William Gilbert's

Investigation of Magnetism

GILBERT

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Preface

What image does the word "Magnet" evoke? To many, perhaps most, it is of some unusual and peculiar ferriginous object (shaped like a horse-shoe?) which attracts bits of iron. If this is your picture, then it is the same as would have occurred to the poets and philosophers of Ancient Greece, and to their successors for nearly 2000 years: Magnetism as a mysterious, isolated, occult phenomenon: akin to magic.

But as viewed by physical science today, magnetism is an ubiquitous phenomenon; a property of all matter. It comes in all sizes and shapes from the sub-atomic to the cosmic. There is magnetism associated with all the elementary particles, with electrons, neutrons, protons, etc., with atoms and molecules, with rocks and crystals, with the whole earth and its environment, with the sun, the stars, and indeed all the heavenly bodies and even the sparse, diffuse matter that occupies the "spáce" between them. By the study of their magnetism we have learned, and continue to learn, something important about physical systems of every variety; the structure of atomic nuclei and the particles of which it is composed; the organization of atoms and molecules in macroscopic matter -- both living and dead; the history and origin of the earth's surface, and the goings on at the surface to sun; the explosions of supernovae and, by inference, the incredibly intense magnetism of the last heavenly spectacular: the rhythmically beating pulsars!

Human artifacts now exploit magnetism as extensively as nature exhibits it . It is present in every aspect of electrical technology, in power, gernerators, motors, telephone, radio and all its variations, computors, etc.; from door-catches to hydroelectricity. We can even use magnetic measurements in the archeological study of the artifacts of the past!

Some 800 or 900 years ago magnetism broke out of the classical frame which had for so long contained it. The first great impetus came from the paramount significance of the magnetic (compass) needle for navigation; the second, in the nineteenth century from the development of electrical technology.

Our contemporary knowledge is the result of labors of many: philosophers, geometers, astronomers, navigators, mariners, explorers, sailors -- military and civil, and their patrons; from instrument makers, engineers, physicians and friars; and more recently from physicists, chemists, geologists, meteorologists, and astrophysicists.

Our interest here centers in the work of one famous pioneer of magnetism: William Gilbert. It implies no belittlement of the work of others that we single out his monumental work:-- De Magnete, as a milestone in the history of magnetism, and treat other matters largely as providing a context for its appreciation.

William Gilbert's Investigation of Magnetism

Synopsis

William Gilbert (1540-1603), physician to Queen Elizabeth I of England, published in 1600, his major work De Magnete, the first comprehensive, systematic, and in the modern sense scientific, account of magnetic phenomena.

Based essentially on experiment, Gilbert's is the first "rational" interpretation of the Earth's magnetism and the action of the Mariner's compass, in terms of observed and measured properties of loadstones and artificial magnets. Not only is De Magnete the first definitive treatise on magnetism, it is probably the first account of systematic experimentation of the kind that now is commonly associated with physical science. More than 200 years after it was written it was described as "one of the finest examples of inductive philosophy that has ever been presented to the world". De Magnete was published some 30 years before Galileo's Two New Sciences and more than 80 years before Newton's Principia.

It is difficult to give a short account of the scope and historical context of Gilbert's work: De Magnete itself presents a superb picture to which no précis can do justice. These notes are intended to provide a few glimpses of the historical background to Gilbert's work, to highlight some of his most important contributions, and to indicate how, in retrospect, this contribution can be appraised.

Some of Gilbert's most significant experiments are reproduced, and the inferences drawn from them are examined in the light of contemporaneous and later understanding of magnetic phenomena.

It may be more profitable to perform some of the experiments -- as detailed in Part II -- before reading later sections (3 to 6) of Part I. In any event much of this is commentary which is intended to be read in conjunction with De Magnete. Particular sections of this relating directly to the experiments are indicated in Part II and are reproduced in Section 7.

Note Regarding Terminology

Not surprisingly in the course of some 400 years, the language and vocabulary of science has changed greatly. Not only have many archaic terms been discarded in favor of later ones; but -- and this is a trickier matter -- where old words and phrases persist it is often with a more formal and precise meaning and sometimes with a quite different connotation. Moreover most scientific writings, in the period of interest here, were originally in Latin. If, as is often the case, and English translation is made much later, it is not easy to interpret a particular Latin phrase without being influenced in some small measure by all the subsequent knowledge of the subject. Very little hindsight can impart to any ambiguity a great deal of prescience!

The definitions below supplement the glossary given in the preface to De Magnete (pp. liii, liv); reproduced in the appendix.

Poles Terrestial-Astronomical -- Intersection of earth's axis of diurnal rotation with a sphere centered at the center of the Earth -- particularly the surface of the earth.

Magnetic - For an ideal terrella -- Points (on surface) at which magnetic "force" is directed directly to the center.

- For a long magnet -- Points (near the ends) toward which magnetic forces appear to converge.

Axis of the Earth -- Axis of diurnal rotation.

of an ideal terrella -- Line through the two poles. Axis of symmetry.

Equinoctial Circle of the Earth -- Equator

of an ideal terrella -- Intersection of the sphere with the mid-plane perpendicular to the magnetic axis.

Meridian (0-180 W or E) of the Earth -- Line of longitude. The great circle passing the point and the poles

of an ideal terrella -- The great circle passing through the point and the magnetic poles.

Parallel (0-90 N or S) of Earth -- Line of latitude; circle through point parallel to the equator.

of an ideal terrella -- Circle through point parallel to magnetic equator.

Horizon Terrestial or Magnetic -- A circle of indefinite radius, centered at the point and lying in the plane tangent to the sphere there.

Cynosura (cynosure) -- Constellation of the Lesser Bear (Ursa Minor) -- containing the pole star.

Variation, Declination or Deviation--Currently known as Declination. The angle (to W or to E) between the actual direction of a compass needle (moving in the horizontal or tangent plane) and the true meridian at the point.

Dip or Inclination -- Currently known as Inclination. The angle made by a magnetic dip needle (freely moving in the plane of the magnetic meridian) and the line from the point to the center of the earth.

Isogonic Lines -- Lines on the Earth's surface connecting points having the same declination (variation).

Isoclinic Lines -- Lines on Earth's surface connecting points having the same Inclination (Dip).

[Note: To specify any point on the earth's surface two coordinates are required (e.g. longitude and latitude). To specify the magnetic field, (a vector) three quantities are required: two angles (e.g. declination and inclination) for direction; and one "absolute" magnitude. -- e.g. of the horizontal component along the meridian. Following Gilbert, we shall be concerned primarily with the angles.]

I. The Loadstone and the Mariner's Compass

In the frequent debates that arose in the early Renaissance period over the relative superiority of "ancient" (classical) and "modern" (post-medieval) knowledge three achievements were repeatedly cited as evidence of the latter's superiority: Gunpowder, the Printing Press, and the Mariner's Compass. (The sixteenth century's equivalents of the Atom Bomb, T.V., and the Jet?) War, the propagation of new ideas, exploration and commerce -- these were some of the major preoccupations of the period; and it is not surprising to find that techniques indispensible to their practice stimulated, not only technical development, but also philosophical speculation; and then, together, became later scientific enquiry.

The magnetic compass, in particular, and its progenitor, the "loadstone" attracted the attentions of people with the widest range of interests. As a manifestation of some mysterious, "occult" force it had its fascination for the scholar, the philosopher and even the theologian (in so far as scholarship, philosophy and theology were distinct activities); as a human artifact with obvious practical importance, it commanded the attention of the craftsman, soldier, navigator, and statesman; as a natural phenomenon and an exemplification of the subtlety of Nature, it was of inevitable attraction to the growing body of Geometers and Natural Philosophers. With this many sided appeal, from the occult to the practical, it is not hard to understand why magnetism was already of much interest in the late medieval period. In addition to the reiteration and elaboration of the numerous, scattered, classical speculations; extensive writings on magnetism issue in a steady stream from the 13th century onwards. These range from Mariner's records to abstract Cosmology; but they all reveal, with rare exception, only the most tenuous interaction between theory and practice. What changes dramatically towards the end of the sixteenth century, is not so much the subject of interest as the method of investigation. There are one or two exceptional works which presage this nascent change; but Gilbert's work is the great milestone in this development. Its interest extends far beyond its subject of immediate concern: Magnetism. It provides a fascinating picture of the rapid flowering of experimental science after several centuries of budding but fitful starts. With Gilbert, the experimental method is still an innovation, whose virtues he is assiduously preaching and whose power he is demonstrating. Only a few decades later it becomes not only practiced widely, but self-consciously advocated and supported by a society which has embarked on the exploration of both the Terrestial Earth and the workings of Nature.

Although the Mariner's Compass only became known, or at least of significance in the Western World after the 12th, or 13th, century. the history of magnetism itself is very much older. It is customary to look for (and find) clues to the origin of most early artifacts and techniques in ancient China: magnetism is no exception. It has been suggested that the directive properties of loadstone were known to the Chinese in the 2nd and 3rd millenium B.C.: the "chariot of the south", which is mentioned in some of the earliest writings, has been interpreted as indicating exploitation of some such principle. According to

> . . . the mythological history of China . . . gathered from the literature of more recent times . . . . . in 2634 B.C. the Chinese Emperor Hoang-Ti was at war with a tributary prince named Tchi-Yeou and they fought a great battle in the plain of Tcho-luo. In order to escape defeat, or its consequences, Tchi-Yeou raised a dense fog which produced disorder in the imperial army -- an anticipation of the smoke-screen of modern times. But Hoang-Ti constructed a chariot upon which stood the dimunitive figure of a man with arm outstretched, and this figure being apparently free to revolve on its vertical axis, the arm always pointed to the South. By this means the emperor was able to locate the direction of the enemy's retreat; Tchi-Yeou was captured and put to death. (Ref. 1)

The inference that this was a magnetically operated device was, apparently, first made by Jesuit missionaries who first went to China in the latter part of the 17th century -- at which time the compass needle was, of course, well known in the west!

Somewhat more substantial evidence of knowledge of magnetic directive properties relates to the development of a sort of "roulette wheel as used by the Chinese geomancer (a cross between a surveyor and a fortune teller). Whether by accident or design, pivoted needles rubbed by magnetic stones (or spinning spoons fabricated from magnetite itself -- which might have been chosen originally for its decorative value) had come into use by about the 10th century A.D. A geomancer privy to their mode of operation could obviously exploit this knowledge to enhance his apparent prophetic powers. Sometime around the 11/12th century this geomancer's art was, apparently, utilized in navigation and surveying.

Whatever the extent of this oriental knowledge and application of magnetism, and whether or not this eventually percolated to the West, there is no doubt that the elementary, but mysterious properties of the loadstone were well-known in classical antiquity, from Homer to Pliny and St. Augustine. The stone's attractive powers are referred to by Thales, Pythagoras, Socrates, Plato, Aristotle, Theophrastus, and in the writings of Epicurians, in particular Lucretius (c. 60 B.C.). The name "magnet" (Μάγνης, or Ηρακλειος, --lapis Heraclius) is usually attributed to the common occurence of loadstones in the mountains of Magnesia, (Lydia, Asia Minor; capital: Heraclius), which rise behind what was the Ionian region on the borders of the Eastern Aegean.

