JHA, xxiii (1992)

JAMES GREGORY AND THE REFLECTING TELESCOPE

A. D. C. SIMPSON,
National Museums of Scotland and University of Edinburgh

The concept of using reflecting optics for constructing a telescope had clearly been appreciated in early seventeenth century continental Europe, and there are grounds for believing that experimental reflecting instruments may have been constructed.[1] These early practical attempts however, although of historical interest in terms of priority for the invention, appear to have passed unnoticed, and the stimulus they might otherwise have provided for further development was lost.

By contrast, the realization of a practical reflecting telescope in Britain in the 1660s may be seen as the first link in a developmental chain of influence that ultimately led to the instrument's firm establishment and its dominant role in observational astronomy in the eighteenth century. Thus in the context of the practical development of the reflecting telescope, and of the international reputation acquired by the London workshops, the early British instruments have a significance which is more certain than that of their Continental precursors.

The reflecting telescope reached a high standard of excellence in the hands of the Scots optical worker James Short (1710–68), who settled in London in 1738 and made a comfortable fortune as an "optician solely for reflecting telescopes".[2] It is perhaps appropriate that his skill should have made the instrument such a conspicuous success, since it had been a fellow countryman, the mathematician James Gregory (1638–75), who had described and constructed the first reflecting telescope in Britain in the preceding century.

James Gregory (Figure 1) was born the youngest son of an Aberdeenshire clergyman, and on his mother's side there was a strong scholarly tradition.[3] Gregory's family and their descendants displayed remarkable academic ability, and over six generations they occupied more than twenty chairs at the Scottish universities and at Oxford. James Gregory himself came to hold the chair of mathematics first at St Andrews and then at Edinburgh, and he was one of the most important mathematicians to work on the development of fluxional calculus. Four years Newton's senior, Gregory has been described by D. T. Whiteside as "the only one of Newton's British contemporaries who could match him in mathematical breadth and profundity".[4] However, his comparative isolation from his mathematical contemporaries, his reluctance to publish his work, and finally his early death, all conspired to restrict his contribution to mathematics.

Gregory's mathematical inclinations were recognised by his elder brother

0021–8286/92/2302–0077 $2.50

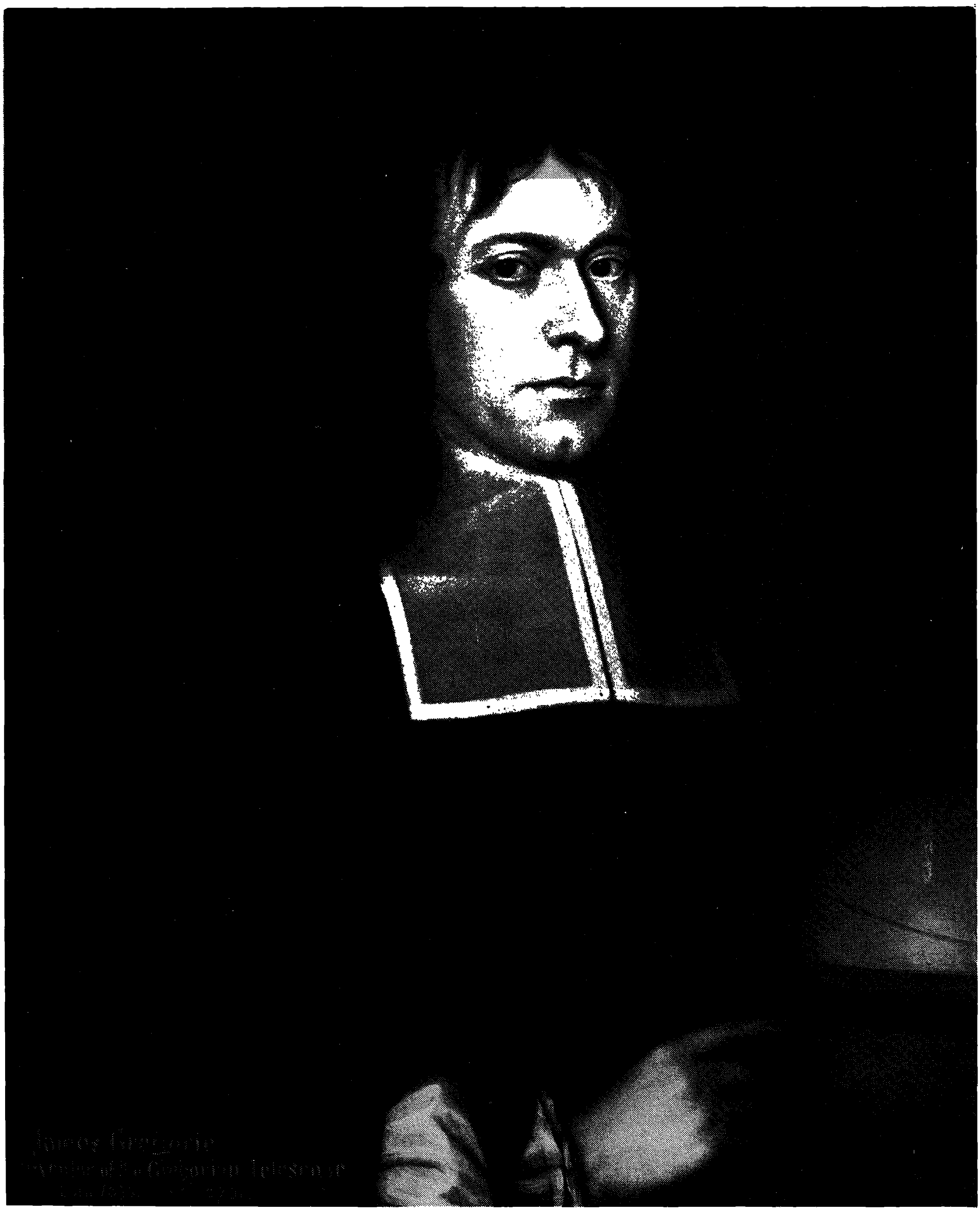

FIG. 1. James Gregory (1638–75): portrait attributed by James Holloway to John Scougall of Edinburgh (*Treasures of Fyvie* [*at the*] *Scottish National Portrait Gallery* (Edinburgh, 1985), 40). National Trust for Scotland, Fyvie Castle (photograph: National Galleries of Scotland).

