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(*b*. Oxford, England, *ca*. 1560; *d*. London, England, 2 July 1621),

mathematics, astronomy, physics.

Little is known of Harriot's early life. In 1584 he was in the service of Walter Ralegh where he had possibly been since 1580, when he finished his undergraduate studies at Oxford. Ralegh, who needed an expert in cartography and the theory of oceanic navigation, sent a colonizing expedition to Virginia in 1585, with Harriot as its scientist "in dealing with the naturall inhabitants specially imployed." He investigated their life, language, and customs and surveyed the coasts, islands, and rivers.

Harriot left Virginia in 1586, having learned, among other things, how to "drink" tobacco smoke, which he recommended in his *Briefe Report* (1588) as a cure for many complaints. When Ralegh turned his activities to Ireland and sought to colonize Munster, he leased Molana Abbey to Harriot. We do not know much about his life there, for he took care to order that all papers concerning the "Irische Accounts" be burned after his death. Although the *Briefe Report* had stressed Harriot's missionary zeal, some years later he joined a circle (Shakespeare's "School of Night") which included the atheist Christopher Marlowe and theists like Ralegh and the ninth earl of Northumberland. When, in about 1598, Harriot left Ralegh and Durham House, Northumberland gave him a yearly pension and living quarters in Sion House, Isleworth, and later (1608?) he lived in a house of his own, near the main building.

Harriot and his patron were imprisoned after the Gunpowder Plot of 5 November 1605. Although the earl was kept in the Tower of London until 1622, Harriot was released after a short time, a search of his papers having produced nothing incriminating. Subsequently he complained to Johann Kepler of impaired health; he was able nonetheless to proceed with his scientific investigations and even to undertake prolonged telescopic observations (1610-1613) of Jupiter's satellites and of sunspots. In 1613 he began to suffer from an ulcer in his left nostril. It proved to be cancerous and led to his death in 1621. He left more than 10,000 folio pages of scientific papers containing measurements, diagrams, tables, and calculations pertaining to important experimental and theoretical work in different fields.

Harriot was an accomplished mathematician who enriched algebra with a comprehensive theory of equations. By using an extremely convenient system of notation he simplified not only algebra, but also many other areas of mathematics. Among his innovations and discoveries is his proof that stereographic projection is conformal and therefore transforms rhumb lines on a sphere into equiangular helixes (logarithmic spirals) in its equatorial plane. He also made ingenious attempts to rectify and

square these spirals. In 1603 he computed the area of a spherical triangle: "Take the sum of all three angles and subtract 180 degrees. Set the remainder as numerator of a fraction with denominator 360 degrees. This fraction tells us how great a portion of the hemisphere is occupied by the triangle."

In about 1614 he resumed his early investigations of rhumb lines and the theory of the Mercator map, and nearly finished a table of meridional parts for this map. These computations were calculated for one-minute intervals, an enormous task that necessitated the use of sophisticated techniques of finite-difference interpolation, on which he wrote a monograph, *De numeris triangularibus*. His notational advances in this treatise are great, but even more interesting, and found only in preliminary drafts, are some symbols, including ,... , for our figured numbers (or binomial coefficients)

Harriot knew that such formulas are valid even when negative integers or fractions are substituted for the number *n*. Not only are his apt notation and sense of structure admirable, but also the exceptional clarity of his exposition, as is evident in both finished manuscript tracts and his rough work sheets.

Harriot's *Artis analyticae praxis*, published posthumously in 1631 (in a poor edition), contains an interesting attempt at a uniform treatment of all algebraic equations, with worked—out examples of linear, quadratic, cubic, quartic, and quintic equations. Because he composed this "practice of the art of analysis" primarily for amateurs, he did not treat negative roots, but in other manuscripts he even considered "noetical" (that is, imaginary) roots, as, for example,

a being the unknown quantity of this quartic, whose solutions appear on the right.

At times Harriot developed his mathematical deduction vertically downward, a method which may be advantageous to the mathematician, but posed a problem for the printer, as did his use of many new symbols. His symbolic shorthand and instructive examples often allowed him to dispense with explicit verbal explanation in mathematical writings. This is also apparent where he made trials of binary number systems. Unfortunately, the exact dates of Harriot's mathematical tracts and discoveries are known only in rare cases.