Socrates (in Plato's dialogue; Ion) remarks that loadstone "not only attract iron rings, but imparts to them a similar power of attracting other rings. . ." Lucretius (De Rerum Natura) describes the phenomena vividly:

> I have even seen some rings from Samothrace dancing, and iron filings in a brazen bowl jump about when the Magnet-stone was placed beneath them. So eager was the iron to escape . . .

There is some ambiguity as to whether the Greeks were familiar with the directive property of loadstone. It is all too easy to read into classical writings hints of some familiarity with what is now a simple and commonplace phenomena. (cf. Sec. 7, pp. 4-7.) But whether they possessed this "secret" or not, there is little doubt that they made scant use of it, if any at all. Nor apparently did they make any deliberate or significant "experimental" investigations to probe its nature. The Greeks were apparently content to be fascinated and occasionally to speculate -- widely and wildly -- on this mystery, whether material or divine. It was not to be ignored in a comprehensive philosophy of Nature, such as the Epicurian; but it probably appeared too trifling and earthy to warrant sustained intellectual attention, or too singular and subtle to form a bassis for such a philosophy.

From the time of Pliny (A.D. 23-79), (who compiled, somewhat indiscriminately, in his "Natural History" the whole legacy of Greek scientific ideas, experience, practice, theories, together with much traditional gossip and hearsay, but added practically nothing new of his own except misinterpretation and error) right through the 12th century there is no record of any major advance in knowledge of the subject. What does grow profusely is the "literature". The few original, basic, honest facts become smothered and corrupted by a rank overgrowth of myth and magic, superstition, legend, and old-wives tales -- crude and naive hearsay passed on from one writer to another, and often passed off as the truth to a gullible and credulous audience; . . . by

> men who have taken the oaths to follow the opinion of others, -- the most senseless corrupters of the arts, -- lettered clowns, grammatists, sophists, spouters, ...Who go a-fishing among the inexperienced and the young for a reputation; who seem to transmit from hand to hand, as it were erroneous teachings in every science and out of their own store now and again to add somewhat of error. (De Magnete, pp. xlix, 15)

. . . .

A thousand years after Lucretius, some new facts about magnetism and new, much more practical interest in the subject begins to emerge, this time in Western Europe, and it comes not from philosophers so much as from practical men -- from ocean-going sailors and explorers. It has been suggested that about this time some knowledge of magnetism and the compass was transmitted from China to the West via the Arabs and the Franks. That this was the time of the Crusades adds plausibility to the hypothesis, but in any event the major development in Western Europe is an essentially independent affair. An Icelandic historian (Are Frode) 1100 A.D. writing about the exploration of Iceland in 868 writes that "... in those times, seamen had no loadstone in northern countries", implying a willingness to believe that even at this early date

-- the Crusades had scarce begun -- that superior knowledge of magnetism existed in faraway places, but had not reached Northern Europe! By the 11th and 12th centuries there were frequent references to loadstones and magnetic needles in navigational reports from many parts of Europe. It also began to be realized at this time that the magnetic needle did not align itself in the precise North-South direction. At first this was probably attributed to some imperfection in its fabrication or use: later, with experience accumulated in a century or two of use, this "deviation" was recognized as fundamental.

One of the earliest references is in the works of Alexander Neckam (a monk of St. Albans, 1157-1217), who towards the end of the 12th century, describes the magnetic needle as being placed on a pivot, and used by mariners to find their course when the sky is covered. A little later (c. 1206) the poet Guyot de Provins refers to the floating compass used by navigators.

In 1269 a most remarkable document was written by one Peter Peregrinus of Maricourt, a contemporary and pupil of Roger Bacon. The circumstances were scarcely less remarkable than the contents. The writer was a soldier, in a military camp under seige, writing to a friend --"Epistola Peter Peregrinus de Maricourt ad Sygernum de Fontencourt Militium de Magnete". This document is the direct progenitor of Gilbert's work, and is undoubtedly the source of much of his inspiration. It is unique -- in the 13th century -- as practical, comprehensive, experimental analysis of a "philosophical" problem; and its author possesses the extremely rare combination (expecially for those times!) of scholarly learning, practical experience and manipulative skill.

In his epistle Peregrinus describes how he has made spherical loadstones ("terrellas"), how he placed his "terrellas" in small boats on water and observed these then orient themselves in particular directions; how a loadstone can create the magnetic properties in pieces of (previously unmagnetized) iron; and how under some circumstances magnetic repulstion, as well as attraction, can be observed.

Peregrinus introduces the concept of "magnetic pole" -- the region of the loadstone (or iron) from which the forces appear to emanate. He also concludes that all magnets possess two such poles; and that a pole of one sort (for example the pole that "seeks" the north), creates in iron a pole of the opposite (south-seeking) sort. These are remarkably perceptive and cogent observations, faithfully recorded: but the "philosophical" outlook bears the scholastic stamp of the period. To Peregrinus it is some heavenly or divince force which causes

> this pole if it were then turned away a thousand times, thousand times could it return to its place by the will of God.

If these contrasts in Peregrinus startle us, they are perhaps no more than to be expected from a worthy pupil of an extraordinary teacher, the devout Franciscan friar Roger Bacon (1214-1294, sometimes described as "a representative of all knowledge of his time")who in many words fervently counseled the virtues of <u>Experimental Science</u>, without which, he warned philosophy could be mere words. It is "the principle of experimental science" he asserted, that

> without experience nothing can be sufficiently known. For there are two modes of acquiring knowledge, namely, by reasoning and experience . . . reasoning does not suffice, but experience does.

In his own scientific efforts it is more reasoning from experience, than active experimentation, that he practises, but he leaves little doubt as to what he preaches.

> This science [i.e. experimental] alone, therefore knows how to test perfectly what can be done by nature, what by the effects of art, what by trickery; what the incantations, conjurations, invocations, deprecations, sacrifices, that belong to magic mean and dream of, and what is in them, so that all falsity may be removed and the truth alone of art and nature may be retained.

And he shares the awareness of most preachers that he is not likely to be heeded by his contemporaries. None too sanguinely he concedes that,

> since this experimental science is wholly unknown to the rank and file of students, I am therefore unable to convince people of its utility, unless at the same time I disclose its excellence and its proper significance. [Ref. 2]

It is still only the 13th century and Roger Bacon for all his fine words, goes either unheard or unheeded. There is no great desire to shed beliefs in "conjurations or invocations": it is two hundred years or more before this "experimental science" is advanced any further, before the practitioners of "art and nature" willfully discard the shrouds of magic mysticism.

Meanwhile the practical art of navigation, much assisted by the magnetic needle, develops rapidly. In turn it stimulates the development of the new instrument, and as the range of ocean-going navigation is extended, sailors acquire and accumulate greater knowledge of its behavior. Attempts to circumnavigate it led to revised notions about the terrestial globe. It is not too difficult to believe the popular story that the discovery that the magnetic deviation (or variation) -- which was then well-known, differed at different points on the earth's surface was made by Christopher Columbus in 1492. According to his son Ferdinand, who accompanied him on this voyage, it was on the 14th of September 1492, when about 200 leagues from the island of Ferro, that Columbus noticed for the first time the variation of the needle.

> A phenomenon which had never before been remarked . . . . He perceived about nightfall, that the needle, instead of pointing to the North Star, varied but half-a-point, or between 5 and 6 degrees to the North-West; and still more on the folowing morning. Struck with this circumstance, he observed it attentively for three days, and found that the variation increased as he advanced. He at first made no

> mention of this -- knowing how ready his people were to take alarm, but it soon attracted the attention of the pilots and filled them with consternation. It seemed that the laws of nature were changing as they advanced, and that they were entering another world subject to unknown influences . . . Columbus tasked his science and ingenuity for reasons with which to allay their fears. He told them that the direction of the compass was not to the pole-star, but to some fixed invisible point. The variation was not caused by any failing of the compass, which like the other heavenly bodies had its changes and revolutions, and every day described a circle round the pole. The high opinion which the pilots entertained of Columbus as a profound astronomer gave weight to his theory, and their alarms subsided.*

Very probably Columbus did in this first westward voyage cross the agonic line (i.e. the boundary between a westward and eastward declination) and observed a changing deviation. His interpretation hardly suggests that he recognized the proper explanation or implications of his observations. It is more likely that an awareness of the general variation of the declination over the globe came slowly from navigational reports over a considerable period rather than from a single explicit discovery. Columbus' report was probably not the first.

Some hundred years later, about 1581, an English sailor, Robert Norman, after 20 years at sea during which time he had made extensive observations of the behavior of the needle, began to manufacture and sell small mariner's compasses. He had observed that the needle normally showed a tendency not only to orient itself in an approximately North-South direction, but that one end

*Washington Irving. Life and Voyages of Christopher Columbús, Vol I. p. 201.

would tend to dip lower and the other tip higher. At first he tried to correct this tendency by a counterbalance weight; but then by rearranging the method of pivoting the needle so that it could turn in a vertical rather than in a horizontal plane, he discovered its "strange and newe propertie of declinying". Not only could the needle now be directed towards some, presumed, point in the heavens, but also apparently to some point down in the bowels of the earth!

Robert Norman wrote a book: The Newe Attractive, (1581), about this new phenomenon of "Dip". So unusual was it, at that time, for a practical workman to engage in investigations and speculations usually reserved for the learned philosopher, -- that the author deemed some justification and explanation to be necessary:

> And albiet, it may be said by the learned in the Mathematicalles, as hath beene already written by some, that this is no question or Matter for a Mechanitian or Mariner to meddle with, no more than is the finding of the longitude, for that must be handled exquisitely by Geometricall demonstration, and Arithmetical Calculation: in which Artes, they would have all Mechanitions and Seamen be ignorant, or at leaste insuficientlie furnished to performe such a matter . . . But I doe verily thinke, that notwithstanding the learned in those Sciences, being in their studies amongst their bookes, can imagine greate matters, and set downe their farre fetchts conceits, in faire showe, and with plawsible words wishing that all Mechanitians were such, as for want of utterance, should be forced to deliver unto them their knowledge and conceites, that they might flourish upon them, at their pleasures;

> yet there are in this land divers Mechanitians, that in their severall faculties and professions, have the use of those Artes at their fingers endes, and can applye them to their severall purposes, as effectually and more readily, than those that would most condemne them.

Here is the practical, unlettered sailor making the same plea for the combination of experience and reasoning, as was made 200 years earlier by the pious and learned friar, Roger Bacon. Both recognized what might be achieved by such a combination; but neither was able to effect it. Not only in the study of magnetism, but in many "mechanical" arts and techniques and sciences was there mounting recognition -- and especially in Italy at the time, (cf. Ref. 11) -- of what might be learned from bringing together the skill and knowledge derived from practice with the erudition and analytic power of scholarship. In the process, of course, much would also be eliminated and discarded: the myths, hearsays, superstitions, and incantations. This was the major accomplishment of William Gilbert. He was not the first to sow the seeds, nor even to till the soil; but his was the first real harvest of experimental science.