David, who was himself an enthusiastic mechanic, natural philosopher and mathematician. David sent him to Aberdeen for his formal education, and after his graduation from Marischal College, he encouraged him to continue his studies. Gregory's first publication, his *Optica promota* of 1663, is a gathering of these early researches in geometrical optics and astronomy, and it is remarkable for its inclusion of a design for a practical reflecting telescope.[5] The volume was based on his reading of al-Haytham, Witelo, Kircher and others, and in the preface he described how "moved by a certain youthful ardour ... I have girded myself with these optical speculations, chief among which is the demonstration of the telescope".[6]

The main text of the *Optica promota* has been described by Whiteside as "interesting more for its revelations of the inadequacies of his early scientific training than for its technical novelties".[7] At Aberdeen Gregory did not have access to a sufficiently comprehensive library, there being a "scarcity of new mathematical books in the Aberdeen Library".[8] Although he had the support of his brother David, which he acknowledged in the preface of the book, he was not at this early stage in contact with other practising mathematicians. Whiteside has noted that Gregory made good use of those optical and astronomical works that were available to him, notably Risner's 1572 edition of al-Haytham and Witelo, but was hampered by an ignorance of the contents of Descartes's *Dioptrique* of 1637, in which the sine law for refraction was first publicly announced.[9]

The 59 optical propositions of Gregory's book deal with catoptrics and dioptrics — that is, with reflecting and refracting optics. These are followed by the description of a reflecting telescope included in a passage termed an *Epilogus*, and finally there are 31 astronomical propositions in a group designated in the title of the volume as an appendix. In the first of the optical propositions Gregory developed an intuitive demonstration of a law of refraction, equivalent to the sine law, allowing parallel light incident on a central conic surface to be refracted to a focus. He then demonstrated an experimental agreement with the table of refraction published by Witelo and Kircher; thus "the mathematics and more subtle observations confirm this most beautiful speculation of dioptrics".[10]

The optical propositions that follow discuss the formation and disposition of images in conic-section mirrors and refracting surfaces and lenses, and Gregory has been careful to stress the parallelism of reflection and refraction. A group of propositions of particular interest demonstrate that the images formed by concave elliptic-section mirrors and convex hyperbolic-section mirrors, of small plane objects that are normal to the axis of the mirror and placed at a focus, are themselves approximately plane; and similarly that the images formed of infinitely distant objects of small angular size by parabolic-section mirrors and conic-section refracting surfaces (and hence lenses) are also approximately plane.[11] These results are, of course, prerequisites for the effective coupling of any such imaging elements to form a telescope, and they represent a departure from those earlier accounts restricted to imaging on the axis of the optical components.

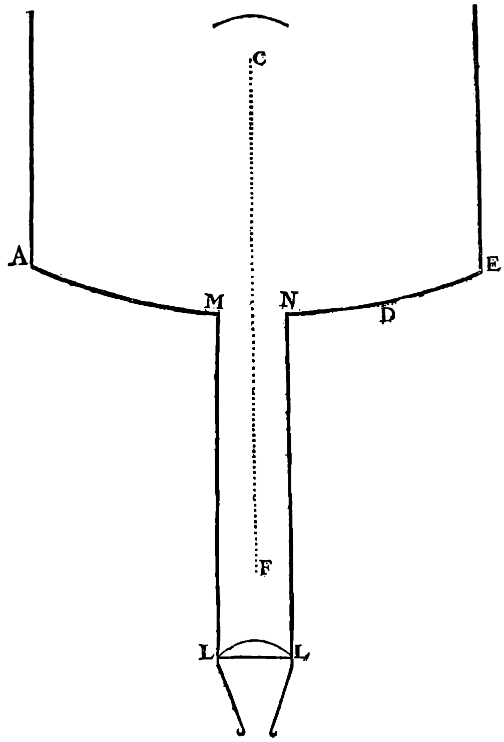

FIG. 2. The optical scheme of Gregory's reflecting telescope proposal: wood-block engraving from *Optica promota* (1663). The primary mirror is *AMNE*, the secondary is beyond the common focus *C*, and the eye-lens *LL* examines the image at *F*. University of Edinburgh Library.

Gregory's train of thought becomes clear at the end of the optical propositions when he departs briefly from geometrical analysis to postulate a practical alternative to the familiar form of telescope (which used a combination of glass lenses), exploiting the parallel characteristics of lenses and mirrors that he had established.

He introduced this by describing three classes of telescope. The first was the standard and purely dioptric form, and suffers from a number of disadvantages, specifically that refracting telescopes had grown too long to be manageable, and that the image quality was poor because of the number and quality of the glasses. The second was purely catoptric, employing a system of mirrors to avoid the defects of the first, but losing too much light at each reflection. However, in a third class of instrument the optical system was a mixture of mirrors and lenses (later to be dubbed catadioptric) and Gregory claimed that this could be devised so as to avoid the disadvantages of the other two classes.[12]

The telescope he proposed had a concave parabolic-section mirror, "exquisitely polished" and with a circular aperture at the centre. Beyond the focus of this speculum was placed "a small elliptic concave mirror, having a common axis and common focus with the parabolic concave mirror".[13] This secondary speculum reflected the light back to a focus beyond the central aperture in the primary mirror, where it could be examined by a conventional dioptric eyelens. Despite the technical difficulties of producing conic-section reflecting surfaces other than spheres, Gregory was convinced that they were ultimately necessary:

> Concerning the mechanics of these mirrors and lenses which have been vainly attempted by others, I being less versed in mechanics make no claim: however I boldly assert that the perfection of optics is sought in vain in spherical lenses and mirrors.[14]

Gregory did in fact commission such an instrument to be made and in view of the criticism later levelled at the attempt, and particularly at the use made of spherical surfaces, it is important to note that Gregory did not insist on non-spherical conic sections. Although the optical propositions of the book had been derived for more general conic sections, "Yet, if anyone wishes, he will be able to apply to spheres the main propositions; although not so perfectly".[15]

The approximation related to the flatness of the image. Although a spherically concave mirror did not bring a parallel beam of light to a point focus, it could nonetheless produce an acceptable focus. The problem, in terms of Gregory's earlier analysis, was that the image of a distant object was no longer flat but was slightly curved (Gregory described it as adopting a spherical surface axially symmetric with the mirror). Since this curvature depended on the size of the concave mirror, it followed that the image surfaces of two optical components could no longer be made to coincide exactly. However, providing they were judged sufficiently close "at least as far as the sense is concerned" (which in practice would mean for instruments of small aperture and narrow field of view) then the approximation was justified.