In his optics research it is easier to fix a chronology. No later than the early 1590's, he made a penetrating study of Ibn al-Haytham's (Alhazen's) *Optics* (Friedrich Risner's 1572 edition). To solve Alhazen's mirror problem he considered the locus of the reflection point for a spherical mirror expanding about its center. He thus anticipated Isaac Barrow, who proposed the same curve in 1669. Then Harriot investigated optical phenomena which Alhazen had neglected, or had not fully explored.

In order to establish a firm basis for the theory of burning glasses and of the rainbow, Harriot began in 1597 to measure the refraction of light rays in water and glass. He soon found that the Ptolemaic tables, then attributed to Witelo, were inaccurate. About 1601 he discovered that the *extensa* (essentially our refractive index) is the same for all angles of incidence. This enabled him to compute refraction for one—degree intervals of the angles of incidence. For water his index of refraction was cosec 48°30' and for glass cosec 40°. In 1606 Harriot sent Kepler refraction angles and specific weights for thirteen substances, but he withheld the sine proportion from him.

Harriot also studied prismatic colors. When he looked through a prism at a white object on a dark background, it seemed to be fringed with a yellow and red border. (Blue is not mentioned.) From the breadth of the colors Harriot computed (1604) refractive indexes of the green, orange, and (extremal) red rays. By pouring liquids into hollow glass prisms, he determined analogous refractive indexes for fresh water, saturated salt water, turpentine, and spirits of alcohol. With his refraction tables Harriot calculated the *refractio caeca* (total refraction) in prisms and the path of solar rays through plano—convex lenses and glass balls. For a ray traversing water drops he found that the *arcus egressionis* (exit arc) $2r{-}i$ should have a maximum value

Although in 1606 Harriot told Kepler that he planned a book on colors and the rainbow, his preserved manuscripts contain no statement of the exact relationship between maximum exit arc and the angular radius R, of the first rainbow, namely

Until the early 1590's Harriot's astronomical researches centered on nautical applications. Observing from the roof of Durham House (1591–1592), he measured an angular distance of 2 ° 56 ' between the celestial north pole and the North Star. Prominent among his suggestions for improved navigational instruments was an ingenious backstaff for measuring solar altitudes. The comet of 1607 ("Halley's comet") was observed by Harriot in London and by his pupil Sir William Lower in Wales. In a letter of 6 February 1610 Lower mentions that Harriot for some years had mistrusted the "circular astronomy" of Copernicus. Accordingly, as soon as Kepler's newly published *Astronomia Nova* reached England in 1609, they both studied it eagerly. Reworking a number of Kepler's computations, they discovered many minor errors. In the summer of 1609 Harriot turned a 6X telescope on the moon. Soon after, when he heard of Galileo's findings, he began a systematic survey of the sky and to this end his assistant and amanuensis Christopher Tooke constructed better telescopes, the finest having a magnification of thirty. A few detailed moon maps, ninety-nine drawings of Jupiter with satellites, and seventy-four folios of sun disks with spots testify to Harriot's hard work and perseverance as an observing astronomer from 1610 to 1613. Despite increasing ill health he was still able to make some observations of comets in 1618.

Harriot's manuscripts reveal little about his possibly extensive chemical researches and not much about his meteorological observations. He once measured the rainfall per square foot on the roof of Durham House, and he apparently possessed a scale for wind velocity. About 1600 he may for some time have been one of Cecil's decoding experts. of great importance are his investigations on free and resisted motion in air. From the roof of Sion House (about fortythree feet) In the summer of 1609 Harriot turned releasing each when the preceding one struck the ground. He determined the total fall time by pulse beats. In order to evaluate his results theoretically, he first rejected as negligible any *gradus naturae* (initial velocity). Then, after some hesitation, he decided to take acceleration proportional to time spent and not to space traversed.

These assumptions yielded fall spaces equivalent to thirteen feet (in other trials sixteen feet) after one second. On dropping bullets of different specific weights simultaneously, he observed no appreciable difference between bullets of iron and lead, but wax bullets lagged behind.