II. William Gilbert

Gilbert's background, education, and attainments were characteristic of a prominent intellectual, influential in the court of Elizabethan England:

> WILLIAM GILBERT -- or Gilberd, as he wrote it -- was born in 1540 at Colchester, County Essex, England, of which borough his father, Jerome (Hieron) Gilbred, was recorder -- "a councillor of great esteem in his profession." Very little that is reliable appears concerning his early years, but it it known that he passed through the Grammar School of his native place and immediately afterward (May 1558) entered St. John's College, Cambridge (whence, some say, he went to Oxford), proceeding B.A. 1560, Fellow 1560-1561, M.A. 1564, mathematical examiner 1565-1566, M.D. 1569, and being elected a Senior Fellow of St. John's during the last named year.
>
> Immediately upon leaving college he travelled on the Continent, "where probably he had the degrre of Doctor of Physic conferred upon him, for he doth not appear to have taken it either at Oxford or Cambridge," and where, as well as in England, he is said to have "practised as a physician with great success and applause." In 1573, he was elected a Fellow of the Royal College of Physicians, and filled therein many important offices, becoming, in turn, Censor (1581-1582, 1584-1587, 1589-1590), Treasurer (1587-1591, 1597-1599), Consilarius (1597-1599), and President (1600). His skill had already attracted the attention of Queen Elizabeth, by whom he was appointed her physician-in-ordinary, and who showed him many marks of her favor, besides settling upon him an annual pension (said to be the only legacy left by her to any one) for the purpose of aiding him in the prosecution of his philosophical studies. [From Preface to <u>De Magnete</u>]

He was certainly well versed in the classics and mathematics, but as a physician he was also, -- and this must have been a rarity -- a scholar who was not totally averse to using his hands in other ways than "pushing the quill". His circle of acquaintances included the leading intellects and the most influential men-of-affairs of his day. Political involvement he seems to have eschewed: his energies and interests were directed to scientific and philosophical matters. He was heir to all the classical scientific speculations from Thales to Pliny; to the legacy of Greek and Alexandrine mathematics; to the already great accumulation of practical knowledge gathered by the ocean-going navigators; to the philosophical exhortations of Roger Bacon and the doctrines of Thomas Aquinas; and very especially to the seminal works of Peter Peregrinus and Robert Norman.

The tasks he set for himself were threefold:

first, to strip away all the false superstitions, myths, gossip, all "the incantations and invocations" in Roger Bacon's phrase, the spurious scholarship, both classical and medieval, that obscured and corrupted the small core of true knowledge of magnetic phenomena;

second, to supplement experience by positive, direct experimental investigation: to probe for new facts as well as to sift and collate the variegated mass of existing knowledge;

and third, to subject all the facts, both practical experience and experimental findings, to philosophical examination and mathematical analysis, so as to arrive at a "true" understanding of magnetism.

The first of these tasks Gilbert goes about (De Magnete, Book I, Chapter 1)* with great vigor and relish. All who have speculated on the subject from Plato and Aristotle to Agricola and Paracelsus are brought up in rapid succession for summary examination and more often than not for instant demolition. Now and again a word of praise or acknowledgement slips in:

> Thomas Aquinas, treating briefly of the loadstone, gets at the nature of it fairly well (D.M., p. 5)

> a small work attributed to one Peter Peregrinus, a pretty erudite book considering the time (D.M., p. 9)

> Robert Norman, skilled navigator and ingenious artificer, who first discovered the dip of the magnetic needle (D.M., p. 15)

But these few acknowledgements to past accomplishments are lost in the stream of denunciations of so many inherited and accepted falsehoods.

Recent investigators no less than ancient ones are castigated:

> . . . they wasted oil and labor, because, not being practical in the research of objects in nature, being acquaint only with books, being led astray by certain erroneous physical systems, and having made no magnetical experiments, they constructed certain raciocinations on a basis of mere opinions, and old-womanishly dreamt the things that were not. (D.M., pp. 5/6)

The remarkable contrast between the paucity of facts -- "that the loadstone attracts iron: its other properties were hid." -- known to the ancients and the vast, centuries-long range of speculations and interpretation which were buttressed by them,

*References are to De Magnete, English Translation of P. Fleury Mottelay. Dover reprint 1958. Abbreviated D.M.

is unceremoniously dismissed (D.M., pp. 2-14):

> . . . lest the story of the loadstone should be jejune and too brief, to this one sole property then known were appended certain figments and falsehoods which in the early time no less than nowadays were by precocious sciolists and copyists dealt out to mankind to be swallowed . . . . and errors have steadily been spread abroad and been accepted -- even as evil and noxious plants ever have the most luxuriant growth. . . .

Such errors and falsehoods are innumerable:

> that a loadstone rubbed with garlic does not attract iron; nor when it is in presence of a diamond.
> (Pliny and Ptolemy)

> Mahomet's shrine having an arched roof of magnets so that people might be fooled by the trick of the coffin suspended in air, as though 'twere some divine miracle. (Matthiolus)

> . . . a loadstone placed unawares under the head of a sleeping woman drives her out of the bed if she be an adulteress; or that by its fume and vapor the loadstone is of use to thieves, . . . or that it withdraws bolts and opens locks, ... frees women from witchcraft and puts demons to flight.
> (Villanova)

> . . . iron held by a loadstone's attraction, being placed in a balance, adds nought to the weight of the loadstone, as though the weight of the iron were absorbed by the virtue of the loadstone, ...
> (Serapio)

> A white loadstone may be used as a philter, ... When held in the hand it cures pains of the feet and cramps . . . . or makes one eloquent . . . .
> (Abohali; Pictorius)

> or, as the astrologer Lucas Gauricus held, that beneath the tail of Ursa Major is a loadstone . . . . and that the loadstone belongs to the sign of Virgo . . . . Gaudentius Merula advises that on a loadstone be graven the image of a bear, when the moon looks to the north, so that being suspended by an iron thread it may win the virtue of the celestial Bear

> The loadstone's force, when failing or dulled, is restored by the blood of a buck; it has been said that a buck's blood frees the magnet from the diamond's sorcery, giving back its lost power when the magnet is bathed in the blood -- this, because of the variance between that blood and the diamond. (Ruellius)

But a strong loadstone can according to

> Marbodaeus, a Frenchman . . . . make husbands agreeable to wives and may restore wives to their husbands.

By disposing of all this clutter Gilbert not only clears the stage for his own work; no doubt much of this lengthy parade of gossip more hallowed by age than truth, is artfully contrived to heighten, by contrast, the scientific rationality and successes of his own deliberations. This style is not a peculiar peccadillo of Gilbert: it is a common practice of scientists of that time to highlight their own experiments, and theories by constantly placing them in juxtaposition with the false assertions of others. Science is still largely expounding by philosophical polemic: new facts and ideas are promoted as much for the refutation of old ones as for themselves. Only much later when experimental science advances into wholly new territory, when discovery brings to light not only the unknown but also the unconceived and unsuspected, (so that both prior concepts and misconceptions are largely absent) only then does exposition free from disputation become commonplace.

The bulk of De Magnete is concerned with the accounts of Gilbert's own experimentation, his interpretations and refutations, and the formulation of the general principles of magnetic phenomena -- including the magnetic properties of the Earth itself. By the end of all this, Gilbert has persuaded himself, if not the reader, of the universality of magnetism -- an intrinsic and natural property of all matter, both terrestial and heavenly. In the final section of De Magnete (Book VI), Gilbert brings all this knowledge of magnetism to bear on general cosmological problems.

He is a thorough-going Copernican, (cf. especially Book VI, Chap. V) familiar with the size of the earth and the orbit of the moon, although he is still using an estimate for the size of the earth's orbit around the sun which is essentially that of Aristarchus (c. 250 B.C.).* He is also familiar with the precession of the equinoxes and the obliquity of the zodiac, and accepts the lunar origin of the tides.‡ He also examines the evidence for the changes in orientation of the earth's axis.

The cosmological picture of a moving earth -- which

> like a wheel supported on its axis rotates upon it from west to east, ...

and also orbiting around the sun

> -- in an oblique circle, towards the fire, just as the sun and moon have their paths . . ,

Gilbert attributes to the ancients:

> Heraclides of Pontus, and Ecphantus, the Pythagoreans Nicetas of Syracuse and Aristarchus of Samos, and, as it seems, many others, . . .

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*This was in the context of Aristarchus' heliocentric picture

‡ See also p. 36, footnote

and of

> the illustrious, mathematician and a very experienced investigator of nature, Philolaus.

It was only later, he asserts,

> when Philosophy had come to be handled by many, and had been given out to the public, then theories adapted to the capacity of the vulgar herd or supported with sophistical subtleties found entrance into the minds of the many. . .
>
> Then were many fine discoveries of the ancients rejected and discredited -- at least were no longer studied and developed. First, therefore, Copernicus among moderns (a man most worthy of the praise of scholarship) undertook, with new hypotheses to illustrate the phænomena of bodies in motion.*
> (D.M., p. 317/8)

A modestly satirical refutation of the Ptolemaic system,

> (supported by calculation and comparison of movements, and generally accepted by mathematicians, while the importunate rabble of philophasters egged them on.)

is a mild exercise for Gilbert. Having dismissed as absurd the whole system of adamantine spheres and the diurnal motion of the whole heavenly system (even,

> the Holy Scriptures do not recognize . . . a revolution of the whole firmament),

he proceeds to adduce the positive evidence for the earth's motions, citing for this purpose the magnetic poles of the earth --

> set at fixed points

and with which the

> poles of the diurnal rotation coincide.

*Very much the same sentiment is expressed in Newton's "System of the World".

It is this innate magnetic polarity, or verticity, of the earth which, to Gilbert makes the diurnal rotation of the earth intelligible -- or even natural. Thus;

> By the wonderful wisdom of the Creator, therefore, forces were implanted in the earth, forces primarily animate, to the end the globe might, with steadfastness, take direction, and that the poles might be opposite, so that on them, as at the extremities of an axis, the movement of diurnal rotation might be performed. Now the steadfastness of the poles is controlled by the primary soul. (D.M., p. 328)

It is not difficult to guess where this style of argument will lead. The earth, as a whole, aligns itself due to its verticity, just as the loadstone does and on a small scale.

> The whole earth would act in the same way, were the north pole turned aside from its true direction; for that pole would go back, in the circular motion of the whole, toward Cynosura [the pole star] . . . .
>
> The whole earth regards Cynosura by its steadfast nature. . . . The earth therefore rotates, and by a certain law of necessity, and by an energy that is innate, manifest, conspicuous, revolves in a circle toward the sun; through this motion it shares in the solar energies and influences; and its verticity holds it in this motion lest it stray into every region of the sky. (D.M., p. 333)

Gilbert has come a long way from the direct (if approximate) statement of Book I. (Chap. IV) that:

> One of the earth's poles is turned toward Cynosura and steadily regards a fixed point in the heavens

to the assertion of Book VI (Chap. VI) that

> the causes of the diurnal motion are to be found in the magnetic energy and in the alliance of bodies. . . .

Bacon

> Some men become attached to particular sciences and contemplations, either from supposing themselves authors and inventors of them, or from having bestowed the greatest pains on such subjects . . . . If men of this description apply themselves to philosophy and contemplation of a universal nature, they wrest and corrupt them by their preconceived fancies, of which Aristotle affords us a signal instance, who made natural philosophy completely subservient to his logic and thus rendered it little more than useless and siputa-tious. (Ref. 3)

Francis Bacon was prone to wordy pontifications about the proper way to do science. But since there is no evidence that he actually practised the art, never

> bestowed the "greatest" pains on such subjects.

He was himself safe from seduction by his

> Idols of the den.