If non-spherical conic-section surfaces could not be achieved, but only spherical ones, then it remained true that the use of mirrors was still preferable to the use of lenses:

> Nevertheless if conic lenses and mirrors are not available, it will be better to use spherical portions in place of ellipsoids and parabolic conoids in catoptrics than it would be to use them in place of hyperbolic conoids in dioptrics since the latter agree with spherical portions less well.[16]

To clarify the relationship between the practical telescope that emerged from this speculation, and the proposal in the *Optica promota*, it is necessary to examine the circumstances of the book's production. Gregory is understood to have been conscious of his restricted scientific opportunities in Aberdeen, and this was the stimulus for the travels which began in 1662 with his journey south to London, when he brought with him the manuscript of *Optica promota*.[17]

During his brief stay in London his book was published and he made arrangements for his travel across Europe. He was helped in this by his fellow countryman Sir Robert Moray (1608?–73), a statesman of great influence at court and Lord of Exchequer for Scotland. Moray was also a central figure in the then young Royal Society of London; indeed, it had been largely through Moray that the King had agreed to become the Society's Patron, and it was at Moray's laboratory at Whitehall Palace that Charles kept in touch with scientific progress.[18] Through his correspondence with the great Dutch scientist

Christiaan Huygens, Moray was a principal link between the London and Continental scientific communities, and he thought sufficiently highly of the young Scots mathematician and his new publication to provide him on 19 February 1663 with an introduction to Huygens.[19]

One might conjecture that since Moray chose to assist Gregory in the first place, he had probably received a similar recommendation from a patron of Gregory's in Scotland. Two possibilities immediately come to mind. The first is the geographer and cartographer James Gordon (1615?–86), minister of the parish of Rothiemay in Banffshire, who with his father Robert Gordon (1580–1661) of Straloch, Aberdeenshire, contributed cartographic and descriptive matter for the Scottish section of Blaeu's *Atlas novus* (1654).[20] Both Gordons had attended university at Aberdeen, and Robert had also studied in France.

The similarity of interests between the Gregory and Gordon families makes it inevitable that they were closely acquainted at the time of James Gregory's departure for London. They were also geographically close, but particularly so after David Gregory, who had been apprenticed to a mercantile house in the Netherlands, returned to Scotland in 1655. On the death of his older brother, David succeeded to the estate of Kinairdie, where he was the immediate neighbour of James Gordon at Straloch, a mere two miles away. The link between the families can certainly be established a few years later.[21]

A second association, this time between Moray and the Scottish establishment, concerns Alexander Bruce (1629–81) of Broomhall, on the north shore of the Forth estuary, who in 1663 succeeded his brother Edward as second Earl of Kincardine.[22] Bruce's strong presbyterian Royalist sympathies allied him closely with Moray and both held political office after the Restoration. Their friendship was probably of long standing, but is known from a remarkable surviving correspondence which begins in 1657 when both were on the Continent — Bruce (in Bremen) is likely to have been representing his family's commercial interests, whereas Moray (in Maastricht) had apparently withdrawn temporarily from active diplomatic and military activity in France on behalf of the Stuart cause.[23] Both men were actively concerned with technical matters, and Bruce, who was in London in 1660 and 1661, became a founder member of the Royal Society, of which Moray was a leading figure. In mid-1661, however, he returned to Scotland where he was appointed to the Scots Privy Council, dividing his time between Edinburgh and the family estates in Fife.[24]

Of his technical interests, Bruce is remembered principally for his development of marine timepieces using short pendulums. He showed one of these to Huygens in London in May 1661, and he tested an improved version on a voyage between Scotland and the Netherlands in December 1662.[25] Huygens had previously tried to do this, and the upshot of discussions between the two at The Hague was that additional mechanisms were acquired from Huygens's clockmaker and tested by Bruce on the return voyage to London at the end of December 1662.[26] Again, an important part of the correspondence with Huygens was conducted through Moray, and it was Moray who reported the results of further sea trials to Huygens in late 1663.[27]

It is considerably more likely that Gregory's connections would bring him into initial contact with Bruce in late 1662, rather than with Moray, and that it was Bruce who recommended that Gregory should procede to London and provided the introduction to Moray. At the very least, it seems inevitable that Gregory would hear from Moray in January 1663 the outcome of Bruce's difficult voyage back from Holland.

Huygens was due to spend the spring of 1663 in Paris, and it was to there that Gregory travelled. Unfortunately when Gregory reached Paris, probably at the end of February or the beginning of March, he found that Huygens had not yet arrived, and he had to be content to leave a copy of his book.[28] Huygens duly acknowledged this to Moray, but as this letter is not amongst those that survive, his opinion of the book is not known.[29]

The object of Gregory's journey was to be Padua in Italy, which then boasted the most renowned university in Europe, and while he was there he was associated with the Scot James Caddenhead, who was professor of logic and subsequently of philosophy. Stefano degli Angeli, a pupil of Cavalieri and Torricelli, had just been appointed to the vacant mathematics chair, and Gregory studied geometry, mechanics and astronomy under him until May 1667.[30]

In the two mathematical works published by Gregory towards the end of his Italian stay, Whiteside finds that "a sheen of confidence gleams through Gregory's work", and from his exposure to the intellectual centre of Italian science "he at last emerges fully aware of his hitherto latent mathematical powers".[31] The *Vera circuli et hyperbolae quadratura*, in which he developed algebraic sequences for determining the area of central conics by convergent series, was published in Padua by October 1667.[32] The work was reprinted in Padua in early 1668, and issued together with Gregory's *Geometriae pars universalis*, which is concerned with problems of geometrical transformation.

