

EDMOND HALLEY, GEOPHYSICIST

Famous for the comet that bears his name and for his efforts in getting Newton's *Principia* published, Halley was a founding father of geophysics holding a special interest in geomagnetism.

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The recent passage of Comet Halley produced a great deal of scientific activity as well as the usual plethora of books, articles and diverse paraphernalia. So why add more? My excuse is that although Edmond Halley is famous for his comet—and rightly so—his contributions to scientific knowledge were much wider than is generally appreciated. Indeed, cometary matters represent a very small fraction of his work. Even if he had made none of his astronomical and other contributions, however, Halley would have left us an important legacy as one of the world's first geophysicists.

True enough, celestial problems were never far from his thoughts and he made fundamental and wide-ranging contributions to astronomy, but he had something interesting and original to say on topics ranging from ancient Greek mathematics to deep-sea diving equipment. In 1691 alone, for example, he published¹ articles on the distance to the Sun, the behavior of water vapor in the atmosphere, the mathematics of infinite quantities, the thickness of gold plating, Julius Caesar's landing in Britain and Pliny's *Historia Naturalis*. He was 35 at the time, and he carried on like this for another half century! Small wonder, then, that he came to be known as the "second most illustrious of Anglo-Saxon philosophers"²—being, as he was, a contemporary of the great genius Isaac Newton. (See the box on page 45.)

Of the various aspects of planetary science that attracted Halley's attention, the Earth's magnetic field seems to have been his first love. While still a teenager, he

made observations of Earth's "magnetic variation"—the difference in angle between geographic and geomagnetic north, nowadays called the declination. In his final portrait, now displayed at the Royal Society in London, and painted when he was 80, we see him holding a sketch of the Earth representing his theory of the origin of the magnetic field.