For all his apt rhetoric and felicitous phrases his scientific insight was but that of an outsider. He could criticize Gilbert's shortcomings, but fail to appreciate (or understand?) his immense achievement. Gilbert might well retort (actually it was William Harvey -- a great scientific contemporary, who discovered the circulation of the blood?) that Francis Bacon

> perceived science like a lord Chancellor.

Another contemporary gives this personal impression of Gilbert

> One saith of him that he was <u>Stoicall</u>, but not <u>Cynicall</u> which I understand <u>Reserved</u>, but not <u>Morose</u>, never married, purposely to be more beneficial to his brethren. Such his <u>Loyalty</u> to the Queen that, as if unwilling to survive, he dyed in the same year with her, 1603. . . .
>
> (D.M. p. xxiv)

On the monument erected by his brothers over his tomb in the Church of the Holy Trinity, Colchester, is a Latin inscription which includes the simple memorial:

> . . . He wrote a book concerning the magnet much celebrated by those engaged in nautical affairs

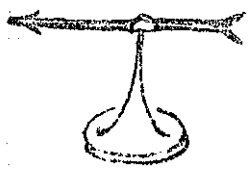
John Dryden was a little less reserved:

> Gilbert shall live till loadstones cease to draw
> or British fleets the boundless ocean awe.

III. Experimental Explorations

A simple, but most effective invention of Gilbert's is his rotating needle, or "versorium", which is simply a light needle

> of any sort of metal (not necessarily magnetic) three or four fingers long, pretty light, and poised on a sharp point after the manner of a magnetic pointer. (D.M., p. 79)



This instrument may have been directly inspired by the mariner's needle, but its exploitation by Gilbert is essentially different, and, in a sense quite original. It is an artifact, perhaps the first, devised expressly as a tool for experimentation. The versorium is not an instrument developed independently for some other (practical) purpose -- as, for example, the apothecary's balance, the astronomer's astrolabe or the chemist's still -- and subsequently pressed into service as an instrument for experimental research: it is explicitly a research instrument. It is the humble ancestor of the vast army of scientific instruments whose development has accompanied the subsequent growth of science. Today it is quite common for practical techniques to emerge from scientific-research instruments. In Gilbert's time it was the other way around; and the first step in this transformation was the conception of research instruments *per se*.

The particular form of the versorium -- an object that could easily turn, made it particularly suited to magnetic investigations where, as Gilbert recognized and repeatedly emphasized, the typical forces produce orientation rather than translatory motion. Nevertheless there was a most important preliminary task to which Gilbert addressed himself, and for which this same instrument proved effective; namely to establish a clear distinction between electrical and magnetic phenomena.

It is one of the mild ironies of the history of science that although the clear formulation of a general principle may be necessary at a particular time to make advance possible, in other circumstances the very same principle can act as a major obstacle to progress. Thus in Gilbert's time, understanding was obfuscated and progress seriously impeded by the confusing similarity of electric and magnetic phenomena; but two centuries later, in the early nineteenth century, the discovery of the essential unity of electrical and magnetic phenomena opened the way to a dramatically rapid development of both subjects. To Gilbert's predecessors both phenomena, electric and magnetic, and apparently these alone, manifested the mysterious, occult, powers of attraction at distance. That the explanation of both was to be sought in causes common or at least kindred seemed natural enough. Yet it was one of Gilbert's major -- if incidental -- accomplishments to demonstrate that they were essentially different; and in so doing to remove much of the mystique of both. (D.M., Book II, Chap. II) He showed -- using his "versorium" as a primitive electroscope -- that the attractive properties traditionally associated with amber (Greek: ηλεκτρον: electron) were shared by many other substances:

> diamond, sapphire, English gem, (Bristol stone, *bristola*), beryl, rock crystal, . . . glass, especially clear, brilliant glass; by artificial gems made of (paste) glass, antimony glass, many fluor-spars, and belemites. Sulphur also attracts and likewise mastich, and sealing wax (of lae), hard resin, orpiment (weakly).

A property so widespread is capable of systematic investigation and thereby loses much of its mystery:

> Nor does the supposed attractive force of amber arise from any peculiar property of its substance or from a special relation between it and other bodies: for in many other substances, if we but search with any diligence, we see the same effect.

Gilbert records -- apparently as a result of his own experiments, -- the influence of atmospheric humidity, of temperature, moisture, heat and flame, and of the essential role of friction or rubbing and polishing; and thereby conclusively demonstrates that the conditions for producing "electrical" attraction are quite distinct from those for magnetic ones. What is good, for electricity may be bad for magnetism and vice versa!

> In all bodies everywhere are presented two causes or principles whereby the bodies are produced, to wit, matter (*materia*) and form (*forma*). Electrical movements come from the *materia*, but magnetic from the prime forma; and these two differ widely from each other and become unlike, -- the one ennobled

> by many virtues, and prepotent; the other lowly, of less potency, and confined in certain prisons, as it were; wherefore its force has to be awakened by friction till the substance attains a moderate heat, and gives out an effluvium, and its surface is made to shine. Moist air blown upon it from the mouth or a current of humid air from the atmosphere chokes its powers; and if a sheet of paper or a linen cloth be interposed there is no movement. But the loadstone, neither rubbed nor heated, and even though it be drenched with liquid, and whether in air or water, attracts magnetic bodies, and that, though solidest bodies or boards, or thick slabs of stone or plates of metal, stand between. A loadstone attracts only magnetic bodies; electrics attract everything. A loadstone lifts great weights; a strong one weighing two ounces lifts half an ounce or one ounce. Electrics attract only light weights; e.g., a piece of amber three ounces in weight lifts only one-fourth of a barleycorn's weight. (D.M., pp. 85,86)

His attempts at a "theoretical" interpretation of the nature of electricity are not quite so happy. Compared with some of the old wives tales which he takes delight in ridiculing, he must have felt his own "explanations" to be singularly "rational": in retrospect they seem to share as many of the limitations and prejudices of his day, as much as advance beyond them.

For example:

> Rock crystal, mica, glass, and other electrical bodies do not attract if they be burned or highly heated, for their promordial humor is destroyed bt heat, is altered, and discharged as vapor. Hence all bodies that derive their origin principally from humors, and that are firmly concreted, and that retain the appearance and property of fluid in a firm, solid mass, attract all substances, whether humid or dry. (D.M., p. 84)

Or, in reference to the loss of attractive powers when amber is wet or"drenched in alcohol, or brandy".

> A breath, then, proceeding from a body that is a concretion of moisture or aqueous fluid, reaches the body that is to be attracted, and as soon as it is reached it is united to the attracting electric; and a body in touch with another body by the peculiar radiation of effluvia makes of the two one: united, the two come into most intimate harmony, and that is what is meant by attraction. This unity is, according to Pythagoras, the principle, through participation, in which a thing is said to be one. For as no action can be performed by matter save by contact, these electric bodies do not appear to touch, but of necessity something is given out from the one to the other to come into close contact therewith, and be a cause of incitation to it.
>
> (D.M., pp. 91, 92)

Humors and effluvia/were attempts at a "mechanical" explanation, and must have appeared much more "scientific" than the divine guidance, or the sympathies, conformities and antipathies which they supplanted. In any event the basic experimental conclusion that magnetism and electricity had (at that stage) to be treated quite separately was a valid and important one. And not only were the two phenomena divorced; a very perceptive difference in their characteristic types of forces and motions was also remarked:

> The difference (distinction) between electric and magnetic bodies is this: all magnetic bodies come together by their joint forces (mutual strength); electric bodies attract the electric only, and the body attracted undergoes no modification through its own native force, but is drawn freely under impulsion in the ratio of its matter (composition). Bodies are attracted to electrics in a right line toward the centre of electricity: a loadstone approaches another loadstone on a line perpendicular to the circumference only at the poles, elsewhere obliquely and transversely, and adheres at the same angles. The electric motion is the motion of coacervation of matter; the magnetic is that of arrangement and order. The matter of the earth's globe is brought together and held together by itself electrically. The earth's globe is directed and revolves magnetically; it both coheres and, to the end it may be solid, is in its interior fast joined.
>
> (D.M., p. 97)

With a little paraphrasing one might write something similar today!

In the thorough scrutiny of the essential differences between electric and magnetic attractions, Gilbert readily becomes involved in studying the physical characteristics of magnetism itself. Much of what he finds and reports was probably already vaguely known, but as a comprehensive account, stripped of all myth and hearsay, of magnetic properties as observed experimentally, De Magnete is certainly a great advance. (cf. Book II, Chap. 4-7 especially!)

Among Gilbert's major discoveries or observations regarding magnetism in general are: the basic similarity between the natural magnetism of the loadstone, and that induced in iron; the destruction of the magnetic attraction by extreme heat (red-hot iron or loadstone); the destruction of magnetism by chemical change (Book II, Chap. 23); that the refined iron extracted from loadstone by smelting can exhibit a greater degree of magnetization than the original stone, since in this way it is "purged of foreign admixture and dross", so that the resulting product is "more homogenic and perfect . . . , albeit deformed by fusion". (D.M., pp. 148/9) Gilbert also describes observations on the manner in which the magnetic influence extends into the surrounding medium; and how this property is transmitted from a loadstone to iron, or from one piece of iron to another.

"The magnetic force is given out in all directions around the body", (but not necessarily uniformly -- shape is important) "and excites magnetic bodies situate at convenient distance"; also it "arrives instantly" -- as does light (the more-or-less accepted view in 1600); but (being "far more subtle than light"),

> it has no relations with air, water or other non-magnetic body . . . . . No hindrance is offered by thick boards, or by walls of pottery or marble, or even of metals; there is naught so solid as to do away with this force or to check it save a plate of iron.
> (D.M., p. 132)*

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*Gilbert here makes an interesting comparison between the ability of magnetic action to penetrate most substances and the similar power of the moon in producing the tides on the earth,

> . . . this movement of the water is produced and the seas rise and fall no less when the moon is below the horizon and in the nethermost heavens, than when she is high above the horizon. Thus the whole mass of earth, when the moon is beneath the earth, does not prevent the action of the moon. (D.M., p. 136)

Although the calendrical connection between the tides and the phases of the moon had been known from antiquity, the advocacy of this connection as a scientific theory, must, at the time have been regarded as either bold and revolutionary or a reverstion to scholasticism. For example Galileo some 30 years later, in the "Dialogues on Two World Systems", (Fourth day) scornfully (and erroneously) dismisses the lunar theory. Presumably it smacked too much of the occult, the old "macrocosm-microcosm" cosmology; and in any case Galileo had his own (incorrect) interpretation of the tides. Gilbert's assertion, not only that the moon could influence the waters on the earth, but that this influence was not diminished by the interposition of the whole mass of the earth, is "action at a distance" with a vengeance. But even this radical assumption is not, in itself, a real theory of the tides: this was not forthcoming for nearly 100 years (Newton).

Amongst other phenomena which Gilbert examines are: the manner in which iron situated near the loadstone "diffuses" the magnetic influence of the latter; how the (primary) magnetism of the loadstone "excites" (secondary) magnetism in iron, which latter can be both temporary and "permanent", and can reach a maximum, "saturation", intensity;

> The natural magnetic force, which in the iron lies confined and asleep is awakened by the loadstone, . . . hence comes the perfect magnetized iron, which is as strong as the loadstone itself. . . and being awakened endures . . . (D.M., p. 149)

There is also an account of how the magnetic properties of a single magnet are transformed when it is cut into different sections -- along the direction of magnetic axis and traversely.

