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(*b*. Drumoak, near Aberdeen, Scotland, November 1638; *d*. Edinburgh. Scotland, late October 1675)

*mathematics, optics,astronomy*.

The youngest son of John Gregory, minister of the manse of Drumoak, James Gregory was descended through his father from the fiery Clan Macgregor and through his mother, Janet, from the more scholarly Anderson family, one of whom, Alexander, had been secretary to Viète. Somewhat sickly as a child, he received his early education (including an introduction to geometry) from his, mother, but after his father's death in 1651 his elder brother David sent him to Aberdeen, first to grammar school and later to Marischal College. After graduating there and further encouraged by his brother, himself an enthusiastic amateur mathematician, James devoted himself to studies in mathematical optics and astronomy.

In 1662, aware of the lack of scientific opportunities in Scotland, he traveled to London, there publishing *Optica promota* (1663), in which he gathered his earliest researches, and making several influential friends, notably Robert Moray, interim president of the Royal Society in 1660. In April 1663 Moray sought to arrange Gregory's introduction to Christian Huygens in Paris, but this was thwarted by Huygens' absence. Subsequently, to improve his scientific knowledge Gregory went to Italy, studying geometry, mechanics, and astronomy under Evangelista Torricelli's pupil Stefano degli Angeli at Padua (1664–1667) and publishing *Vera circuli et hyperbolæ quadratura* (1667) and *Geometriæ pars universalis* (1668). About Easter 1668 he returned to London; there, backed by John Collins' glowing reviews of his two Italian treatises and much in demand for his fresh contact with recent developments in Italian science, he was elected to the Royal Society on 11 June. Soon after, he made Huygens' attack upon the originality and validity of his *Vera quadratura* and also the publication of Nicolaus Mercator's *Logarithmotechnia* an opportunity for publishing in riposte certain newly composed *Exercitationes geometricæ* of his own.

In late 1668, probably through Moray's intercession, he was nominated to the new chair of mathematics at St. Andrews in Scotland. In 1669, shortly after taking up the post, he married a young widow, Mary Burnet, who bore him two daughters and a son. Much of his time during the next five years was passed in teaching elementary mathematics and the principles of science to his students: "I am now much taken up," he wrote in May 1671, "& hath been so al this winter bypast, both with my publick lectures, which I have twice a week, & resolving doubts which som gentlemen & scholars proposeth to me, ...al persons here being ignorant of these things to admiration," His London correspondent Collins, a good listener if incapable of appreciating Gregory's deeper insights, was his sole contact with mathematical and scientific developments in the outside world; through him he received extended transcripts of letters written by Isaac Barrow, René-Françoisde Sluse, Huygens and Newton on a variety of topics, and in return he made Collins privy to many of his researches into equations, infinite series, and number theory.

Early in 1671, when the Académie des Sciences made tentative plans to invite two "Englishmen" (one of them Mercator) to Paris as *pensionnaires*, Moray campaigned actively on Gregory's behalf, but the proposal was not implemented. In 1672 Gregory joined the St. Andrews University "clerk" William Sanders in drafting a scornful reply to a recently published book on hydrostatics by the Glasgow professor George Sinclair: to Sanders' *Great and New Art Of Weighing Vanity*, whose title page named as its author "Patrick Mathers, Arch-Bedal to the University of St.Andrews," Gregory contributed a minute dynamical essay, "Tentamina quaedam de motu penduli et projectorum," Backed in turn by Sanders, the next year he implemented a long-cherished desire in the face of considerable resistance from his fellow professors, founding at St.Andrews the first public observatory in Britain. Charged with the university's commission, he traveled to London in June 1673 to purchase telescopes and other instruments and to seek John Flamsteed's advice regarding its equipment. Whether or not he did, as he intended, break his Return journey at Cambridge to see Newton is not Known. His hopes for the new observatory were soon Quashed. During his absence the students at St. Andrews had rebelled against their antiquated curriculum, publicly ridiculing the regents; and Gregory, with his radical ideas on introducing the "new" science, was made the scapegoat: "After this the servants of the Colleges got orders not to wait on me at my observations; my salary was also kept back from me; and scholars of most eminent rank were violently kept from me,...the masters persuading them that their brains were not able to endure [mathematics]." In 1674 Gregory was glad to accept the newly endowed professorship of mathematics at Edinburgh, "where my salary is double, and my encouragements much greater"; but within a year of his appointment a paralyzing stroke blinded him one evening as he showed Jupiter's satellites through a telescope to his students. A few days later he was dead.