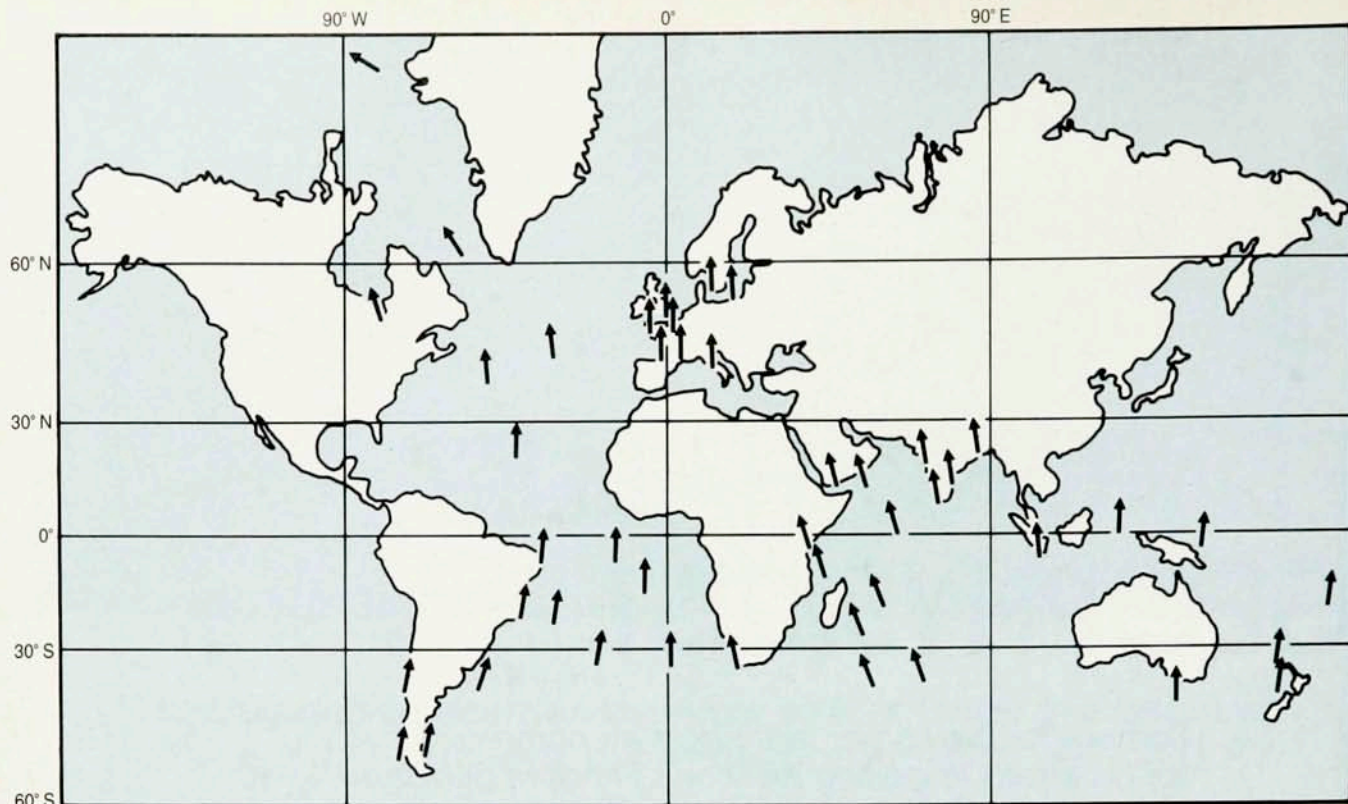
Mapping Earth's magnetic pattern

In Halley's first formal paper³ concerning the geomagnetic field, which was published in 1683, when he was 27, he managed to gather together 55 determinations of the declination, just enough to enable him to discern a global magnetic pattern. Of course, the directional properties of the compass had been used for navigational purposes for centuries. Indeed it was from navigators' logs that Halley gleaned much of his information. That directions to true north and magnetic north are not parallel was known in Europe in the early 15th century, although accurate determinations were not made for another hundred years. In China precise measurements had been made for centuries, the earliest recorded⁴ being that of the astronomer I-Hsing, about 720 AD.

The first really scientific theory of the origin of the Earth's magnetism was put forward in 1600 AD by William Gilbert,⁵ physician to Elizabeth I of England. He thought that the planet was permanently magnetized, like a lodestone, with two diametrically opposed poles situated at the geographic poles. So far as practically minded men contemplated an underlying theoretical model, this idea became the basis of magnetic navigation.

Because Gilbert supposed the solid parts of the Earth to be magnetic, he thought that in coastal waters the compass should be deflected toward an adjacent land

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Deviation of the compass. Arrows show the deviation from true north at 46 localities around the globe based on Edmond Halley's 1683 data.³ Halley compiled 55 values of the angle (then referred to as the "variation," nowadays called the "declination"), but several places were represented by more than one reading. To explain the observed pattern, he suggested that the Earth has four magnetic poles located at approximately 83° N, 6° W; 75° N, 119° W; 74° S, 90° W; and 70° S, 120° E.

mass. Halley pointed out that there were several instances in his compilation where this was not true, "but most remarkably upon the coast of Brazil," where the needle "turns quite the contrary way." Halley also pointed out that "not long since" a certain "Mr. Bond, an old teacher of navigation," had put forward a modification of Gilbert's model consisting of a magnetic dipole whose axis diverged from the Earth's spin axis. Halley quickly dismissed this suggestion by pointing out that sites on the same longitude meridian should have declinations in the same sense, whereas the actual data provided counterexamples. The most prominent of these is a comparison between declinations at "Hudsons Straights and the mouth of the River Plate," which are about on the same meridian and yet "at one place the needle varies 29½ degrees to the West, at the other, 20½ degrees to the East."