Gregory returned to London in late spring 1668 to find that the *Vera circuli* had been enthusiastically received and that he was in demand for his recent contact with Italian science. He was elected to the Royal Society in June, and remained in London for some months before moving to the ancient university at St Andrews in Fife to take up the new chair of mathematics, thought to have been secured for him by Sir Robert Moray, who was at this time at the height of his influence in Scottish affairs.

Apart from a brief visit to London in 1673, Gregory's sole contact with current mathematical developments after his departure for Scotland was apparently through his London correspondent John Collins (1625–83), a mathematician who held a variety of Government accountancy posts. Through the Royal Society, and also on his own account, Collins conducted a wide correspondence with the principal mathematicians of the day, both at home and abroad, encouraging the interchange of mathematical news and playing a significant part in the promotion of mathematical publishing.[33]

Collins's early contacts with Gregory had been concerned largely with the availability of scientific books in Italy, and it had been Collins who reviewed Gregory's work so favourably in London and promoted him in the Royal Society. Latterly Collins was the intermediary between Gregory and Newton when the merits of their respective designs for reflecting telescopes were under discussion.

During his first visit to London in 1662–63 Gregory attempted to have his proposal for a reflecting telescope put into practice, and the work was placed in the hands of Richard Reeve of Long Acre, who at the time was the most accomplished optical worker in the capital. The popular story is that Gregory was introduced to Reeve by Collins, with whom he had struck up a close friendship.[34] On the whole, this version of events seems unlikely. The earliest extant correspondence between Collins and Gregory dates only from early 1668, shortly before Gregory was due to depart from Italy. On that occasion Collins reminded him that "it was once my good hap to meet with you in an alehouse, or in Sion College", a comment which certainly suggests that their acquaintance was slight and their correspondence not yet established.[35]

Nor was Collins privileged to receive one of the 150 copies of the first impression of the *Vera quadratura* distributed by Gregory in autumn 1667. Instead he was lent one by Samuel Thomson, the London stationer who had earlier published Gregory's *Optica promota*.[36] Collins certainly maintained contacts with a number of the stationers, and the several mentions of Thomson in his early correspondence with Gregory suggests that Thomson had been the initial link between the two mathematicians. Gregory remained in touch with Thomson: when the stationer died in late 1668, Collins wrote to Gregory in St Andrews to report that "your acquaintance Mr Samell Thompson is dead", and it is clear that Thomson was at the time supplying Gregory with copies of the Royal Society's *Philosophical transactions*.[37]

If John Collins had been the means of introducing Gregory to Richard Reeve in 1663, one would have expected him to have retained an interest in the telescope project. It should have placed him in a strong position to make some contribution to the later correspondence about the instrument that Reeve constructed. Instead, the absence of any personal recollection from Collins suggests that he was not aware of the work at the time. There is no clear evidence for such an early interest in optical instruments on Collins's part, and his most likely contact with scientific apparatus would have been through the Royal Society, to which he was elected only in 1667.

In passing, it is worth noting that Samuel Thomson himself may conceivably have acted as an intermediary, proposing to Gregory that he should put his ideas into practice before he left for the Continent: Thomson was reasonably well connected and almost certainly had contact with the extended scientific community. Although the publishing output of Thomson, and of the printer John Hayes who produced the *Optica promota* for him, reveals no bias towards works on mathematics or natural philosophy, they had in the previous year combined to produce Robert Hooke's first (and anonymous) publication, *An attempt for the explanation of the phaenomena*, on capillary action.[38]

It is an indication of Thomson's social status that he sent his son John to university, and he was described not by his trade but as 'gentleman' when John matriculated at Oxford, from which he graduated in 1668 before transferring to

Cambridge.[39] Thomson's executor was his fellow publisher, sometime associate in business and neighbour, Samuel Gellibrand, son of the London physician Henry Gellibrand (d. 1615) and brother of Henry Gellibrand (1597–1637), the celebrated professor of astronomy at Gresham College.[40]

On balance, however, it is much more likely that it was Sir Robert Moray who provided the stimulus for the practical work that Gregory commissioned and who recommended Reeve's services. The work was undertaken shortly before Gregory went abroad and at a time when Moray is known to have been taking an interest in him.[41] Moray was certainly personally acquainted with Reeve, who for a number of years had been the principal provider of telescopes and microscopes for the English astronomers and natural philosophers who were now associated with the Royal Society.

But Moray also had a particular involvement in promoting practical optics and specifically in the problem of manufacturing non-spherical lenses. Under his presidency of the Royal Society in 1661 he had set up a committee, on which he served together with Lord Brouncker, Sir Paul Neile, John Wallis, Jonathan Goddard and Christopher Wren, "to consider all sorts of tools and instruments for making glasses proper for perspectives, for the use of the Society; and to meet together on Fridays for that purpose".[42] The Society for a time even employed an optical technician, John Cock, to work for them.[43] In late 1665 Moray was using his influence with the King and in the Society to promote the activities of a French mechanic, de Son, who had persuaded him of his ability to grind the conic-section lenses which Descartes had stipulated were necessary for the improvement of optical performance, and who spent some time at the Court at Whitehall attempting to produce parabolic-section lenses.[44]

Richard Reeve is first recorded in the early 1640s, working for the mathematician John Pell in perhaps the first serious attempt in England to put Descartes's recommendations into effect.[45] His confidence that he could grind hyperbolic-section lenses was not rewarded with success — nor would efforts later in the century be successful, although the goal remained seductively appealing and attracted the considered attention of, amongst others, Christopher Wren and the talented curator of experiments to the Royal Society, Robert Hooke. Instead, a programme of empirical improvement in the performance of telescopes saw the focal lengths of objective lenses increased to the limits of technical competence in efforts to achieve greater and greater resolution.