Written in his twenty-fourth year, Gregory's *Optica promota* is—with the notable exception of its "Epilogus"—interesting more for its revelations of the inadequacies of his early scientific training than for its technical novelties. Deprived in Aberdeen of a comprehensive library and contact with any practicing scientist, Gregory nevertheless made good use of available books on optics (Friedrich Risner's 1572 edition of Ibn al-Haytham [Alhazen] and Witelo ["authores perobscuri et prolixi"], Kepler's *Paralipomena*, Kircher's *Ars magna lucis*) and astronomy (Galileo's *Nuncius sidereus*, Kepler's *Astronomia*, Seth Ward's *Astronomia geometrica*). Ignorant of Descartes's *Dioptrique* (1637) and of the sine law of refraction there first publicly announced, in his opening pages Gregory presents an analogical "proof" that all rays incident on a central conic parallel to its main axis are refracted to its further focus for a suitable value of its eccentricity (in fact, as Descartes had shown, when it is the inverse refractive ratio). Departing from the particular cases of infinite and zero refraction when the conic is a circle and a straight line respectively and the parabolic case of reflection (unit negative refraction) and relying on his intuition that the interface is a conic, he "interpolates" the general *mensura refractionis* and then gives his model—equivalent to the sine law he nowhere cites— an experimental basis by displaying its agreement with the refraction tables of Witelo and Kircher.

The following optical propositions (2-59) extend Gregory's Cartesian theorem to systems of conical Lenses and also develop the allied properties of reflection in conical mirrors; a neusis construction of the generalized Ibn-al Haytham problem of finding the Point(s) of reflection in a general surface (prop. 34) is attained by roughly determining the tangent members of the family of spheroids whose common foci are the object and image points. In his historically significant epilogue Gregory explains how the deficiencies of the conventional pure reflectors and refractors encouraged him to design a compound "catadioptrical" telescope in which their defects were minimized. As an example he sketches "unum hujus perfectissimi generis telescopium" in which a parabolic mirror reflects parallel incident rays to a primary focus, on whose further side they are reflected back through a hole in the center of the first mirror by a small concave elliptical one to a secondary focus and thence through a plano-convex lens to the eye.

In 1663 the London optician Richard Reive was commissioned by Gregory to construct a six-foot "tube" to this design but failed, according to Newton in 1672, to polish its conical mirrors correctly. Newton's own improved design (1668[?]) used a plane mirror to reflect the rays from a spherical main reflector to the side of the telescope tube, and in 1672 through Collins he and Gregory exchanged letters arguing the relative merits of the two mountings. (The 1672 Cassegrain design, in which rays converging on the primary focus are reflected to the secondary focus before they reach it, was dismissed by Gregory as "no great alteration.") The astronomical appendix to the *Optica* (props. 60-90) is of no importance, but it serves to reveal once again Gregory's limited awareness of current scientific research. Much influenced by Seth Ward's *Astronomia* (1656), he here describes at some length geometrical methods for computing solar, lunar, and (hopefully) stellar parallax. A remark (prop. 87, scholium) that the conjunctions of the sun and Earth with Venus or Mercury would have a "pulcherrimum usum" for this purpose ignores the practical difficulties earlier encountered by Jeremiah Horrocks in his observations of the Venus transit in 1639 (first published in 1672). His schemes of planetary computation embody either the Keplerian "hypothesis Ptolemaica" of motion in an excentric circle with equant at the bissextile point or the slightly better Boulliau-Ward hypothesis of elliptical motion round the sun at a focus with mean motion round the second focus.