Halley proposed that the global declination pattern implied four poles. The figure above shows his data plotted on a map. Diverging arrows point away from north poles, converging ones toward south poles. Despite the paucity of data—of which Halley himself was fully aware—he inferred the approximate locations of his proposed four poles. These he designated as:

▷ The European North Pole, lying "near the Meridian of the Lands end of England and not above 7 degrees from the Pole Arctick"—that, is about 83° N, 6° W

▷ The American North Pole, situated "in a meridian passing about the middle of California, and about 15 degrees from the North Pole of the World"—75° N, 119° W

▷ The American South Pole, "about sixteen degrees" from "the South Pole of the World" and "some twenty degrees to the Westward of Magellans Straights"—74° S, 90° W

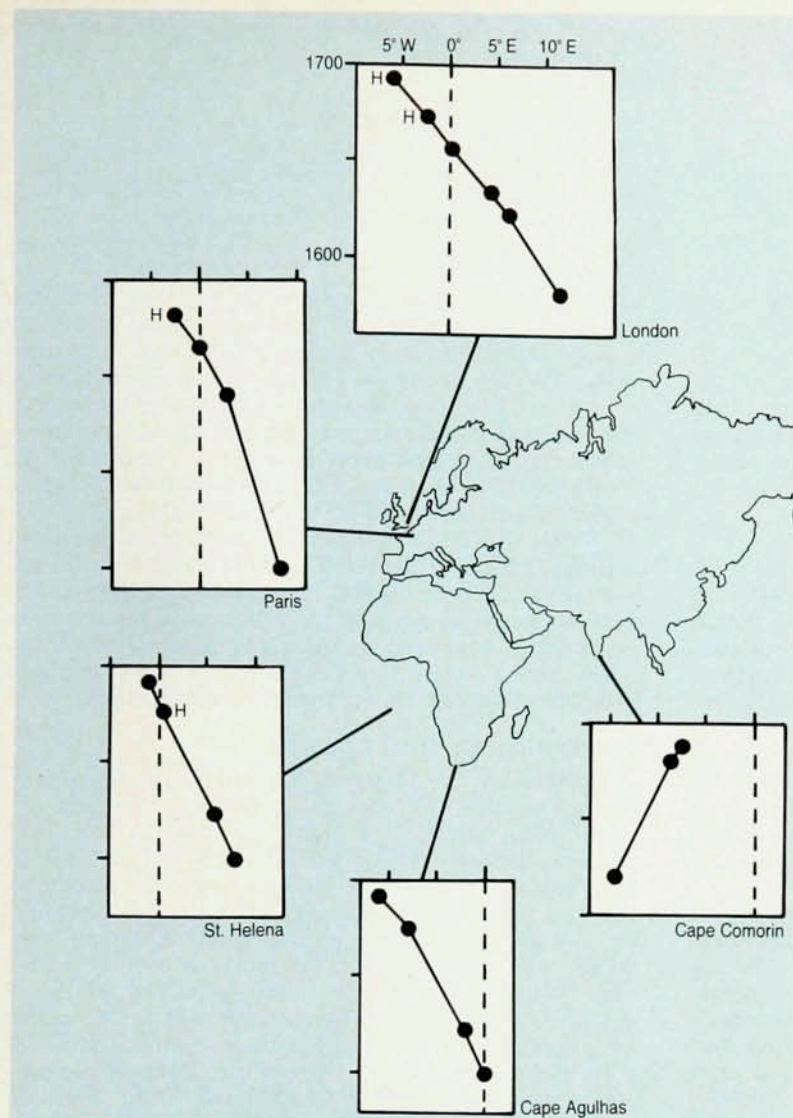
▷ The Asian South Pole, "being little less than 20 degrees distant" from the Earth's spin axis and "in a Meridian which passes through Hollandia Nova and the Island Celebes"—70° S, 120° E.

Cognizant of the complementary roles played by empirical observation and underlying fundamental theory, Halley stressed the need for additional data and for a proper understanding of the decrease with distance of the attractive power of a magnet. But it is remarkable that after centuries of effort, culminating in the recent magnetic satellite mapping project called MAGSAT, Halley's suggestion of four poles still has a great deal of merit.

In a recent paper, Jeremy Bloxham and David Gubbins (University of Cambridge) report a technique for extrapolating surface and satellite observations downward to the surface of the Earth's core.⁶ They find evidence for what they term "static flux bundles"—permanent regions of intense flux emerging from the core. They find not just two flux bundles, with one at each pole, as expected for a dipole field, but four. Admittedly, these are not precisely where Halley located his four poles, but considering the limitations under which he was working, the similarity is very striking.

