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(*b*. Bedford [now Fulton] County, Pennsylvania, 29 January 1817; *d*. Maywood, Kansas, 18 September 1891)

mathematical geophysics.

After Laplace, Ferrel was the chief founder of the subject now known as geophysical fluid dynamics. He gave the first general formulation of the equations of motion for a body moving with respect to the rotating earth and drew from them the consequences for atmospheric and oceanic circulation. He contributed to meteorological and tidal theory and to the problem of "earth wobble" (changes in the axis and speed of the earth's rotation).

Born in remote south-central Pennsylvania, Ferrel was the eldest of six boys and two girls born to Benjamin Ferrel and his wife, whose maiden name was Miller. In 1829 the family moved across Maryland into what is now West Virginia, where Ferrel received the usual rudimentary education during a couple of winters in a one-room schoolhouse. A shy and solitary boy, he avidly devoured the few scientific books he acquired by arduous trips to Martinsburg, West Virginia, or Hagerstown, Maryland. Stimulated in 1832 by a partial solar eclipse, by 1835 he had taught himself, with only a crude almanac and a geography book as guides, to predict eclipses. Not until 1837, when he was twenty, did he learn "the law of gravitation, and that the moon and planets move in elliptic orbits."[1] With money saved from schoolteaching, in 1839 Ferrel entered Marshall College, Mercersburg, Pennsylvania (later merged with Franklin College in Lancaster), where he "saw [for] the first time a treatise on algebra."[2] Lack of money forced him to leave after two years of study, and he returned home to teach school for two years. He completed his degree in 1844 at the newly founded Bethany College in Bethany, West Virginia.

Ferrel then went west to teach school, first in Missouri and then in Kentucky. In Liberty, Missouri, he found a copy of Newton's *Principia* (presumably the Glasgow edition, with the 1740 tidal papers added), and later he sent to Philadelphia for a copy of Laplace's *Mécanique céleste* (in Bowditch's translation). In 1853, aged thirty-six, Ferrel wrote his first scientific paper. He moved to Nashville, Tennessee, the first city in which he had ever lived, in 1854, and there, while teaching school, he became an important contributor to the *Nashville Journal of Medicine and Surgery*. Through Benjamin Apthorp Gould, in whose *Astronomical Journal* he had published his first and some subsequent papers, Ferrel was offered his first scientific post, on the *American Nautical Almanac* staff. He remained with the *Almanac* in Cambridge, Massachusetts, from 1858 to 1867, when Benjamin Peirce of Harvard persuaded Ferrel to go to Washington to join the U.S. Coast Survey, of which Peirce was the new superintendent. In 1882 Ferrel joined the U.S. Army's Signal Service (predecessor of the Weather Bureau), where he remained until 1886. On his retirement at age seventy he moved to Kansas City, Kansas, to be with his brother Jacob and other relatives, but the lack of "scientific associations and access to scientific libraries"[3] in the West led him to return to Martinsburg, West Virginia, in 1889 and 1890. He died in Maywood, Kansas, at the age of seventy-four.

A painfully shy man, Ferrel never married, nor did he found a school in his subject. He did not apply for any of his scientific positions, yet he became a member of the National Academy of Sciences (1868), an associate fellow of the American Academy of Arts and Sciences, an honorary member of the meteorological societies of Austria, Britain, and Germany, and a recipient of the honorary degrees of A.M. and Ph.D.

Ferrel's career as a scientist began about 1850 with his study of Newton's *Principia*. Concentrating on tidal theory—in which Newton's work had been extended in papers presented to the French Academy in 1740 by Daniel Bernoulli, Euler, and Maclaurin and published in editions of the *Principia* after Newton's death—Ferrel conjectured "that the action of the moon and sun upon the tides must have a tendency to retard the earth's rotation on its axis."[4] In his *Mécanique céleste* Laplace had discounted any effect of the tides on the earth's rate of axial rotation. In his first published paper (1853) Ferrel showed that Laplace had neglected the second-order terms that should cause tidal retardation. Since Laplace had claimed to account for all the observed acceleration in the moon's orbit without tidal friction, Ferrel suggested that the latter might be counteracted by the earth's shrinking as it cooled. When about 1860 it became clear that Laplace's theory could not account for the observed value of the moon's acceleration, Ferrel returned to the problem in a paper read to the American Academy of Arts and Sciences in 1864. Although others reached the same general conclusion independently, Ferrel's was the first quantitative treatment of tidal friction, a problem that continues to be of scientific interest.