A still unpublished addendum to the *Optica* (David Gregory, B29, Edinburgh), composed some time after Gregory's arrival in London in 1663, contains a revised discussion of reflections in mirrors and refractions in thin lenses according to the newly encountered sine law of refraction. One theorem, a "notion" of a "burning-glass" (concave leaded spherical glass mirror) was communicated without proof to Collins in March 1673 and published by William Brown in 1715.

By late 1667 a sheen of confidence gleams through Gregory's work. Having absorbed at Padua all that some of the finest intellects in Italian science (Angeli, Gabriele Manfredi, and others) could teach him, he at length emerges fully aware of his hitherto latent mathematical powers. Of the two treatises stemming from his Italian sojourn, the *Vera circuli et hyperbolae quadratura* is the more original. Generalizing a procedure used by Archimedes in his *Measurement of a Circle*, in the case of a general central conic Gregory recursively defines an unbounded double sequence $i_n$, $I_n$ of inscribed/circumscribed *mixtilinea*. Given a conic are bounded by its chord and the intersecting tangents at its end points, $i_0$, $I_0$ are the inscribed triangle and circumscribed quadrilateral bounding the central sector cut off by the arc and the lines joining its end points to the conic's center. By dividing the arc at the point where it is parallel to its chord, two half-arcs are formed, yielding $i_1$, $I_1$ as the total of the two triangles/quadrilaterals inscribed/circumscribed to the two component conic sectors; a similar bisection of the two half-arcs produces corresponding bounding *mixtilinea* $i_2$, $I_2$, and so on. Gregory proves (props. 1-5) that $i_{n+1}$,$I_{n+1}$ are, respectively, the geometric mean of $i_n$, $I_n$ and the harmonic mean of $i_{n+1}$, $I_n$; that is,

In the terms of Gregory's "definitiones" 1-10 the general pair $i_{n+1}$, $I_{n+1}$ forms a "series convergens" (monotonically increasing/decreasing double sequence) of terms "analyticè compositi" (recursively defined by addition, subtraction, multiplication, division, and root extraction) out of the preceding "termini" $i_n$, $I_n$; he also proves that as $n$ increases indefinitely, the difference between $i_n$ and $I_n$ becomes arbitrarily small—whence (p. 19) the "ultimi termini convergents" can be "imagined" to be equal and their common value ($I=\lim_{n\to\infty} i_n=\lim_{n\to\infty} I_n$) is defined to be the “termination” (limit) of the “series,” As an example of the power of this new terminology and analytical structure he derive purely algebraically The generalized Snell–Huygens inequalities for the central conic:

Most tellingly, Gregory reasons that if a “quantitas” (function) can be “compounded” in the “same way” from $i_{n+1}$, $I_{n+1}$ as from $i_n$, $I_n$—say by $\Phi(i_n, I_n)=\Phi(i_{n+1}, I_{n+1})$—then the “termination” $I$ is defined by $\Phi(i_n, I_n)=\Phi(I,I)$. The function $\Phi(i_n, I_n)$, i.e.,

appropriate to his particular double sequence he was unable to determine, but by considereing the “imbalance” of the parametrization $i_n = a^2 ( a + b )$, $I_n = b^2(a + b)$, and so $i_{n+1} = ab (a+b)$, $I_{n+1}=2ab^2$, he sought to “prove” not only that Φ cannot be a rational function, which this makes plausible, but also that it cannot be algebraic, which does not follow at all; in that case $I$ would not be analytically compounded from $i_0$, $I_0$ and hence the “true” (algebraic) quadrature of the general conic sector—and of the whole circle in particular—would be impossible. Gregory’s ingenious if ultimately ineffective argument was somewhat impercipiently attacked by Huygens when he received a presentation copy of the *Quadratura*; his rebuff, still commonly allowed, that the limit sector $I$ could conceivably be determined in a different, algebraic way from the initial *mixtilinea* $i_0$, $I_0$ is in fact invalid since Gregory’s argument concerns the structure of the function Φ, not the passage of $i_{,n}$, $I_n$ to the limit $I$ (disposed of in the equality $\Phi (I,I)=I$). The latter half of the *Quadratura* is of some computational interest: on setting $i_0 = 2$, $I_0 = 4$, then $I = \pi$; while if $i_0 = 99/20$, $I_0 = 18/11$, then $I$ = log nat 10. These and other circle/hyperbola areas are accurately calculated to fifteen places.