Wandering poles

In addition to the spatial morphology of the geomagnetic field, Halley tackled the problem of the field's temporal behavior. That the declination varies with time had been recognized some 50 years earlier by a London astronomy professor, Henry Gellibrand, but the observed changes were very slow and Halley wrote, in an article published in 1683, "that it will require some hundreds of years to establish a compleat doctrine of the Magnetical System."



Temporal changes in magnetic declination—the difference in angle between magnetic and geographic north—as observed at five sites. Data are from Halley's 1692 paper.⁷ Halley's own observational data are indicated by "H." The top of each graph represents the year 1700. The vertical dashed lines correspond to a "true" (zero declination) compass reading.

Nevertheless, it was in this article that he planted the seed that was to bear fruit almost a decade later when he next broached the subject.

A century earlier, in October 1580, William Borough had recorded the declination at London as 11° 15' east of north, but in June 1622 Edmund Gunter recorded it as only 6° 0' east. Gunter noted the difference in values, but attributed it to inaccuracy of the earlier work. However, a decade or so later, Gellibrand found that the declination had continued to diminish, and by June 1634 it had decreased to 4° 5' east. Convinced of the reality of this change, Gellibrand announced the discovery of what is nowadays called the "secular variation."

It is an unfortunate historical fact that the word "variation" was originally used for the declination, which is a spatial quantity, whereas nowadays the term is used for slow temporal changes in the magnetic field. This usage must be borne in mind when reading older manuscripts.

As we have seen, Halley was already thinking about the problem of the secular variation of declination when he published his 1683 article. In 1692 he published a paper in which he summarized the available data germane to these changes of the compass, and proposed a bold hypothesis to explain them.⁷ For the declination of London he quoted the observation of Bond, who had found

a value of 0° in 1657, 23 years after Gellibrand's announcement, and then went on to say: "1672. my self observed it 2° 30' to the West; and this present year 1692 I again found it 6° 00' West. So that in 112 years the direction of the Needle has changed no less than 17 degrees."

Realizing the global nature of the magnetic field, Halley took care to include other examples. These illustrated measurable secular variation at sites ranging from western Europe through the south Atlantic to India. (See the figure above.) But different signatures were seen at different sites. Although the declination in the eastern Atlantic became steadily more westerly throughout the 17th century, in India it became more easterly. From the limited data available in 1683, Halley had already suggested—albeit tentatively—that his proposed four poles were moving to the west.

One can easily follow Halley's argument if one imagines the effect in London, for example, of his European North Pole. To produce the easterly declination observed by Borough in 1580, this pole would have to have been situated well to the east of London. By 1657 it was due north of London, resulting in 0° declination, and by 1692, from Halley's own results, it lay to the west. Similar reasoning holds for the other examples, including the data from India. There, between 1620 and 1688, the declination

changed by about 7° toward the east, which is in accord with a westerly motion of the so-called Asian South Pole.

Thus was born the idea of a westward drift, a seminal concept that has remained almost as fixed in the geophysical mind as that of circular planetary orbits did in the astronomical mind. But geophysics still awaits its Kepler. In fact, the geomagnetic field remains poorly understood, and the secular variation in particular has turned out to be a very difficult problem.

The internal Earth

Halley, however, thought he had solved the problem by combining his earlier idea of four magnetic poles with a new proposal for the internal structure of the Earth. Noting that no magnet he had ever seen or heard of possessed more than two poles, he argued that the Earth had two solid parts, each of which carried a pair of poles. These he took to be an external "shell" and a concentric inner "nucleus," separated by a suitable fluid enabling relative motion between them. Modern seismology demonstrates that the Earth does indeed have a liquid layer—the outer core—sandwiched between a solid shell (the combined mantle and crust) and a solid inner core.