Gilbert's concepts and experimental methods are a great advance over those of his predecessors. He makes frequent use of the "versorium" to explore the distribution and to assess quantitatively the strength of the magnetism of the different bodies. Taken altogether, his experimental findings support his major thesis: that magnetism is not so much an innate property of the material of the loadstone or of iron, but has to do with some ordering and configuration. Many of the properties he identifies and the concepts he introduces are, notwithstanding the archaic language, quite basic, and indicate his remarkable feeling for what is the true nature of magnetism. And theorizing aside, there can be no question about the perception which is revealed in his account of his observations, and his emphatic assertion that experiment, properly conducted, is the real arbiter of truth: "How easy it is to make mistakes and errors in the absence of trustworthy experiments, whilst investigating the hidden causes of things . . . " (D.M., p. 255)

IV. The Terrella

The most celebrated investigations of Gilbert's are his experiments with the "Terrella" (little Earth) -- a piece of loadstone, carefully selected and cut in the form of a sphere. Such artifacts had already been used by Peter Peregrinus (cf. p.12), but Gilbert's work is far more comprehensive, and forms the basis of his interpretation of the earth as itself a great natural magnet. In this context it is natural enough that a spherical loadstone is most likely to suggest the earth's magnetic properties: the terrella is probably the first example of a physical model being used experimentally. Of course, as used by Gilbert, it is not a proper dynamical scale-model, in the modern sense of the term; it is only a suggestive one. But it must have provided a compelling demonstration that esoteric, occult, or divine influences need not be invoked to explain the "mysterious" properties of the compass needle. A rational explanation, and moreover one that could be explored experimentally, was possible, indeed plausible.*

The initial step (D.M., pp. 22-25) is to demonstrate the essential symmetries -- two poles and the equatorial plane -- of the terrella. Gilbert's definition of the poles (" . . . answering to the earth's poles") and the procedure he describes for locating them indicate clearly that these are not to be regarded as some singular physical objects; nor "mathematical points, but natural points of force that through the cooperation of all its parts excel in prime efficiency". (D.M., p. 67) The poles

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*Such an interpretation might be regarded as a curious sort of reversal of the old "microcosm-macrocosm" theories. Here it is not the (actual) global events that are reflected in local happenings; but, conversely, the small-scale phenomena which provide the pattern for the global. Myth is replaced by (explicit) analogy. It is somewhat later that the more general concept of a single set of laws equally applicable to local, terrestial and heavenly phenomena, becomes firmly established.

define the axis of the symmetry of the terrella. This is termed by Gilbert the "verticity" of the loadstone, as a whole (D.M., p. 48); a most important concept which Gilbert emphasizes and refers to repeatedly. To correlate the two poles of the terrella with the north and south terrestial poles, the terrella as a whole is used as a "versorium" -- by placing it in a "round, wooden vessel . . . in a tub of water . . . where it may float freely". It can turn it under the (magnetic) influence of the Earth itself. The part which turns to Earth's north is designated the SOUTH pole, and similarly the NORTH pole.* (cf. Lowdstone)

Some further elucidation of the loadstone's properties is necessary (D.M. pp. 28-31), to provide a more secure basis on which to make comparisons with the earth. Especially significant (at least for stones selected for their uniformity), is the invariable appearance of two poles in loadstones of simple shape, and in the separate parts when they are divided transversely to the axis (D.M., p. 29) Θ ϕ

Later (D.M., pp. 115-122) he discusses how the magnetic "energy is ordered in magnetic bodies"; in particular the variation of the force of attraction at different latitudes on the terrella; and again how verticity or "the poles are dominant in virtue of the force of the whole" -- (witness the fact that this symmetry is destroyed when the sphere is cut into hemi-spheres or quadrants: the poles in these parts are in different positions from the original ones -- and no longer nicely symmetrical).

Superficially, De Magnete does not appear to be a very mathematical work. Nonetheless it is clear that Gilbert has a strong mathematic sense, expressed primarily in geometrical rather than

*There are several conventions for the magnetic poles: cf. "north-seeking", "marked pole", etc. It should be noticed that any such terminology is only conventional, and not a permanent convention The earth's magnetism is not fixed with respect to the earth's rotation: There is abundant evidence that in past epochs it has actually been reversed!

in algebraic or numerical language. (The alliance of mathematics and natural philosophy was still an innovation in Gilbert's day, and mathematics was still, primarily, that of the Greeks: Genometry.) Examples of perceptive geometrical descriptions abound: Magnetism is the result of a form of intrinsic ordering of which the "verticity" is the manifestation. (D.M., p. 108) Each element of the loadstone (or iron) makes its particular contribution; the overall force results from a super-position of the effects of these elements (pp. 117-120). The essential property of the force is a "turning" motion rather than a net attraction (or repulsion), arising from the joint attraction of opposite and repulsion of the similar poles. (pp. 122, 161, 177, 183, etc.) The forces decrease with distance -- it has a sphere of influence -- "orbis virtutis" (pp. 150, 151), but it is not the same at all points equidistance from the center, which is the true center of the terrella. Moreover Gilbert recognizes that it is essentially the angular position on the terrella i.e. the latitude and longitude (with respect to the axis), not the particular locality, which determines the direction of the force at any point; so that the characteristic pattern of the forces may be observed on a (mathematical) spherical surface of any arbitrary radius. (D.M., p. 307) (This is a correct result only for an ideal uniformly magnetized sphere, it is not generally true.)* Gilbert describes how this may be demonstrated experimentally. Whether he first observed or guessed this result it is, in either case, a remarkably astute conclusion.

On account of their great practical importance, two features of the terrella's magnetic forces are investigated thoroughly: variation (declination) and dip (inclination). Gilbert is convinced that "ideally" the magnetic axis and the axis about which the earth rotates should coincide; indeed his cosmology implies

*See Appendix p. A-5

a deep connection between the magnetism and the rotation of the celestial bodies.* Consequently any observed difference is attributed to local irregularities of the Earth's crust (or observational errors), and the plausibility of such an interpretation is supported by experiments with modified terrellas. More significant is the exploration of Dip on the model terrellas, where the major features of the known terrestial variation of dip are reproduced. In brief these experiments with terrella suffice to explain with remarkable fidelity all the major facts about the Earth's magnetic properties known at the time.

Although at times (e.g. p. 130) Gilbert's pictorial interpretation of the variation of magnetic force with position is rather naive, the overall picture is still remarkably perceptive. Each element of the loadstone is endowed with its own intrinsic, permanent verticity (and thus a North and South pole). These persist even if the stone is cut into parts. The pattern of force for the whole (or any piece) can be inferred (at least in principle) by superposing the coordinated efforts of all the ordered, constituent elements. Fortunately such a picture of the Earth's magnetism (although hardly acceptable today as an actual physical model) does lead to the major observed magnetic properties of the Earth. Thus Gilbert is able to make a preliminary presentation of "a few arguments of prima facie cogency for his thesis -- that the earth is a giant magnet similar to the loadstone -- a 'till now unheard of view of the Earth", to be "confirmed by subsequent experiments and demonstrations". (p. 64) There are general speculative comments on the nature of the earth's interior (cf. ". . . the loadstone and all magnetic bodies . . . . . . seem to contain with themselves the potency of the earth's core and of its innermost viscera" (p. 66), as evidenced by the fact that the loadstone is

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*Hence Gilbert's use (and the later abandonment) of the term "deviation", which implies some departure from the ideal.

(originally) part of the earth; so that it "derives properties from the Earth extempore, and acquires verticity" (p. 67)

To appreciate these ideas they must be viewed in the context of what was known in Gilbert's time about the Earth's magnetic influence.

V. The Earth and Its Magnetism

It is easy to forget that in the 16th century it was still rather a novelty to describe the local geography in terms of the geometry of the earth as a whole, i.e. using the now common concepts of longitude (meridian) and latitude (parallel). (It was in this century that the Earth was first circumnavigated!) They are introduced by Gilbert (D.M., pp. 124-128) by analogy with the then apparently more familiar astronomical concepts.

> Astronomers, in order to account for and observe the movements of the planets and the revolution of the heavens . . . have drawn in the heavens certain circles and bounds, which geographers also imitate so as to map out the diversified superficies of the globe and to delineate the fairness of the several regions. (p. 125)

The terrestial poles, equator ("equinoctial circle"), parallels and meridians are defined in terms of astronomical observations, and fixed points on earth: their counterparts on the "terrella" in terms of magnetic properties. There would, Gilbert assumes, be strict correspondence between the two, were it not for the local irregularities of land, ocean, mountain, etc. on the Earth, (the terrella is, of course, assumed to be "ideal").

The terrestial pole that points "to Cynosura [the constellation Ursa Minor containing the pole-star] is called the North Boreal or Arctic pole; the opposite one is called South, Austral, or Antarctic. . . . they are reference points of direction and position."

The analogy between the earth and the terrella is now apparent, but one must bear in mind that when investigating the influence of an ordinary loadstone, (on the surface of the earth!) the magnetic forces result from both the terrella and the Earth. (Only if the terrella is an exceptionally strong one, can the Earth's force be neglected.) Moreover there is also the (gravitational) force of the Earth which acts everywhere toward its center. To similate these more complex circumstances, Gilbert describes (pp. 163-165) experiments with two terrellas -- a large one to simulate the earth and another near it to simulate the terrella, an arrangement which demonstrates the proper analogy between the two systems. However there are other, subtler, matters where the analogy between Earth and terrella is by no means straight-forward. As long as one is concerned with the magnetic forces outside the earth or the terrella the analogy between the two can be drawn without enquiring too deeply about what it is inside either object which produces the magnetic efforts. But when the questions invoke some knowledge of the interior, -- as does Gilbert's enquiry about the relationship between the direction of the verticity of the loadstone when actually in the ground, and the direction it will take up when removed from the ground, and mounted to turn freely -- then one is probing much subtler matters. So that although Gilbert's picture of the overall magnetism of the Earth is based on a rather imprecise "philosophical" principle, and is far from a true physical picture, he does show extraordinary insight into the true state of affairs.

> A loadsdone mined in this debris of the earth's surface and of its projections, whether it be part of a considerable vein, gets from the earth its form and imitates the nature of the whole. All the inner parts of the earth are in union and act in harmony, and produce direction to north and south. Yet the magnetic bodies that in the topmost parts of the earth attract one another are not true united parts of the whole, but are appendages and agnate parts that copy the nature of the whole; hence, when floating free on water, they take the direction they have in the terrestial order of nature. We once had chiselled and dug out of its vein a loadstone 20 pounds in weight, having first noted and marked its extremities; then, after it had been taken out of the earth, we placed it on a float in water so it could freely turn about; straightway that extremity of it which in the mine looked north turned to the north in water and after a while there abode; for the extremity that in the mine looks north is austral and is attracted by the north parts of earth, just as in the case of iron, which takes verticity from the earth. Of these points we will treat later under the head of "Change of Verticity." (p. 184)

Essentially he assumes that the basic magnetism is produced by some inner, uniform core of the earth; and that it is this magnetism which induces the magnetism in the topmost parts "which are not the true united parts of the whole". Induced magnetism is of opposite polarity (verticity) to that of the inducing magnet, whereas the magnetism of a piece of a terrella which forms an integral part of the whole is in the same direction. Both these propositions can be and are tested experimentally (cf. p. 186/7 and 192/3).