Gregory’s second Italian treatise is more eclectic in spirit, being designedly a tool kit of contemporary geometrical analysis of tangent, quadrature, cubature, and rectification problems. In the preface to his *Geometriae pars universalis* he expresses his hope that by “transmuting” the essential defining property of a given curve, it may be changed into one of an already known kind; the “universal part of geometry” presaged in his title is that which comprehends such general methods of geometrical transformation. Under that manifesto Gregory produces a systematic exposition of elementary calculus techniques which he freely admits are largely reworkings and generalizations of approaches pioneered by others. Pierre de Fermat’s assignment of linear bounds to a convex arc, itself an improvement of Christopher Wren’s 1658 discussion of the cycloid, is developed into a general scheme, demonstrated by an extended Archimedean exhaustion proof, for rectifying an arbitrary “curva simplex et non sinuosa”; Grégoire de St. Vincent’s use of a “ductus plani in planum” (the geometrical equivalent of a change of variables under a double integral) is applied to reduce the quadrature of a given plane curve to the “planification” of a “hoof” section of a cylindrical surface and thence to the quadrature of a second curve. Another method of quadrature, that by transform to the subtangential curve, stems from Roberval. A geometrical tangent method is borrowed, again by way of Fermat, from Wren’s tract on the cycloid, while an analytical one making use of Jacques de Beaugrand’s notation for the vanishing increment “nihil seu serum *o*” of the base variable is a revision of that expounded by Descartes in his 1638 *querelle* with Fermat and published by Claude Clerselier in 1667, illustrated by an Example (a Slusian cubic) deriving from Michelangelo Ricci.

Above all, Wren’s concept, earlier broached by Roberval and Torricelli in the instance of the Archimedean spiral and Apollonian parabola, of the arc length” preserving “convolution” of a spiral into an equivalent Cartesian curve reappears, much extended and given rigorous exhaustion proof, in Gregory’s favorite transform of an “involute” into an “evolute,” while vigorous use is made of the Pappus-Guldin theorems relating the quadrature and cubature of solids and surfaces of revolution to their cross-section and its center of gravity. On this basis Gregory was enabled to furnish Simple proofs results in the theory of higher curves and the “infinite” spirals beloved of his tutor Angeli, replacing their previous crude, disparate forms by a logically immaculate, standardized demonstration. But too modern an interpretation of Gregory’s book should be avoided: what to us (in prop. 6) may seem a proof of the fundamental theorem of the calculus was for him merely a generalization of William Neil’s method for rectifying the semicubical parabola, and its wider significance is not mentioned.

The *Geometria* also affords a glimpse of Gregory’s scientific interests at the close of his Italian stay. A proposition on the Fermatian spiral allows him to discourse on its origin (in 1636) as a modified Galilean path of free fall to the earth’s center and to comment on the current controversy between Angeli and Giovanni Riccioli on the motion of the earth (one which he reviewed for the Royal Society in June 166: on his return to London). Again, certain appended nonmathematical passages deal briefly with the optical effect of the apparent twinkling of the stars and with the conjectured composition of cometary tails conceived of as a steamy “exhalation” lit up by the sun and, most important for future physical astronomy, offer the suggestion that the apparent brightnesses of stars of the same magnitude are inversely proportional to the squares of their distances with the corollary that Sirius—taken to be of the same magnitude and brightness as the sun—is 83,190 times its distance.