Reeve was the optical technician principally responsible for the improvements made in England, and his work parallels that of prominent optical workers in Italy and France, such as Eustachio Divini and Giuseppe Campani.[46] Reeve was associated first with the optical development work for Dr Jonathan Goddard and the London natural philosophers meeting at Gresham College in the mid-1640s, and then with Sir Paul Neile and the Royalist Interregnum group centred around Seth Ward at Wadham College, Oxford, in the 1650s.

Reeve's developing skills raised him to the status of optical specialist and he dominated the commercial supply of telescopes and microscopes. It was, for example, a Reeve compound microscope that was used by Christopher Wren for his significant microscopical researches at Oxford, and a Reeve telescope of the impressive length of 35 feet with which Wren developed his theory of the structure of Saturn's ring. Reeve's instruments were much sought after for observing the transit of Mercury in 1661, and he perhaps reached the height of his reputation in 1664 with the eventual success of an enormous 60-ft telescope, which was subsequently acquired by Robert Boyle for Hooke's use.[47]

The trial carried out by Reeve for Gregory in 1663 appears to have been brief and, from the instrument maker's point of view at least, fairly inconclusive. It would probably have been forgotten completely had not Reeve been working with Robert Hooke developing the apparatus used in Hooke's microscopical researches, and subsequently published in the *Micrographia*. Hooke was able to make some trials with the mirrors which had been ground for Gregory and which had clearly remained in Reeve's hands, and these may well have been the inspiration for other reflecting instruments he constructed, and in particular for reflecting microscopes, with which he had some success.[48]

These trials however only came to light in early 1672 when Hooke was asked by the Royal Society to assess Newton's paper announcing his new theory of light and colour. Only now, and to demonstrate that Newton had not been the first to grind concave telescope mirrors, did Hooke describe how he had experimented (unsuccessfully) with "one of six foot radius, which about 7 or 8 years since Mr Reive made for Mr Gregory wth wch I made severall tryalls".[49]

Hooke's critique of Newton's paper was sent on to Newton by the Royal Society's Secretary Henry Oldenburg. And when Newton in turn was asked by Oldenburg to comment on a new reflecting telescope proposal — the design of the Frenchman Cassegrain — he pointed to the similarities of Cassegrain's and Gregory's designs, and drew support from the apparent failure of both Gregory and Hooke for his contention that neither was practical, whereas of course his own design was eminently so.[50] However, Newton had misunderstood the situation, and in subsequent correspondence it emerges that this misunderstanding centred on whether the failure was due to attempting the theoretically required non-spherical surfaces, and on whether Gregory's experiment had been a serious attempt to produce a finished instrument. Gregory felt obliged to enter the discussion in late 1672 to protect his proposal, which was being associated with Cassegrain's in Newton's cutting criticisms, and in the course of an extended correspondence a number of valuable details emerged.

Newton had initially assumed that the mirrors had been intended to have paraboloid and ellipsoid surfaces. He had based this on Hooke's claimed difficulty in generating a parabolic section which had discouraged him from making further experiments, and also on Gregory's statement in his *Optica promota*, quoted above, that non-spherical surfaces had been "attempted in vain".[51] However, for Gregory's volume to have been printed in time for his departure for Paris, the work by Reeve must have been done after Gregory's comment was printed, and Gregory in fact closed the discussion by noting in May 1673:

> I think no thing can be inferred concerning the tryal of my telescope from my assertione; seeing the trial was after that assertion: but Mr Newton could not be supposed to know this.[52]

Although to some extent Newton and Gregory remained at cross purposes, it seems clear from Gregory's comments that the "vain attempts by others" at non-spherical surfaces were reported efforts, unconnected with his own work. In particular, he was not saying that other workers (such as Reeve), who had the practical skills that he lacked, had failed to produce such surfaces for him. However, for Gregory to have been aware that such attempts had been made suggests that this comment was added to the text of his book after he had arrived in London. Early discussion with Moray, or with Reeve himself, would quickly have informed Gregory of unsuccessful attempts to grind non-spherical surfaces — presumably those of Bressieux in Paris in 1659, but probably also English enterprises such as Edward Baily's work for Francis Smethwick in 1660.[53] Equally, Gregory's description of the length of conventional refracting telescopes as having grown too long to be manageable is likely to have been a topical reference to the first Reeve 60-ft telescope. This was begun in 1662 (but did not meet with any success until 1664), and again this was information that Gregory would have been unlikely to encounter until he reached London.[54]

One might indeed postulate that the possibility of actually constructing a telescope did not occur to Gregory until he reached London, and that the text of the *epilogus*, which in several ways stands apart from the rest of the work, was written only after his arrival and immediately before the book was printed. There is also some indication that the preface to the volume was altered at the same time. Firstly, Gregory mentioned Descartes's work of which he had now heard, but which he had not yet seen, but also he promoted "these optical speculations, chief among which is the demonstration of the telescope" in a manner that suggests he was aware of the topical nature of the device.[55] This is not to imply that there is any discontinuity in the collation of the book — on the contrary, the text of the *epilogus* appears at the most appropriate point within the book, running on from the optical propositions, and the collation is continuous and uncomplicated.

It seems clear that before events had taken a practical turn Gregory was persuaded that parabolic surfaces were not readily obtainable, and he had lowered his sights to spherical surfaces, which, he could demonstrate, were a good approximation. He certainly made a definite distinction in a subsequent letter between the "vain attempts" at non-spherical surfaces and "my experiment with Mr Rives".[56] The experiment took the form of an attempt to grind and polish a large spherical concave mirror with a radius of about 6 feet and therefore with a focal length of 3 feet, together with spherical secondary mirrors.

The commission was not as unusual as might be supposed. Reeve required to fashion accurate spherically concave metal tools in which to polish objective lenses, and Gregory's proposal in effect called for a suitable tool to be polished to form the main mirror.[57] However, the polishing would have to be done on a larger diameter convex tool, which needed to be specially cast.