Harriot next turned his attention to ballistic curves, which he proved (on certain suppositions) to be parabolas with oblique axes (upright axes if air resistance could be neglected). He did not expressly say that he regarded air resistance as constant, but applied the kinematic rule of did numbers 1, 3, 5, 7,..., not only for the vertical component of fall, but also "in inverse order" to the oblique component of motion subject to air resistance. Later James Gregory also proposed tilted parabolas in *Tentamina de motu projectorum* (1672), but Harriot's mathematical deduction had been more elegant. It appears from Harriot's manuscripts that he had studied printed tracts of William Heytesbury, Bernhard Tornius, and Aluarus Thomas on problems of uniform and difform change. Some of Harriot's diagrams on uniform difform motion resemble those of Nicole Oresme.

In 1603 and 1604 Harriot measured specific weights. For those metals and chemical compounds which could be obtained nearly pure, his results agree remarkably well with modern values. Near the end of his life he wrote a small treatise entitled *De reflectione corporum rotundorum* (1619) that contains two suggestive diagrams and a small web of equations, which, when unraveled, emerge as relations between the velocities of balls before and after collision. He lacked, however, any concept equivalent to the modern principle that kinetic energy is preserved in perfectly elastic collision. Apparently he considered this last treatise fundamental to understanding how atoms collide with other atoms or light globules. Two or three of his rough diagrams show light globules zigzagging between layers of atoms.

Harriot was acquainted with older mathematicians like John Dee and, according to Anthony à Wood, Thomas Allen had been his teacher at Oxford. Harriot soon surpassed these two and all other English mathematicians of his time. Apart from a few letters exchanged with Kepler, there is no documented knowledge of correspondence or personal contact with scientists of his own rank but scanty references suggest that distinguished contemporaries like William Gilbert, Bacon, and Briggs knew something of Harriot's scientific work. The mathematicians of Harriot's own circle were Nathaniel Torporley, Walter Warner, and Robert Hughes. He was also closely acquainted with such scientifically minded men as William Lower, Thomas Aylesbury, Robert Sidney, and Lord Harington.

George Chapman, the poet, praised Harriot as a universal genius and a connoisseur of poetry. Long after Harriot's death, at the time of John Aubrey, rumors still persisted of Harriot's disputes with theologians. Although his favorite maxim is said to have been *Ex nihilo nihil fit*, such heretical opinions are not prominent in his extant manuscripts, and a bookseller's bill reveals that between 1617 and 1619, Harriot bought many tracts on Christian theology. Several of his minor manuscripts deal with infinity and its paradoxes.

Harriot seldom complicated his planned scientific treatises and never published any of them. This may largely be explained by adverse external circumstances, procrastination, and his reluctance to publish a tract when he thought that further work might improve it. Unlike Kepler, Harriot did not commit his inner thoughts and personal motives to paper. During the last years of his life, weakened health prevented his preparing any manuscript for the press. His will delegated this task to Torporley. Walter Waner, supervised by Aylesbury, then took over in 1627 and published the *Artis analyticae praxis*, but the planned edition of Harriot's major works came to nothing.

In the summer of 1627 Aylesbury and Warner measured refractions in several glass prisms and then calculated refraction tables modeled on Harriot's. Warner's young friend, John Pell, wrote to Mersenne on 24 January 1640 that Harriot had found the law of refraction. When, however, in 1644 Mersenne published, in *Universae geometriae... synopsis* (pp. 549-566), a posthumous tract by Warner on the sine law, Harriot's name was not even mentioned. Pell, who had borrowed some Harriot manuscripts from Aylesbury, later said that if Harriot had "published all he knew in algebra, he would have left little of the chief mysteries of that art unhandled" (S. P. Rigaud, *Correspondence of Scientific Men*, p. 153). After 1649, when Aylesbury was forced to leave England, Harriot's papers disappeared, but in 1784 F. X. von Zach rediscovered them under stable accounts in Petworth House, Sussex. Harriots reputation has alternately waxed (owing to excessive praise by John Wallis and Zach) and waned (as a result of criticism by J. E. Montucla and Rigaud). More recently, on the basis of comprehensive and penetrating studies of his surviving manuscripts, his name is becoming increasingly important.

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