Mathematics retained its central place in Gregory’s affection until his death. Back in London he published a compendium, *Exercitationes geometricœ*, containing primarily an “Appendicular” to his *Vera quadratura* which refuted Huygens’ objections to its argument but also appending a number of miscellaneous theorems in geometrical calculus. The “Appendicula” itself is noteworthy for its concluding “theorema” (that if $a_n$, $A_n$, $b_n$, $B_n$ are two convergent Gregorian sequences with respective terminations $A$, $B$ and if for all $r$ $\Phi(a_n, A_n) > \Phi (b_n, B_n)$, then $A > B$) and for its twenty-seven narrow upper and lower bounds to the sector of a central conic. Since an “approximatio” to the sector $I$ is said to *k*-plicate the “true note” of the *mixtilinea*

when it compounds $i_\Phi I_\Phi$ j = 0, 1, 2, . . *n* so as to equal $I + O (I^{2k+1})$, Gregory’s method clearly made use of the series expansion of one or other of the elementary circle functions. To illustrate the power of the techniques elaborated in his *Geometria*, Gregory also, in ignorance of Harriot’s prior resolution, reduced the theory of the plane chart (Mercator map) to “adding secants” (integrating sec $x$ over a given interval, $0 \leq x \leq a$), effecting this elegantly if long-windedly by an involved appeal to a “ductus plani in planum.” In addition, he gave analogous quadratures of the tangent, conchoid, and cissoid curves; and, further to expedite the “additio secantium naturalium” near the origin, he elaborated simple rules for integrating) $y \approx ax^2 + bx$ and $y \approx ax^3 + bx^2$, $x$ small. The former of these is the first published instance of “Simpson’s” rule. His rigorous geometrical deduction of the Mercator series for $\pm \log (1 \pm x)$ is of minor importance.

After his return to Scotland, Gregory made no further published contribution to pure mathematics, but his private papers reveal that the last half dozen years of his life were ones of intensive research. His executor William Sanders tells us, “His Elements of plain Geometry, with some few propositions of the solids; his Practicall Arithmetick, and Practicall Geometry taught at St. Andrews...are but of small moment, being contrived only for the use of such scholars as cannot be at pains to study the Elements.” The lost *Tractatus trigonometricus*, in which he reduced “All Trigonometry rectilineal and spherical...unto five-short canons,” on the lines of Seth Ward’s *Idea* (1654), was no doubt also intended for professorial lectures. But his real energy was reserved for deeper matters. At Collins’ instigation Gregory spent much time on the theory of equation and the location of their roots; achieving success in the case of the reduced cubic and quartic by introducing an appropriate multiplying factor and equating all terms in the resolvent except those involving cube/fourth powers of the unknown to zero, the sought to solve the general quintic in a similar way by adjoining a factor of the fifteenth degree but failed to notice that the resulting equations to zero implied—ineluctably —a sextic eliminant. His papers on Fermatian equations, rational Heronian triangles, and other topics in Diophantine analysis are (much like Newton’s contemporary studies, likewise inspired by the appearance of the Samuel Fermat-Jacques de Billy *Diophantus* in 1670) more workmanlike than profound: the “skailzy brods” (writing slates) found on his desk after his death contained his abortive calculations for Jacques Ozanam’s unsolvable problem of cubes.