After three more papers published locally, Ferrel returned to tidal theory in 1856 with his second paper in Gould's *Astronomical Journal*. In it he suggested that Laplace was in error when he claimed that the diurnal tide would vanish in an ocean of uniform depth. Ferrel's criticisms were parallel to Airy's, and both were strongly opposed by Kelvin. The problem of "oscillations of the second kind" to which they relate remains of current scientific interest.

In both these early papers Ferrel established the basis of his contributions to the theory of tides. Laplace had ignored fluid friction, which was not successfully treated mathematically until Navier and Poisson in the 1820's and Saint-Venant and Stokes in the 1840's inaugurated the modern theory. In tidal studies Airy (1845) assumed friction to be proportional to the first power of the velocity, in which case (as in Laplace's) the equations are linear. Thomas Young (1823), although he assumed friction to be proportional to the square of the velocity, failed to introduce the required equation of continuity. Ferrel's major contribution to tidal theory was thus to begin the full nonlinear treatment necessitated by realistic assumptions concerning friction.

After joining the Coast Survey, Ferrel made important contributions to the techniques of tidal prediction. He extended the nonharmonic developments of the tide-producing potential beyond the points reached by Laplace and Lubbock, and he gave the first reasonably complete harmonic development. Here his endeavors were parallel to those of Kelvin, who was responsible for the first tide-predicting machine (probably the earliest piece of large-scale computing machinery). In 1880 Ferrel, too, designed a tide predictor, which went into service in 1883. Although it was an analogue machine like Kelvin's, Ferrel's gaye maxima and minima rather than a continuous curve as its output. Ferrel also made considerable progress in dealing with the shallow-water tidal components and in using tidal data to calculate the mass of the moon.

His studies of astronomical and geophysical tides established Ferrel's claim to a modest place in the history of science. His claim to a major place in this history lies elsewhere: He was the first to understand in mathematical detail the significance of the earth's rotation for the motion of bodies at its surface, and his application of this understanding to the motions of ocean and atmosphere opened a new epoch in meteorology. From Maury's *Physical Geography of the Sea* (1855) Ferrel learned of the belts of high pressure at 30° latitude and of low pressure at the equator and the poles. Looking for the cause of this distribution of pressure, Ferrel realized that since Laplace's tidal equations were of general application, both winds and currents must be deflected by the earth's rotation.

Pressed to write a critical review of Maury's book, Ferrel instead put his own ideas into "An Essay on the Winds and Currents of the Ocean" (*Nashville Journal*, October 1856), a precise but nonmathematical account of the general circulation, and on joining the *Nautical Almanac* staff he began to develop his ideas in mathematical form. In Gould's *Astronomical Journal* early in 1858 Ferrel made explicit the notion of an inertial circle of motion on the earth and used it to explain the gyratory nature of storms (although purely inertial motions are now known to be common in the ocean but almost absent from the atmosphere). In a series of papers published in his colleague J. D. Runkle's *Mathematical Monthly* in 1858 and 1859, then collected to form a separate pamphlet published in New York and London in 1860, Ferrel developed a general quantitative theory of relative motion on the earth's surface and applied it to winds and currents. His result, now known as Ferrel's law, was "that if a body is moving in any direction, there is a force, arising from the earth's rotation, which always deflects it to the right in the northern hemisphere, and to the left in the southern" (1858).[5] This theory and its derivation were carried to a wider audience by a summary article in the *American Journal of Science* for 1861.

Like others who treated relative motion and its geophysical consequences at about the same time, Ferrel appears to have been indebted to Foucault's pendulum (1851) and gyroscope (1852). Ferrel's treatment was remarkable for its clarity and generality, and by continuing to develop his ideas in a series of publications extending over thirty years, he pioneered in the development of meteorology from a descriptive science to a branch of mathematical physics.

When he began, meteorological thought was dominated by the unphysical ideas of Dove, who, drawing on Hadley's explanation of the trade winds (1735), insisted that the earth's rotation acted only on meridional atmospheric motions to deflect them only zonally. Although Ferrel agreed that temperature differences between equatorial and polar regions drove both atmosphere and ocean, he supported by mathematical deduction his insistence that all atmospheric motions, whatever their direction, were deflected by the earth's rotation. His application of this principle to explain both the general circulation and the rotary action of cyclonic storms began to be generally accepted in the 1870's, as weather forecasting services spread over Europe and North America. In his theory of the general circulation Ferrel developed the basic principle that on the rotating earth, convection between equator and pole must be chiefly by westerly winds. He gave the traditional three-cell diagram of the circulation, abandoned only since about 1950, as it has become clear that this scheme of an average circulation pattern along any meridian, although heuristically useful, is not supported by the data. Ferrel modified Espy's convection-condensation theory of cyclonic storms, and he gave a plausible account of the great force of tornadoes.