Reeve, assisted by Christopher Cock who subsequently became a prominent independent worker, ground the metal on a convex tool but was unable to obtain a suitable polish.[58] This lack of polish (described by Gregory as a "great defect in the figure") would, he believed, counteract the advantages which he had ascribed to reflecting telescopes, and as his time in London was now short he made only hasty trials.[59] Indeed it appears that it was Gregory's impatience to be away that curtailed the experiment: Reeve and Cock believed they would have better success with a smaller diameter mirror, although presumably of the same focal length, "for they undertook indeed to polish a less speculum to me upon the tool".[60]

Gregory, however, had "thought it not worth the pains to trouble myself anie further with it", but by this time secondary mirrors had already been constructed and combined with the primary with sufficient success to see "transient views of the object".[61] Probably they would have performed better had Gregory mounted them in a proper tube, but he had been "so possessed with the fancie of the defective figure [i.e. the uneven polish], that I wold not be at pains to fix everie thing in its due distance".[62] It is of interest to note that although Gregory's description of the telescope in *Optica promota* had shown a concave secondary in the combination later known as the Gregorian form, Gregory in fact made his trials "both with a little concave & convex Speculum" so that he also produced a working demonstration of the Cassegrain form.[63]

The reputation of Gregory's telescope has suffered as much from his own writings as those of Newton and Hooke. In particular, seen against the ideal requirements of his published design, the Reeve attempt was a failure. However, given that Gregory appreciated that spherical mirrors provided a satisfactory approximation for practical purposes, and indeed that he claimed that they would be better than spherical lenses, then an attempt that aimed to produce only spherical surfaces was perfectly reasonable.

In what he set out to do, namely to demonstrate his proposal using spherical surfaces, Gregory achieved some success. It is certainly less than fair to claim, as King has done, that the mirrors "were worse than useless".[64] It is also misleading to suggest, as is normally done, that the main object was the generation of aspheric surfaces.[65]

The importance of the instrument lies not in any partial success that may be claimed for it, but in the influence that it exerted on Robert Hooke, the practical experience that it afforded, and the stimulus that it provided for subsequent discussion.[66]

Acknowledgements

I must acknowledge my debt to the late Eric Forbes, Professor of the History of Science at Edinburgh University and an original member of the Editorial Board of this journal, for his encouragement with the preparation of an earlier version of this paper.

REFERENCES

1. P. E. Ariotti, "Bonaventura Cavalieri, Marin Mersenne, and the reflecting telescope", *Isis*, lxvi (1975), 303–21.
2. For a recent discussion of Short see T. N. Clarke, A. D. Morrison-Low and A. D. C. Simpson, *Brass & glass* (Edinburgh, 1989), 1–6.
3. This account is drawn principally from D. T. Whiteside, "James Gregory" in *Dictionary of scientific biography*, ed. by C. C. Gillispie, v (New York, 1972), 524–30, supplemented by *James Gregory tercentenary memorial volume*, ed. by H. W. Turnbull (London, 1939).
4. *The mathematical papers of Isaac Newton*, iii: *1670–73*, ed. by D. T. Whiteside (Cambridge, 1969), p. xiii.
5. J. Gregory, *Optica promota, seu abdita radiorum reflexorum & refractorum mysteria, geometrice enucleata; cui subnectitur appendix, subtilissimorum astronomiae problematon resolutionem exhibens* (London, 1663).
6. Turnbull (ed.), *op. cit.* (ref. 3), 454, translating Gregory, *op. cit.* (ref. 5), preface A3r.
7. Whiteside, *op. cit.* (ref. 3), 525.
8. Trans. from Gregory, *op. cit.* (ref. 5), preface A3r.
9. Whiteside, *op. cit.* (ref. 3), 525. The Marischal College Library copy of Risner's *Opticae thesaurus, Alhezeni Arabis libri septem, nunc editi ... item Vitellonis Thuringo-Poloni Libri X* ... (Basel, 1572) was bequeathed in 1613, and is now in Aberdeen University Library. The latter also has a copy in its Gregory Collection, but whether this copy was in James Gregory's hands at this early period cannot be said. I am grateful to the Librarian, Aberdeen University Library, for providing this information.
10. Turnbull (ed.), *op. cit.* (ref. 3), 455, translating Gregory, *op. cit.* (ref. 5), 13.
11. Propositions 37–43.
12. Gregory, *op. cit.* (ref. 5), 92–93. There is an intriguing possibility that Gregory may have encountered the designs by Mersenne for catoptric telescopes. These were published in a number of Mersenne's works including the *Harmonica* (Paris, 1635), of which there was a copy in Marischal College Library (but the provenance is unknown), and in the *Cogita physico-mathematica* (Paris, 1644), a copy of which was in the Gregory family collection (although again its acquisition date is unknown). Both are now in Aberdeen University Library. I am grateful to the Librarian, Aberdeen University Library for these details.
13. Trans. from Gregory, *op. cit.* (ref. 5), 93. Although Gregory described the mirrors as being co-focal, he had the secondary placed "in" and not "near" the focus of the primary. Turnbull noted that Gregory corrected this in his annotated copy, now in the Library at the University of St Andrews: Turnbull, *op. cit.* (ref. 3), 456.
14. Trans. from Gregory, *op. cit.* (ref. 5), 95.
15. *Idem.*
16. *Idem.* The *Epilogus* then concludes with the words "Hic itur ad astra". I am indebted to the late Dr Robin Schlapp for checking my translation of this passage.
17. Whiteside, *op. cit.* (ref. 3), 524. There appears to be no direct evidence for Gregory's departure in 1662, but the book could not have been printed, so carefully proof-read and bound by mid-February if Gregory had not been in London from at least the end of the year. I am grateful to Professor D. T. Whiteside for his comments on this aspect.
18. See D. C. Martin, "Sir Robert Moray, F.R.S.", in *The Royal Society: Its origins and founders*, ed. by H. Hartley (London, 1960), 239–50.
19. *Oeuvres complètes de Christiaan Huygens*, iv: *Correspondence 1662–63* (The Hague, 1891), 318, 330.
20. On the Gordons see particularly J. C. Stone, "Robert Gordon of Straloch: Cartographer or chorographer?", *Northern Scotland*, iv (1981), 7–22.
21. A. D. C. Simpson, "Sir Robert Sibbald", in *Royal College of Physicians of Edinburgh Tercentenary Congress*, ed. by R. Passmore (Edinburgh, 1982), 59–91, p. 82.
22. See A. J. Youngson, "Alexander Bruce, F.R.S., second Earl of Kincardine (1629–1681)", in Hartley (ed.), *op. cit.* (ref. 18), 251–8. The date of death of the first Earl is normally given merely as 1662: however, it is clear from his correspondence and from the records of the