A related, and even subtler problem which Gilbert skirmishes, is how the magnetic forces can be responsible for the cohesion of the whole earth mass (as Gilbert tends to believe), and yet two pieces of magnetized material -- if free to move -- can align so as to mutually cancel each other's magnetism. (There must be other forces present to account for the permanence of magnetism itself. Gilbert's urge is to explain everything in terms of magnetic properties. This is a weakness both of his physics and his cosmology.)

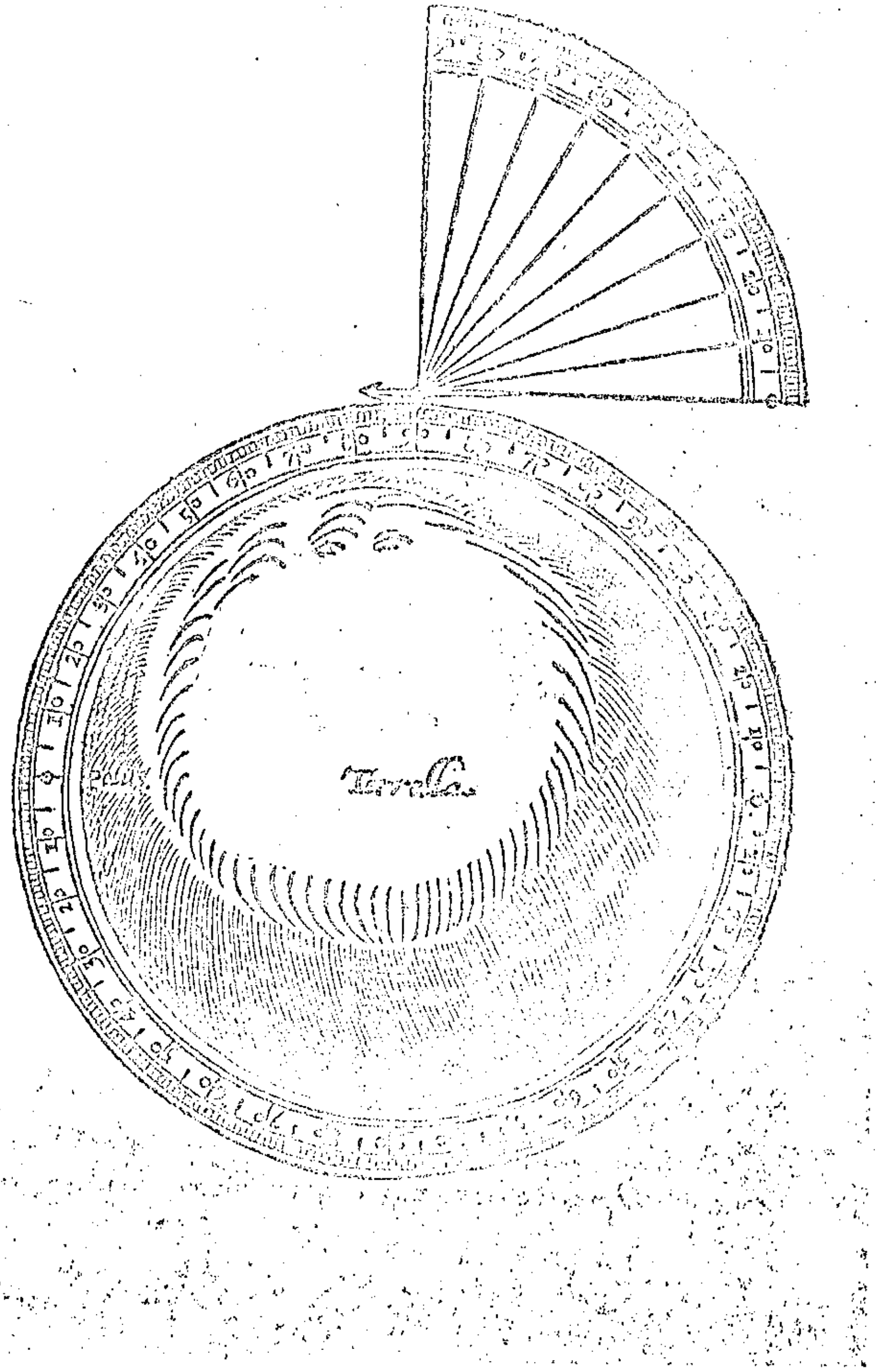
Gilbert assumes, as has already been emphasized, that the difference in direction between the true (astronomical-geographic) north (or south) and the alignment of the magnetic needle is a "variation" caused by irregularities in the earth's surface. He demonstrates this effect experimentally (pp. 183-185) with a terrella "whose surface has sensible imperfections". In so far as the earth's surfaces do not change (in historical times) Gilbert asserts (pp. 240, 241) that "the variation is constant at a given place, ... save there should be a great break-up of a continent and annihilation of countries, as of the region Atlantis, whereof Plato and ancient writers tell."

Had Gilbert written a few decades later, he would have known that the "variation" is far from being constant for all time, it changes dramatically -- much to the consternation of the navigators who first discovered this fact. Moreover these changes, due to goings on in the interior of the earth, are of a totally different time-scale from the hypothetical continental changes to which he alludes.

Whatever his view of the cause of the "deviation" (and its change with time) Gilbert does clarify a matter which had been partly resolved earlier by Robert Norman; namely that "deviation" does not arise from the attraction towards some singular terrestial (or heavenly) object, it is rather a change in the direction of the magnetic force at each place. This is an important example of a general proposition! It is a "turning" rather than a lateral movement which characterizes magnetism.

Book IV concludes with a detailed proceedure -- a combination of magnetic and astronomical measurements -- for determining the "variation" both on land and at sea. There is also a brief review of the observed variation in different parts of the world, with the observation that "the variations are greatest in regions nigh to the poles" (p. 269). This finds a ready explanation in terms of Gilbert's theory of variation, since near the poles the magnetic force controlling the horizontal orientation of the needle is weakest. But this is not the full story: the axis of the general magnetism of the earth is not, as we now know, aligned with the earth's axis of rotation

Ideally, Gilbert's magnetic "versorium" would be a magnetized needle, pivoted and balanced on its center, able to turn freely in any direction whatsoever. He does in fact attempt to realize such an instrument in practice (pp. 301/2), by floating a needle mounted on a piece of cork. The orientation of such a needle is then characterized by two angles (which could be "deviation" and "dip"). However one must recognize, as does Gilbert, the fact that practical instruments, as used in navigation, are not so constructed: the two angular movements are separated and usually embodied in different instruments. For the compass needle, the freedom is to turn about a vertical axis (i.e. an axis pointing to the center of the earth); for the Dip circle the turning is about a horizontal axis and in a plane which contains the direction of the compass needle at that point. These axes are, of course, related to the direction of the force of gravity at the point. But these precise circumstances do not pertain to the terrella-model. Here the direction of gravity is always downwards vertically -- not to the center of the terrella; but we do have the advantage that we can turn this around! To explore the dip in this case, it is simplest to use a compass needle -- i.e. a needle with vertical pivot-axis -- and turn the terrella, so that the magnetic meridian direction is horizontal. This is essentially the method shown, (p. 286), and the one used in reproduction of Gilbert's ex-


Terrella

periments in the laboratory. In so far as the loadstone is an ideal, uniform one, one may also, with this arrangement verify that the angular pattern of the magnetic forces is the same at all radial distances from the center. (cf. pp. 306/7)

All this observation, experimenting, analysis and synthesis, inference and speculation, testing of new theories and rejection of old ones, culminates in Gilbert's mind in a concept of magnetic force, and the Earth's in particular, which though ill-defined in may particulars, is in general outlines quite definite and to its author, apparently quite vivid. It is a force "without error and without the injuries of ills and disease", one that can "exert an un-ending action, quick, definite, constant, directive, motive, imperant, harmonious, through the whole mass of matter." In the final section of De Magnete (Book VI) the perspective widens. Gilbert presents magnetism as universal phenomenon whose elucidation now helps to understand the motions of the earth and their relation to the universe as a whole. It is a very much Copernican universe; but Gilbert goes far beyond describing the motion of its parts: he believes he is in possession of a major clue to understanding the underlying causes of these motions: It is, of course, magnetism!*

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*These speculations are further elaborated in Gilbert's posthumous work: De Mundo nostro Sublunari Philosophia nova, (1631). cf. De Magnete, footnote p. 346.

VI. Postscript

Gilbert's De Magnete is undoubtably a great landmark in the history of Magnetism, and indeed in the history of Experimental Science as a whole. Yet its influence was not as profound or widespread as one might expect. It was certainly widely acclaimed in its day. Galileo and Kepler both praised Gilbert, but it is difficult to trace in their work, or in the great surge of scientific activity in the latter part of the 17th century any specific development of Gilbert's ideas. What did advance rapidly in this period was a practical knowledge of terrestial magnetism as stimulated and required by the growth of intercontinental navigation. As for the understanding of magnetism itself, as a physical phenomenon independent of its particular manifestation by the Earth, the assessment that there was no advance for 200 years after Gilbert is not grossly exaggerated. To understand this one should, perhaps, distinguish between the philosophical, scientific, and practical implications of Gilbert's work.

Gilbert using both the weapons of polemic and of experiment swept away from the whole subject of Magnetism the accretions of myth and superstition that it had gathered over the centuries; it is for this service that Galileo regards Gilbert as

also Kepler

> . . . worthy of extraordinary applause for the many new and true observations that he made, to the disgrace of so many fabulous Authors, that write not only what they do not know, but whatever they hear spoken by the foolish vulgar, never seeking to assure themselves of the same by experience, perhaps because they are unwilling to diminish the bulk of their Books!
>
> (Ref. 6.)

Gilbert's rational picture of the Earth as an immense globular magnet was undoubtedly of the greatest value at a time when the geometrical-geographical concept of the Earth as a sphere was acquiring immense practical importance. But Gilbert's terrestial magnetism did not stop there. On the one hand, the cosmological framework in which these concepts were set was modern (Copernican) and was therefore met with the predictable hostility towards such heresy. (Galileo's copy of De Magnete ". . . was given to him by a Perpatetick Philosopher of great fame, as I believe to free his library from contagion".) Yet Gilbert's philosophy and cosmology went far beyond the Copernican -- in a direction which his contemporaries and successors must have found hard to comprehend, still harder to follow. In this respect Gilbert replaced the whole congeries of varigated, diverse legends, myths, and superstitions about magnetism by a single universal principle -- one grand speculation which "explained" both microcosm and macrocosm. But his speculation was only a myth: he had replaced innumerable miserable myths, with a single grandiose one!

If Gilbert's extravagant cosmological ideas probably made both "conservatives" and "progressives" of his day somewhat wary of embracing his ideas, they certainly influenced Gilbert's own scientific deductions. His assertion that the deviation (declination) at any point on the Earth's surface is fixed for all time was certainly not warranted by the evidence,-- (this error may have been suspected at the time by Jesuit writers; it was established beyond doubt a few decades after Gilbert's death) -- but to deny this assumption would have disturbed his whole cosmological picture.