By 1880 meteorology seems to have caught up with Ferrel's ideas, and he was not always able to accept the advances of the following decade that built upon his innovations. The Ferrel-Espy convection-condensation theory explains tropical hurricanes but not midlatitude storms, yet about 1890 Ferrel argued vigorously against Hann's ideas on the latter type of storm. He was also unwilling to admit the role of wind stress in the generation of ocean currents. Yet Ferrel had led in bringing sound physical principles, expressed with the tools of mathematical analysis, to bear on the largest problems of oceanic and atmospheric motion: thus at his death he was called "the most eminent meteorologist and one of the most eminent scientific men that America has produced."[6] This eminence came to Ferrel for "having given to the science of meteorology a foundation in mechanics as solid as that which Newton laid for astronomy."[7]

NOTES

1. MS autobiography, printed with minor changes in *Biographical Memoirs. National Academy of Sciences*, **3** (1895), 291.

2.*Ibid*., 292.

3. Quoted from a letter of Ferrel by Frank Waldo in *American Meteorological Journal*, **8** (1891), 360.

4. Autobiography, 294.

5. "The Influence of the Earth's Rotation Upon the Relative Motion of Bodies Near Its Surface," in *Astronomical Journal*, **5** (1858), 99.

6. W. M. Davis, *American Meteorological Journal*, **8** (1891), 359.

7. Cleveland Abbe, *Biographical Memoirs. National Academy of Sciences*, **3** (1895), 281.

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I. Original Works. Ferrel's most significant paper, "The Motions of Fluids and Solids Relative to the Earth's. Surface," appeared originally in *Mathematical Monthly*, **1** and **2** (Jan. 1859-Aug. 1860) and was republished with notes by Waldo as Professional Papers of the U.S. Signal Service, no. 8 (Washington, D.C., 1882). Other papers on meteorology, including his 1856 "Essay on the Winds and Currents of the Ocean," were reprinted as no. 12 of the same series (Washington, D.C., 1882). Ferrel also wrote three treatises: "Meteorological Researches for the Use of the Coast Pilot," published in three pts. as appendixes to *Report of the Superintendent of the U.S. Coast Survey for 1875* (Washington, D.C., 1878), *1878* (Washington, D.C., 1881), and *1881* (Washington, D.C., 1883); "Recent Advances in Meteorology," published as app. 71 to *Report of the Chief Signal Officer to the Secretary of War for 1885* (Washington, D.C., 1886), as Professional Papers of the Signal Service, no. 17, and as House Executive Document no. 1, pt. 2, 49th Congress, 1st session; *A Popular Treatise on the Winds* (New York, 1889). Ferrel's major work on tides is his *Tidal Researches*, appended to the *Coast Survey Report for 1874* (Washington, D.C., 1874); and he described his tide predictor in app. 10 to the *Coast Survey Report for 1883* (Washington, D.C., 1884). Ferrel's bibliography, in *Biographical Memoirs. National Academy of Sciences*, **3** (1895), 300–309, lists more than 100 items; it is preceded (287–299) by an edited version of his autobiography, the holograph MS of which is in the Harvard College Library.

II. Secondary Literature. Cleveland Abbe's memoir, in *Biographical Memoirs. National Academy of Sciences*, **3** (1895), 267–286, is the fullest; more concise is William M. Davis' in *Proceedings of the American Academy of Arts and Sciences*, **28** (1893), 388–393. Alexander McAdie wrote a biographical article, accompanied by a portrait, in *American Meteorological Journal*, **4** (1888), 441–449; memorial articles by Simon Newcomb, Abbe, Davis, Waldo, and others are *ibid*., **8** (1891), 337–369. K. Schneider-Carius, *Wetterkunde. Wetterforschung* (Freiburg, 1955), a sourcebook in the Orbis Academicus series, is useful on the history of meteorology. Among the older works, Frank Waldo, *Modern Meteorology* (London, 1893), in the Contemporary Science Series, gives—if anything—too much attention to Ferrel. Ferrel's place in the history of tidal theory is easier to assess, thanks to Rollin A. Harris, *Manual of Tides—Part I*, app. 8 to *Coast Survey Report for 1897* (Washington, D.C., 1898); pp. 455–462 of this excellent history are devoted to Ferrel.

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