Ibid.*, p. 122.

with others. He could not endorse observing the sun through coloured glasses 'because they tinge the Rayes into the same colour' and the colour 'superinduces a haziness and dimness upon the Figure'<sup>149</sup>. The method of projection of the telescopic image of the sun onto a screen had the defect of reducing contrast in the image<sup>150</sup>. Worst of all was to contract the aperture of the lens, because 'by reason of a certain property of Light not taken notice of yet by Optick Writers, the edges of Objects seeming ragged'<sup>151</sup>.

Hooke's hope expressed in the following passage from the treatise shows the origin of his Helioscope. He wrote that the contrivance:

'would be of exceeding great use in all manner of *Perspectives* and *Telescopes*, if we could find a good material that would make the Reflections very strong and full...by it, 'twould be possible to contract the Tubes for long Glasses into very short lengths, and so make them of easie use and manage'<sup>152</sup>.

He noted that the best reflection was achieved by quicksilvered glass.

Hooke's *Helioscope* has not attracted much attention from historians of science, but its historical meaning and value is revealed when we see it in the context of Hooke's telescopic studies. Helioscopes were conceived as a by-product of the improvement of long telescopes. Hooke's selenoscope, which appeared in his diary on 1 January 1676, also had the same origin<sup>153</sup>.

It should be noted that in the same treatise Hooke also described an instrument for precision observations, his observation of the eclipse of the moon on 1 January 1675, and a universal joint which could be applied to drive telescopes &c. The treatise originated in Hooke's telescopic observations.

#### The Galilean Observation Paradigm and Hooke

This Chapter has shown that Hooke's telescopic research was made in the tradition of observational astronomy, especially within the second stage of the Galilean Observation Paradigm. Hooke performed detailed observations of the moon, the sun and the planets. Selenography, the theory of Saturn, and surface markings on the

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<sup>149</sup> *Ibid.*, p. 123.

<sup>150</sup> *Ibid.*, p. 124.

<sup>151</sup> *Ibid.* Here Hooke referred to the phenomenon of diffraction he had discussed 'in my *Animadversions*, pag. 35'.

<sup>152</sup> *Ibid.*, pp. 124-125.

<sup>153</sup> Simpson (1989), p. 56; *Diary 1672-80*, p. 206.

planets and their satellites were all within Hooke's scope. Hooke used long telescopes for his observations. This was the natural stream of telescopic research in England which Goddard, Neile, Wren and others also followed.

Previous historical studies on Hooke have been focused only on his research in microscopy, mechanics, optics, geology and instrumentation. The astronomical aspect of Hooke's research has been almost entirely forgotten. However, matters were different in his own time. His telescopic observations attracted considerable interest at the Royal Society, as the frontispiece of Sprat's *History* included Hooke's illustration of long telescope. Natural philosophers overseas also studied Hooke's observations throughout the 1660s. Hevelius was interested in Hooke's observations of Jupiter and Mars. He went so far as to order a long telescope to Hooke's design. Auzout was also interested in Hooke's observations of Jupiter, and asked Oldenburg to write about the details of them in 1665<sup>154</sup>. Hooke's observation was no less important in the 1670s. In 1673, Oldenburg wrote to Hevelius that he had not had an opportunity to see the new satellites of Saturn discovered by Cassini 'because of Mr. Hooke's ill-health'<sup>155</sup>.

Hooke's telescopic research was a product of the Galilean Observation Paradigm in England. But he did not simply follow the tradition. He contributed to the formation of a new phase of observational astronomy: the birth of precision astronomical observation utilising specialised instruments for the purpose. We see in the next Chapter that Hooke developed the instruments himself, advocated their use, and performed his own astronomical observations with them.

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<sup>154</sup> Auzout to Oldenburg, 22 June 1665 (O. S.), *Oldenburg Corresp.*, **2**, pp. 410-427 (pp. 418 & 425).

<sup>155</sup> Oldenburg to Hevelius, 5, September 1673, *ibid.*, **10**, pp. 181-184 (pp. 182 & 184).