Turning to Gilbert's impressive investigations of the physical properties of magnets and magnetism, the picture is quite different. Here experiment rather than philosophical speculation reigns supreme, and Gilbert's achievements and influence are unquestionable. He demonstrated the great power and virtue of experiment, in particular in exposing the essentially different and distinctive characters of magnetism and electricity. In many of his deductions from experiment he shows powerful flashes of insight into some subtle but essential feature of magnetism. But his concepts are often too vague or shadowy to exploit further. Ideas about basic physics and chemistry of matter were still primitive in Gilbert's time: to attempt a full physical interpretation of the essence of magnetism was premature by several centuries! In any event, the major conclusion from Gilbert's work was, in a sense, negative -- a dead-end! Magnetism and electricity were separate and distinct -- each to be examined sui generis. In retrospect one can see that this conclusion -- fully justified at the time, and indeed essential to clear the way for further experimental exploration -- imposes severe limits to what can be understood about the nature of magnetism. It took more than two centuries -- in the first of which (17th) a whole conceptual framework of physics was to be formulated, and in the second (18th) the whole subject of electricity was to be created experimentally, virtually ab initio -- before the real bridge between electricity and magnetism was discovered, -- by Oersted in 1820. Little wonder then, that in all this time little progress was made in the exploration of the nature of magnetism beyond the stage where Gilbert left it.

With the discovery of electro-magnetism and its laws in the early 19th century, and with the rapid development of its technical applications in the latter part of the century -- practical interest in magnetic materials mounted rapidly, and persists to our own day. During most of its history, this later development has been predominently empirical, stimulated by the needs and experience of practical engineers, who, as is so often the case, do not wait for a complete, theoretical explanation of a phenomenon before putting it to use. Slowly in the past hundred years or more both the general principles and the subtle intricacies which, together, characterize magnetism have emerged. We know that magnetism -- at the elemental level -- is a universal property of matter.

What produces the immense variety of magnetic properties in different materials is the particular subtle and complex arrangement of the "elements" in particular cases. There is indeed a certain prescience in Gilbert's insistence that magnetism, intrinsically, is there all the time; it ". . . is not generation, but restitution and re-formation of a confused form" (p. 109) that is the essential feature of magnetism.

The physical principles, necessary to "explain" the intricate nature of magnetism -- and especially its most striking manifestation in iron and similar materials -- so called Ferromagnetism -- far transcend anything of which Gilbert could have had the slightest inkling. First there is the whole body of knowledge we now know as classical-electromagnetism. After this, but before the advent of quantum mechanics a mere 40 or 50 years ago, there were all the investigations of, and attempts to understand magnetic properties of particular materials -- e.g. why iron, cobalt, and nickel are "magnetic" and copper, silver, etc. are not -- all essentially empirical and phenomelogical. Even today with the full armory of theoretical physics, and the immense knowledge of the structure of atoms, molecules, and the patterns of their ordering in solid materials (crystallography, metallurgy, etc.), magnetism in all its subtle manifestations still has its mysteries; so that the development of new magnetic materials is, even today, an art as well as a science!

If all the basic principles were known, and their method of application fully mastered, then one would expect the "best" magnetic materials to have been already specified and made. Yet only in the past year or two, a new "permanent" magnetic material (an alloy of) has been discovered (or invented) which in many, practically important respects is not a little better, but <u>several times</u> better than anything made before. (cf. Section 7, p.74) The belatedness of this discovery is not the result of lack of interest, or of trying. Producing special magnetic materials is quite an industry today, and over the past few decades a whole succession of "improved" materials have been developed for a great variety of applications. It is hard to believe that even now, the end of the line has been reached.

It is in the third sphere of activity -- the exploitation of magnetism in navigation -- that Gilbert's immediate influence is, perhaps, most clearly discernible. His contribution was twofold: first, a comprehensive, rational picture of the Earth's magnetism which provided a sound -- albeit not entirely correct -- framework in which to interpret the scattered measurements from different parts of the globe; second; a clear exposition of the principles of the different magnetic instruments and their practical realization. The navigators of the 17th century were probably unencumbered by, or not too sensitive to, the profundities and niceties of rival philosophical theories. Their business was wider and better navigation and for them the earth's magnetism, whatever its origins or significance, could be exploited -- provided it was fully known rather than fully understood. Gilbert demonstrated what was the general pattern, and how it could be examined; extensive and patient observations by natural philosophers and astronomers as well as navigators were required to produce a comprehensive and reliable picture.

Shortly after Gilbert's time, around 1635, there was published the first convincing evidence that the "variation" of the compass needle at a fixed point was not constant with time: This was by Henry Gellibrand, Professor of Astronomy in Gresham College, London. This discovery was made possible by the steady accumulation, by Gresham's predecessors, of systematic observations of the declination, over a period of several decades and with sufficient accuracy that the recorded changes could not be attributed to the crudity of the measurements. The discovery of this gradual change over periods measured in decades, (which is now termed the "secular" change) had profound implications. Practically it meant that mariners' charts of magnetic variation had to be constantly checked and brought up to date. (Reliance on out-dated charts had led to some spectacular errors in navigation in the 15th and 16th centuries) Philosophically, the implications were equally dramatic -- (although perhaps not fully realized at the time). The phenomenon of the earth's magnetism was related to the earth as a whole, apparently some intrinsic property, and yet it could change measurably in the matter of mere decades. So much for the immutability of the heavenly bodies -- and for Gilbert's basic cosmology! Here was a new challenge to the Natural Philosophers.

In the 17th and 18th centuries both comprehensive survey and detailed, sensitive measurements and observations extended the knowledge of the Earth's magnetism. In 1700 Edmund Halley produced the first extensive chart of magnetic "variation" -- covering the whole Atlantic Ocean, both northern and southern hemispheres. The first chart showing the variation over the whole earth was published in 1768 by Johann Carl Wilke in Stockholm. (cf. Section 7, pp. 68-70)

The major function of the mariner's "magnetic needle" had been all along, to determine direction at sea, especially when a covered sky made navigation by the sun and stars impossible. Very soon arose the tantalizing possibility of determining location at sea -- by a combination of magnetic and astronomical measurements. (The latter, when the skies were clear, gave the latitude: the great problem was always longitude.) Observations, on land and sea in the 15th century already showed that declination was different at different places on the globe, so that once a map of declination was made, it could, if sufficiently complete and precise, be used to supplement astronomical measurements. There were however two difficulties, at least. Declination was not easy to measure precisely at sea, and in any event required simultaneous measurement of both compass and sun (or stars). Secondly, the realization that a declination map, even if it could be made, could not be compiled once and for all undermined the whole prospect. The discovery of Dip -- and the development, by Gilbert of an instrument to measure it, offered an attractive alternative. Dip could be measured even under a closed sky -- all that was needed was a level base or horizon. Moreover -- as was already suggested by Gilbert's work, -- the change of Dip over the earth's surface might be a good deal less irregular then Declination. This was the idea behind the proposal, by William Winston (1667-1752) a professor of mathematics at Cambridge (incidentally Newton's successor), that the dip-needle might be the means of measuring longitude at sea. Later the idea was proposed that a combination of Dip and Declination (plus astronomical observations) at sea could enable exact positions to be found.

Despite the limitations and ambiguities (and there were additional ones when iron ships replaced wooden ones!), the 18th and 19th centuries witness continuous and intensive development of the compass needle and dip-circle as navigational instruments. In this same period there grew up an impressive, world-wide network of continuously recorded observations of the earth's magnetism. Until recently, astronomy and magnetism thus provided the scientific basis for all long-range navigation on sea and in the air. Only in the last few decades have these traditional methods been supplanted by more precise and versatile ones based on radio-signals.

The practical importance of terrestial magnetism, ensured a sustained, continual interest in the observation and interpretation of many new related phenomena. In 1722, George Graham, a famous instrument maker, in London, observed (discovered) that a small, but highly significant, rapid variation of the declination could occur in a matter of <u>hours</u>:

> After many trials I found that all needles . . . would not only vary in their direction on different days, but at different times on the same day; and this disturbance would sometimes amount to upwards of 30' (half of one degree) in one day.

Later (1759) Canton (who also made important contributions to the study of electricity) observed, also in London, that these daily changes were greater in summer (typically 13') than in winter (7'). Contemporaneously, these variations were being studied by Andreas Celsius and Hiorter in Upsala. From some 20,000 observations over a period of more than three years, Hiorter, in 1747 came to an astonishing conclusion:

> A motion of the magnetic needle has been found which deserves the attention and wonder of everyone. Who would have thought that northern lights (Aurora Borealis) would have a connection with and a sympathy with the magnet, and that these northern lights, when they draw southwards across our zenith or descend unequally towards the eastern and western horizons could within a few minutes cause considerable oscillations of the magnetic needle through whole degrees? (Quoted in Ref. 1)

Correspondence with Graham in London showed conclusively that exceptionally violent distrubances of the compass needle occured simultaneously at London and Upsala; and both were synchronized with strong Auroral lights. Clearly as Hiorter concludes, the Aurora are no local phenomena! One might even deduce their occurence from observing the magnetic needle! This whole intriguing phenomenon of "magnetic storms", their relation to aurora, and the connection of both with conditions on the sun (sunspots and solar flares) were recurring mysteries for many succeeding generations of physicists. The subject took a new important aspect with the advent of radio, when it was observed that conditions for long-range propagation of radio-waves were likewise related to solar and auroral activity.

Today, even if not all of the details are understood, we are familiar with a whole range of complex interactions between the sun, its radiations and the Earth: the normal radiations -- visible and invisible -- from the sun; the exceptional: sun spots, solar flares, and erruptions; and the resultant phenomena of Van Allen Belts, aurora, ionospheric layers, etc. and their many changes in the earth's magnetic field. In a sense we now understand far better the causes of the small, rapid, secondary changes in the earth's magnetism, than the main phenomenon itself: the origins of the normal, slowly varying, magnetism. We know that over the centuries the poles have drifted over hundreds or thousands of miles; other less direct evidence indicates that over longer periods hundred of thousands or millions of years the whole direction of the polarity may have reversed -- and that more than once. There are plausible models -- invoking vast convection currents of matter inside the earth -- which suggest how the main part of the earth's magnetism is produced. But the interior of the earth is still an inaccessible region -- which leaves much room for speculation about its magnetic and other properties!

We study the rocks to learn about the local variations of magnetism, and to infer something of the earth's past (magnetic) history; we study indirectly, the magnetism of other heavenly bodies to provide us with a broader perspective about magnetism on a cosmic scale; and most recently we measured the magnetism of the earth's nearest neighbor, the moon, and subject its rocks to detailed scrutiny. Both our knowledge and understanding of magnetism, from the atomic scale to the cosmical have grown immeasurably since Gilbert's day: It is a moot point which has has grown more.

About 150 years ago, Christopher Hansteen, (1784-1873) of Norway, who devoted great labors to the study of magnetism, exhorted his contemporaries in these words:

> The mathematicians of Europe since the times of Kepler and Newton have all turned their eyes to the heavens to follow the planets in their finest motions and mutual perturbations: it is now to be wished that for a time they would turn their gaze downwards towards the earth's centre, where also there are marvels to be seen; the earth speaks of its internal movements through the silent voice of the magnetic needle. We should also learn much if we could construe the flaming script of the polar lights.
>
> (Quoted in Ref. 1)

Since Hansteen's days the marvels of magnetism have indeed been seen, not only down in the earth, but everywhere in the vast heavens and in the innermost particles of matter. Gilbert in his unbridled enthusiasm for magnetism saw it as a universal agency, a primary cause of the whole spectacle of the cosmos. We may smile benignly at Gilbert's grand vision: it was after all an understandable hallucination. For have we not confirmed that magnetism is indeed an ubiquitous and universal property of matter; and whether faintly discernible or overwhelmingly strong, a manifestation of matter in all forms and sizes, from the minutest to the grandest parts of the universe?