Privy Council that he only assumed the title between March and July 1663. On masonic links between Bruce and Moray, and on Moray's contacts with the operative masons' craft guild in Maastricht in 1659, see David Stevenson, *The origins of Freemasonry: Scotland's century, 1590–1710* (Cambridge, 1988), 171–7.

23. *Ibid.*, 252.
24. *Record of the Privy Council of Scotland*, 3rd ser., i: *1661–64* (Edinburgh, 1905), 8. He was present regularly at meetings, but there was a gap in attendance between August 1662 and June 1663.
25. Bruce to Huygens, 29 January 1664: Youngson, *op. cit.* (ref. 22), 253–4.
26. J. H. Leopold, "Clockmaking in Britain and the Netherlands", *Notes and records of the Royal Society of London*, xliii (1989), 155–65, p. 159, where the clockmaker is identified as Severijn Oosterwijck of The Hague. The timepieces, which had 7-inch pendulums, are referred to in the correspondence as Bruce's, which implies that he had purchased them: Huygens to his brother, 28 December (N.S.) 1662, and Bruce to Huygens, 2 January 1663: Huygens, *op. cit.* (ref. 19), 285, 290.
27. Results of the tests between April and September 1663 on a voyage to Lisbon are printed in *ibid.*, 446–51.
28. Huygens's correspondence had misled Moray into thinking that he would leave for Paris earlier. When he heard at the end of March that Huygens was still at the Hague he wrote there to say that he had sent a letter to Paris by the hand of a young man who had instructions to leave it with Huygens's father (then resident in Paris) if Huygens had not yet arrived. This young man also had a present to give him of "a book of which he is the author, called Optica promota, which treats Dioptrics and Astronomy, and of which I wish to say nothing so that you may reach a judgement in full": trans. from letter of Moray to Huygens, 27 March 1663, *ibid.*, 330. The letter which Gregory was carrying was written by Moray on 19 February, so we may perhaps assume that the *Optica promota* was published in February and that Gregory left for Paris towards the end of the month. Huygens arrived in Paris on 24 March.
29. Huygens's opinion was given in a letter which Moray did not receive. The book was acknowledged in another of 22 May, but his comments were reserved until he met Moray about two weeks later at the start of a stay in London: Huygens, *op. cit.* (ref. 19), 351, letter of Huygens to Moray, 1 June (N.S.) 1663. By this time Bruce had returned to Scotland — he attended a Privy Council meeting in Edinburgh on 2 June 1663.
30. F. Enriques, "James Gregory e il suo soggiorno in Italia", in Turnbull (ed.), *op. cit.* (ref. 3), 465–8, p. 465; Whiteside, *op. cit.* (ref. 3), 524.
31. Whiteside, *op. cit.* (ref. 3), 526.
32. Huygens was sent a copy on 28 September 1667: *Oeuvres complètes de Christiaan Huygens*, vi: *Correspondence 1666–69* (The Hague, 1895), 154.
33. For Collins see D. T. Whiteside, "John Collins", in *Dictionary of scientific biography*, ed. by C. C. Gillispie, iii (New York, 1971), 348–9.
34. For example, in A. C. Stewart, *The academic Gregories* (Edinburgh, 1901), 28, followed by Turnbull (ed.), *op. cit.* (ref. 3), 3.
35. Turnbull (ed.), *op. cit.* (ref. 3), 47: draft letter of Collins to Gregory. The inclusion of a passage from Isaac Barrow in the letter suggests it was dated after 6 March 1668, which was the date of Barrow's letter to Collins. The letter, which had an enclosure, gives the impression of being in part a repeat of an opening letter from Collins, and it was this earlier letter that Gregory answered on 16 March 1668 (Turnbull did not change the occasional Gregorian 'New Style' dates of manuscripts), shortly before leaving Padua. Sion College was founded in London in 1623 as a college and almshouse, and had a substantial library.
36. *Ibid.*, 45: Collins to Gregory, undated draft, early 1668.
37. *Ibid.*, 55: Collins to Gregory, 30 December 1668.
38. Paul G. Morrison, *Index of printers, publishers and booksellers in Donald Wing's Short-title Catalogue ... 1641–1700* (Charlottesville, Virginia, 1955), entries G1912 (excudebat J. Hayes pro S. Thomson) and H2612 (by J. H. for Sam Thomson). J. H. and John Hayes entries cease after the ruin of his business in the fire of 1666. On Hooke's volume see G. Keynes, *A bibliography of Robert Hooke* (Oxford, 1960), 6–8.
39. *Alumni Oxoniensis ... 1500–1714*, ed. by J. Foster (Oxford and London, 1892), 1477.
40. *Ibid.*, 556; H. R. Plomer, *A dictionary of the booksellers and printers who were at work in England, Scotland and Ireland from 1641 to 1667* (London, 1907), 81, 179.
41. Turnbull (ed.), *op. cit.* (ref. 3), 240: Gregory to Collins, 23 September 1672.