By reference to the little data he had, Halley proposed that the European North Pole and the American South Pole were attached to the inner nucleus, with the American North Pole and Asian South Pole consequently residing in the shell. Then to obtain a westward drift he simply supposed that, although the nucleus and the shell rotated about the same axis, the nucleus rotated more slowly. He explained this by having the outer shell receive the original impulse responsible for the daily rotation; this impulse was gradually transmitted to the nucleus via the intervening fluid—the solid inner body simply hadn't caught up yet. The shortfall seemed to imply a period of about 700 years for the nucleus to fall one complete revolution behind the shell. In view of such a long time scale he urged all "Lovers of natural Truths" to continue to observe the phenomenon so that a complete theory might be forthcoming.

It is fascinating to the modern reader to see how, after several pages of closely argued scientific deduction, Halley could have devoted the second half of the 1692 article to a discussion of the utility of such an inner nucleus. Taken at face value, this appears to be a striking example of medieval prejudice muddying the waters of rational insight—the last vestiges of teleological necessity. At the time Halley was in trouble with clerical authorities and had just been turned down as Savilian Professor of Astronomy at Oxford on account of his supposed heresy. Apparently it was felt that he held the view that the Earth was eternal, which, of course, would preclude any act of divine creation. It seems that he was indeed interrogated, but although he defended himself vigorously, the appointment eluded him.

In any event, I can't escape the feeling that, smarting from this blow, he took the opportunity of endowing his new model of the Earth with properties enhancing the glory of the Creator. Thus he describes how this inner world may have been provided "by the Almighty Wisdom

as to yield as great a Surface for the use of Living Creatures." In fact, he goes on to suggest that there may be several concentric shells—a sort of global apartment block. To what extent he had his tongue in his cheek is hard to say, but he no doubt had in mind that these extra shells might come in very handy if, and when, new data required a more complex model of the geomagnetic field. With a pair of poles on each shell, his model was capable of infinite adjustment—and all to the glory of God.

This digression is speculative, but it is interesting to note that when the Savilian Chair of Geometry at Oxford became vacant some 12 years later, Halley got the job. But by then he was 48 years old, and his reputation had been considerably enhanced by his achievements in the intervening years. Again these range over a wide variety of topics, but foremost among them is geomagnetism.

Contour maps and auroras

In 1698 Halley took charge of the first ocean voyage to be planned expressly for scientific purposes, serving not only as the chief scientist on board, but also as the ship's captain. Between 20 October 1698 and 10 October 1701 the *Paramore* made three voyages under his command, two into the Atlantic and one in the English Channel.⁸ For the Atlantic voyages he was charged, among other things, with penetrating as far south as possible with a view toward determining in more detail the pattern of magnetic declinations. The outcome was an enormous achievement in terms of enquiry into and understanding of our global environment: Armed with 200 new measurements spread over 100° in latitude and 70° in longitude, and seeking a method of representing them in a readily intelligible form, he invented the contour map.

This technique is now so commonplace that it is taken for granted—think, for example, of the isobars on the daily weather map—but as a creative act, it rivals in importance Faraday's lines of force, which were to prove so important to the development of electromagnetism more than a century later.

Halley's Atlantic chart shows these lines of equal declination, which for many years were called "Halleyan Lines," but which are now blandly labeled "isogonic lines." Apart from their purely scientific significance, these charts were of considerable importance for navigation and were in demand for at least 50 years after their first appearance (probably in 1701). Indeed, Halley lost no time in extending their scope by incorporating data from the Indian Ocean and the Far East into a so-called World Chart, published about a year later.

It was felt at the time that isogonic lines not only would enable navigators to allow for the offset of the compass, but might actually provide a solution to the longstanding problem of longitude determination at sea. If a ship happened to lie in a region where the isogonic lines ran roughly north-south, then a determination of declination could provide a longitude fix. In the days before John Harrison built the first reliable marine chronometers, this was of immeasurable value to naval and mercantile shipping.

Shortly after the completion of the English Channel

Biographical Sketch of Edmond Halley

Edmond Halley was born on 29 October 1656 in what is now north London. He was the son of a wealthy merchant and was sent to the famous school St. Paul's for his early education. He excelled in all branches of classical learning, but soon developed a deep interest in astronomy and related sciences.