Gregory’s letters to Collins are filled with a miscellany of calculus, problems, among them his quadrature and rectification of the logarithmic spiral and “evolute” logarithmic curve, which had, briefly made its introductory bow in the preface to his *Geometria*. and his construction of the tangent to the “spiralis arcuum rectificatrix” introduced by Collins for use in the “Mariners Plain Chart.” His grasp of the subtleties of infinite series in particular quickly matured. His independent discovery of the general binomial expansion in November 1670—in disguised Form as that of antilog $((a/c)(\log (b + d) - \log b))$—was matched a month later by his use of a “Newtongauss” interpolation formula to insert general means in a given sequence of sines. As a climax, in February 1671 Gregory communicated without proof a number of trigonometrical series, notably those for the natural and logarithmic tangent and secant, and in April 1672 a series solution of Kepler’s problem (intended for publication in Collins’ edition of Horrocks’s *Opera posthuma*, but the bookseller took fright) regarding which he observed that “these infinite serieses have the same success In the roots of equations.” Two examples—the series extraction of the root $e$ of the conchoid’s defining equation

$L^2e^2 = (L + a)^2(L^2 - a^2)$

and the inversion of the Kepler equation

were later published by David Gregory, without direct acknowledgment, in his *Exercitatio geometrica* (1684). Until the printing in 1939 of Gregory’s notes, jotted down on the back of a letter from the Edinburgh bookseller Gideon Shaw in January 1671, it seemed, likely that these expansions were obtained by straightforward elementary methods, but we now know that he employed, twenty years before even Newton came upon the approach, a Taylor development of a function in terms of its *n*th-order derivatives.

Of Gregory’s scientific pursuits during this last period of his life too little is known. His “Theory of the whole Hydrostaticks comprehended in a few definitions and five or sixe Theorems” (David Gregory, D18) is seemingly lost, although a short 1672 paper in which he proved Huygens’ theorem relating atmospheric height logarithmically to barometric pressure still exists in several versions. In our present state of knowledge it seems impossible to determine how far William Sanders drew upon Gregory’s hydrostatical ideas in his largely scurrilous *Great and New Art of Weighing Vanity*, but extant preliminary computations in Gregory’s hand confirm, contemporary report that the appended “Tentamina quædam de motu penduli et projectorum” is uniquely his. of considerable historical importance as a bridging text between Galileo’s *Discorsi* and Newton’s *Principia*, these nine small duodecimo pages are a highly original contribution to dynamics. Independently deriving Huygens’ Galilean generalization that the square of the instantaneous speed of a body falling freely under simple gravity in a smooth curve is proportional to the vertical distance fallen (and indeed anticipating an objection to Huygens’ definition of the fall curve as the limit of a chain of line segments, which Newton put to Huygens in 1673), Gregory deduced the elliptical integral expressing the time of vibration in a circular pendulum and gave its infinite-series expansion for a small arc of swing. Subsequently, framing the supposition that the resistance is constant in magnitude and direction (opposite to that of initial motion), he determined that the resisted path of a projectile under simple gravity is a tilted parabola with main axis parallel to the resultant instantaneous force—a theorem, we now know, which had been found seventy years before by Harriot.

The “Fourty or thereabout of excellent Astronomical propositions invented” for the compleeting that art” found after his death doubtless originated in his correspondence with Colin Campbell during 1673-1674 on theoretical astronomy, during the course of which he solved—yet again in ignorance of a prior solution by Harriot—the Keplerian problem of constructing a planetary ellise, given three foca1 radii in magnitude and position. Apart from his keen discussion with Newton in 1672 on the respective merits of their “catadioptrical” reflecting telescopes, little evidence has survived of Gregory’s continuing interest in optics.

For all his talent and promise of future achievement, Gregory did not live long enough to make the major discovery which would have gained him popular fame. For his reluctance to publish his “several universal methods in Geometrie and analyticks” when he heard through Collins of Newton’s own advances in calculus and infinite series, he posthumously paid a heavy price: the “Extract from Missing ʳ Gregories Letters” drawn up by Collins in 1676 for Leibniz’ enlightenment were used by Newton in 1712 solely to further his claim to calculus priority and were thereafter forgotten. Gregory’s published works had little contemporary impact; his *Vera quadratura* was successfully sabotaged by Huygens, his *Geometria* quickly overshadowed by Barrow’s *Lectiones geometricæ*. We are only now beginning to realize the extent and depth of his influence, mathematically and scientifically, on Newton. A comprehensive edition of his work is sorely needed.

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