42. T. Birch, *The history of the Royal Society of London* (London, 1756–57), i, 20: 10 April 1661.
43. A. D. C. Simpson, "Robert Hooke and practical optics: Technical support at a scientific frontier", in *Robert Hooke: New studies*, ed. by M. Hunter and S. Schaffer (Woodbridge, Suffolk, 1989), 33–61: on John Cock see p. 43.
44. *The correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall, ii: *1663–65* (Madison, Wisconsin, 1966), 560–641 *passim.*
45. *A collection of letters illustrative of the progress of science in England*, ed. by J. O. Halliwell (London, 1841), 72–74.
46. This discussion of Reeve is taken from A. D. C. Simpson, "Richard Reeve — the 'English Campani' — and the origins of the London telescope-making tradition", *Vistas in astronomy*, xxviii (1985), 357–65, and the more extended account in Simpson, *op. cit.* (ref. 43).
47. *Ibid.*, 39, n. 20.
48. *Ibid.*, 45.
49. The date must refer to Hooke's experiments, rather than to the original work for Gregory. This reference is apparently the cause of the confusion about the date of Gregory's departure for the Continent, which is sometimes claimed to have been in 1664: see, for example *The correspondence of Isaac Newton*, i: *1661–75*, ed. by H. W. Turnbull (Cambridge 1959), 115, n. 4, and H. C. King, *The history of the telescope* (London, 1955), 71. It may also have led Professor Eva Taylor to claim (incorrectly) that two telescopes were made, in 1663 and 1668: E. G. R. Taylor, *The mathematical practitioners of Tudor and Stuart England 1485–1714* (Cambridge, 1954), 246.
50. *Correspondence of Newton*, i (ref. 49), 154: Newton to Oldenburg, 4 May 1672.
51. Hooke's comment that the parabola was more difficult to describe than the hyperbola or ellipse related to geometrical constructions that were potentially useful in the grinding of conic surfaces: for example the property of generating a hyperboloid by a line (i.e. cutting edge) skew to the conoid's axis had been proposed by Wren. Hooke was preoccupied with the need to be able to produce the figure mechanically.
52. *Correspondence of Newton*, i (ref. 49), 279: Gregory to Collins, 13 May 1673. From the sense of this and of the letter it answers, the trial is that of Gregory and not Hooke. Gregory understood the "trial" of the instrument as the attempt to put the design into practice and not the subsequent experimentation with the components to test their effect. Newton initially assumed that Hooke had been involved in Gregory's original construction attempt, and therefore assumed that careful efforts to produce non-spherical surfaces would have been made. Gregory, aware that Hooke had not been involved, made comments only on his own work, and began to resent Newton's pedantic interpretation of his earlier published comment which was having the effect of denigrating his instrument. The original mirrors are unlikely to have survived until this time, and had probably been seized with Reeve's goods in late 1664; Reeve's death, four years after this, prevented him contributing to the debate: Simpson, "Reeve" (ref. 46).
53. Simpson, *op. cit.* (ref. 43), 44. It seems very likely that the work of John Cock for the Society in 1660–61, referred to above in connection with Moray's committee, was also directed towards aspheric lenses. Cock was also associated with John Beale's attempts to "perfect" lenses in 1659–60: Oldenburg to Hartlib, 23 July 1659, and Oldenburg to Beale, 4 September 1660, *The correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall, i: *1641–62* (Madison, Wisconsin, 1965), 288, 329.
54. Hooke stated that Reeve's first 60-ft lens was made in 1662: Oldenburg to Auzout, 23 July 1665, *Correspondence of Oldenburg*, ii (ref. 44), 442.
55. Gregory, *op. cit.* (ref. 5), preface A3r; Turnbull (ed.), *op. cit.* (ref. 3), 454. Subsequent detailed study of Descartes after his arrival in London caused Gregory to revise his *Optica promota*, but although part of the manuscript for this survives and Gregory at one time intended to publish it, yet it was never printed: Turnbull (ed.), *op. cit.* (ref. 3), 41–43, 55, 118, 262, 458–9; Whiteside, *op. cit.* (ref. 3), 526.
56. *Correspondence of Newton*, i (ref. 49), 240: Gregory to Collins, 23 September 1672. Newton later came to the conclusion that the trial had been only of spherical mirrors, but Gregory was not prepared to confirm this: *ibid.*, 271: Newton to Collins, 9 April 1673.
57. The radius of curvature was the same as that of the faces of the 6-ft objective lenses which Reeve was offering commercially at the time: T. H. Court and M. von Rohr, "New knowledge of old telescopes", *Transactions of the Optical Society*, xxxii (1930–31), 113–22, p. 121.
58. Gregory provided the only evidence that Cock was working for Reeve at this period in his letter to Collins of 7 March 1673: *Correspondence of Newton*, i (ref. 49), 259.
59. *Ibid.*, 240: Gregory to Collins, 23 September 1672.

60. *Ibid.*, 259: Gregory to Collins, 7 March 1673. The primary mirror had received only a preliminary polish with "a cloath and puttie".
61. *Ibid.*, 240.
62. *Ibid.*
63. *Ibid.* This has been noted, but without comment, by J. T. Desaguliers, "Appendix ... containing, an account of the reflecting telescope; ... with original letters which passed between Sir Isaac Newton and Dr. James Gregory ...", in D. Gregory, *Elements of catoptrics and dioptrics, translated ... by William Browne* (2nd edition, London, 1735), 218–88, p. 212.
64. King, *op. cit.* (ref. 49), 71.
65. This is assumed for example by Desaguliers, *op. cit.* (ref. 63), 212; J. Pringle, *A discourse on the invention and improvements of the reflecting telescope* (London, 1778), 7; A. Danjon and A. Couder, *Lunettes et télescopes* (Paris, 1935), 611; Turnbull (ed.), *op. cit.* (ref. 3), 3; H. C. King, "Early development of the reflecting telescope", *The refractionist*, xxviii (1939), 340–55, p. 341; King, *op. cit.* (ref. 49), 71; Z. Bechler, "'A less agreeable matter': The disagreeable case of Newton and achromatic refraction", *The British journal for the history of science*, viii (1975), 102–26, p. 104.
66. Hooke's work is assessed in Simpson, *op. cit.* (ref. 43).