Before leaving school, he made his own determination of the magnetic declination. In July 1673 he entered Oxford University and soon made important theoretical and observational contributions to astronomy. At the age of 18 he began a significant correspondence with the Astronomer Royal, John Flamsteed, and by 1676 had published his first scientific paper in the *Philosophical Transactions of the Royal Society*. Later that year Halley voluntarily left Oxford before graduating, to seize the opportunity to take part in an expedition to St. Helena to chart the southern skies. Upon his return, two years later, he presented the results to the Royal Society and was elected a fellow. In 1683 he published his theory of the Earth's magnetic field, a topic that had attracted him as a youth and that continued to do so throughout his long and productive scientific career.

Apart from his own researches, he played a key role in persuading Isaac Newton to publish the *Principia*, providing

both money and his own editorial services to see it through the presses. Halley's second paper on terrestrial magnetism appeared in 1692, but he continued to study a wide variety of astronomical and mathematical topics. The most memorable of these is of course his work on cometary orbits, which eventually led to his remarkably accurate prediction of the return of the comet that now bears his name.

Between 1699 and 1701 Halley was the central figure in the first oceanic voyages undertaken purely for scientific purposes. In these he was the ship's captain as well as the chief scientist on board. Shortly after his return he published a map of the geographical variation of the magnetic declination, which was a seminal contribution not only for its geophysical content, but also because of his invention of the contour map.

In 1704, at the age of 48, he was appointed Savilian Professor of Geometry at Oxford, and in 1720 he succeeded Flamsteed as Astronomer Royal. Despite his many duties, he remained active in research, publishing his final paper on magnetism in 1732, and his final scientific paper (on a lunar eclipse) in 1737 at the age of 81. He continued observing at Greenwich until the last few months of his life. He died 14 January 1742.

survey, Halley resigned from the Navy and plunged back into the scientific mainstream in characteristic fashion. As far as the magnetic field was concerned, his interest continued unabated. Of course, he was heavily involved with the preparation and subsequent revisions of the isogonic charts. To this end he kept in touch with new data as they became available, publishing his final paper on the subject in 1732, when he was well into his seventies.

Halley made yet another highly original contribution to geomagnetism. On 6 March 1716 there occurred an outstanding display of the aurora borealis, plainly visible in the night sky over London. He observed it in great detail; he also took pains to gather and collate other eyewitness accounts from around the country, all of which he brought together in a lengthy article published later that year.⁹ In itself, this would have been an important step forward in a subject shrouded in mystery and superstition. But he went much further, actually proposing an underlying physical mechanism.

The keystone of Halley's hypothesis was a connection between the aurora and the geomagnetic field. This was a brilliant stroke, not only because the data at hand were so few, but also because it turns out to be correct! We now know that there is indeed an intimate connection between the trajectories of the electrically charged particles responsible for auroral displays and the morphology of the Earth's magnetic field. Of course, he didn't get everything right. Whereas we now know that these particles are injected into the near-Earth environment from the solar wind, Halley suggested that they originated inside the Earth and streamed outward. No prizes for guessing their source: Where else but the fluid layer between the outer shell and the inner nucleus? This might strike the modern reader as comical, but one should not forget that to the 17th-century mind the existence of pervasive, imponderable fluids of this kind was very much the order of the day.

More than a comet's tail

Personal bias, and the need to avoid producing just a long list of Halley's achievements, has limited my article to a discussion of his geomagnetic work. But how does one adequately assess such a long and productive life of application and insight? Certainly to remember him only

for his comet is unjust.

Perhaps, as Colin Ronan suggests in his biography,¹⁰ "father of modern geophysics" is a more appropriate accolade for Halley. Perhaps we should emphasize his contributions as Astronomer Royal for more than 20 years; or perhaps we should recall that despite being overshadowed by Newton, he was no dog in the manger—in fact, it was Halley who coaxed the reluctant Newton to write the *Principia*, putting up the money and personally seeing it through the press.

But to me, the most endearing thing about Halley was not the way he lived, but the way he died. Although he seems to have suffered a minor stroke, apparently his memory and judgment remained unimpaired to the last. In the end he called for a glass of wine "and having drunk it presently expired as he sat in his chair without a groan."¹¹ Oh, happy man!

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