7. References

All references to W. Gilbert's De Magnete are to P. Fleury Mottelay's translation, (Dover Publications, N.Y., 1958). This translation was first published in 1893; the 1st edition of De Magnete in 1600.

Reference Number

1. Geomagnetism by Sidney Chapman (London) and Julius Bartels (Potsdam) 2 vols. Oxford, Clarendon Press. 1940
This was the definitive work on the Earth's magnetism -- when it was published in 1940. Section on History of Earth's magnetism has extensive references.

2. Roger Bacon Opus Majus (2 vol.) Translated by R.B. Burke Russell & Russell New York, 1962

3. Francis Bacon Novum Organum

4. Lucretius On the Nature of the Universe (De Rerum Natura) Transl. J.H. Mantinband, F. Ungar Pub. Co. N.Y., 1965

5. Die Physik Paul La Cour and Jakob Appel (German Translation by G. Siebert), F. Vieweg & Sohn Braunschweig 1905 (An elementary text book of physics written from a historical viewpoint)

6. G. Galileo Dialogues Concerning Two New Sciences Tr. by H. Crew and A. De Salvio Dover reprint, orig. 1914 Macmillan Co.

7. William Whewell History of the Inductive Sciences 2 vol. 3rd edition (Article on History of Magnetism Vol. II, Book XII) D. Appleton N.Y., 1858

8. History of Science Ed. René Taton (Engl. Tr.:A.J. Pomerans) Vol. I, Pt. III., Chap. 4; Vol. II, Pt. II., Chap. 5. Basic Books, N.Y. 1963

9. Articles in Encyclopedia Brittanica on Magnetism
9.a. 8th Edition. Vol. XIV. by David Brewster
9.b. 14th Edition. by E.C. Stoner

10. J. Daujat <u>Origine et formation des théories de l'électricité et du magnétisme</u> Paris 1947

11. Paolo Rossi <u>Philosophy, Technology, and the Arts in the Early Modern Era</u> (Transl. Salvator Atlanosio) Harper-Row 1970

12. <u>Scientific American</u> Dec. 1970

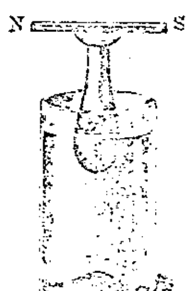
13. <u>The Search for the Magnetic Monopole</u> Science Progress <u>LI</u>, 601, (1963)

26.17. Summary of important events in the history of geomagnetism up to about 1850.

A.D. 1030–93.	The Chinese encyclopaedist Shon-Kua described the magnet pointing south.
About 1187.	Alexander Neckam of St. Albans described the magnetic compass.
About 1450.	Sun-dials made in Nuremberg showed marks for magnetic declination.
About 1492.	German road maps containing the figure of a compass indicating the declination.
1538–41.	João de Castro, on a voyage to the East Indies, made forty-three determinations of magnetic declination.
1544.	Letter by Georg Hartmann of Nuremberg, referring to the magnetic inclination.
1576.	Robert Norman, *The Newe Attractiue.*
1600.	William Gilbert, *De Magnete.*
1635.	Henry Gellibrand discovered the secular variation of declination.
1672.	Daniel Tilas died (inventor of the Swedish mining compass for magnetic propecting).
1698–1700.	Halley's voyages in the Atlantic Ocean on the *Paramour Pink.*
1701.	Halley's sea chart of the whole world.
1721.	William Whiston's charts of inclination.
1722.	George Graham discovered non-secular time-variations.
1741 April 5.	Simultaneous magnetic observations by Celsius at Upsala and Graham at London; discovery of the relation between magnetic disturbance and aurora.
1759.	Solar daily variation found to be greater in summer than in winter (by Canton).
1770.	Wilcke observed that auroral rays are parallel to the magnetic inclination.
1782.	Cassini found that the daily variation of declination is independent of the daily variation of air-temperature.
1799–1804.	A. von Humboldt's expedition to America.
1819.	Hansteen's *Untersuchungen über den Magnetismus der Erde.*
1820–35.	Arago's observations of the magnetic declination at Paris.
1826.	Poggendorff introduced readings by means of mirror and scale.
1837.	The earth inductor invented by Weber.
1838.	Gauss's *Allgemeine Theorie des Erdmagnetismus.*
1839.	Lloyd introduced the magnetic balance for recording the variations of the vertical intensity.
1836–41.	The Göttingen Magnetic Union.
1839.	Establishment of the British Colonial Observatories (Sabine).
1846.	Charles Brooke constructed photographic apparatus recording magnetic variations.
1850.	Kreil found the lunar daily variation of declination at Prague.
1851.	Schwabe discovered the sunspot cycle.
1852.	Sabine found the effect of the sunspot cycle in the disturbances of declination at Toronto.

das Wasser legen sie eine Nadel, die in einem Holzkreuz befestigt ist, und wenn sich das Holzkreuz frei drehen kann, so zeigt die Nadel Norden und Süden." — Eine derartige Nadel bewegt sich jedoch etwas träge, da das Wasser einen bedeutenden Widerstand leistet. Kepler (1, § 72), der über den Kompaß schrieb, gab dem Schwimmer eine etwas andere Form, bei der der Reibungswiderstand des Wassers weniger störend war. Die Nadel wird von einem birnförmigen Behälter getragen (Fig. 157), und der Reibungswiderstand läßt sich noch weiter dadurch vermindern, daß man als Flüssigkeit ein Gemisch von Wasser und Spiritus verwendet.

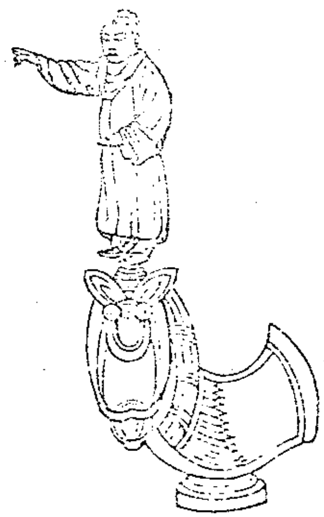
Fig. 157.



Keplers Richtungsnadel.

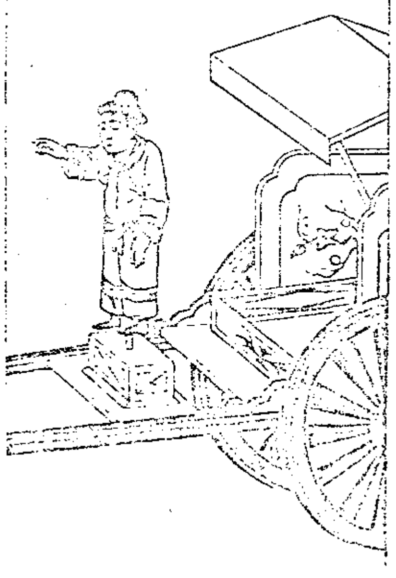
§ 195. Die ältesten chinesischen Erzählungen über den „Südweiser" knüpfen sich jedoch nicht an schwimmende Nadeln, sondern an die sogenannten magnetischen Wagen, die der Sage nach 2000 Jahre vor unserer Zeitrechnung in Gebrauch gewesen sein, dann aber verloren gegangen und erst im 3. Jahrhundert n. Chr. wieder zum Vorschein gekommen sein sollen. Der magnetische Wagen hatte einen Südweiser, der in einer menschlichen Figur verborgen war, die sich leicht um eine vertikale Achse drehen konnte. Die Figur bestand aus Nephrit, einem in China vorkommenden Mineral, und deutete, wohin auch der Wagen gefahren war, mit ausgestrecktem Arm nach Süden. Im Arm ist die richtende [illegible]

Fig. 158.



Chinesischer Südweiser.

Fig. 159.



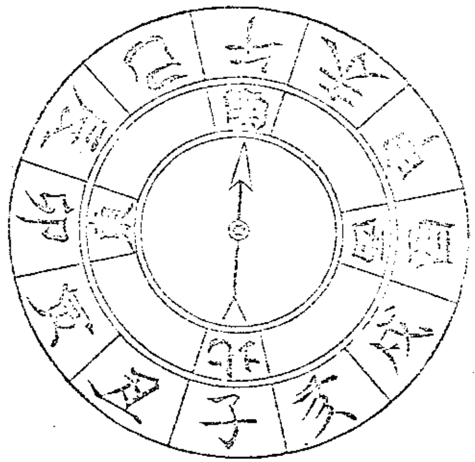
Magnetischer Wagen aus Japan.

Magnetnadel verborgen. Die Fig. 158 und 159 stellen einen chinesischen Südweiser und einen magnetischen Wagen aus Japan vor, dessen Könige diesen nützlichen Apparat von den Chinesen im 7. Jahrhundert kennen lernten.

Mit Hilfe dieser Wagen konnten die Kaiser von China den Weg durch die ausgedehnten unbewohnten Strecken in ihrem Reiche finden. Die Nadel gab nämlich fortwährend an, in welcher Richtung sich der Wagen bewegte. Außerdem war der Wagen mit einem Zählwerk versehen, durch welches die Anzahl der Umdrehungen der Räder angegeben wurde. Jedesmal wenn eine Meile zurückgelegt war, schlug eine kleine Figur an eine Glocke, und nach jeder zehnten Meile wurde von einer zweiten Figur eine andere Glocke angeschlagen. Der magnetische Wagen gab also nicht nur die Richtung, sondern auch die Länge des zurückgelegten Weges an.

§ 196. Die Magnetnadel diente bei den Chinesen auch als fester Wegweiser. Eine richtige Verwendung fand sie ferner bei der Feststellung der Richtung, in der ein Haus erbaut werden sollte. Dies war eine feierliche Handlung, die von einem Magier ausgeführt wurde. Das Glück des Hauses hing in nicht geringem Grade von der Genauigkeit ab, mit der die Richtung bestimmt wurde. Diese brauchte nicht notwendigerweise die Nordsüdrichtung zu sein. Auch andere Richtungen konnten ihre Bedeutung und ihren glückbringenden Einfluß haben. Es kam daher eine Teilung in Gebrauch, vermittelst deren man die verschiedenen Richtungen in bezug auf Norden und Süden bestimmen konnte. Fig. 160 stellt eine alte japanische Kreisteilung vor. Die Magnetnadel hat die Form eines Pfeils und deutet mit der Spitze nach Süden. Der innere Kreis gibt die vier Himmelsgegenden Süd, Ost, Nord und West an. Der äußere Kreis ist in zwölf Teile eingeteilt, deren jeder mit einem Zeichen versehen ist, welches den Namen eines Tieres bedeutet. Dieselben zwölf Zeichen finden sich in Fig. 161 (a. f. S.), einer chinesischen Einteilung mit drei Kreisen, von denen der äußere die den zwölf Zeichen entsprechenden Tiere darstellt. Norden hat die Ratte [illegible], Osten den Hasen, Süden das Pferd und Westen das Huhn. Der [illegible] Kreis der Fig. 161 enthält die wissenschaftlichen Zeichen für die [illegible] Himmelsrichtungen, Nord, Nordost, Ost u. s. w.

Fig. 160.



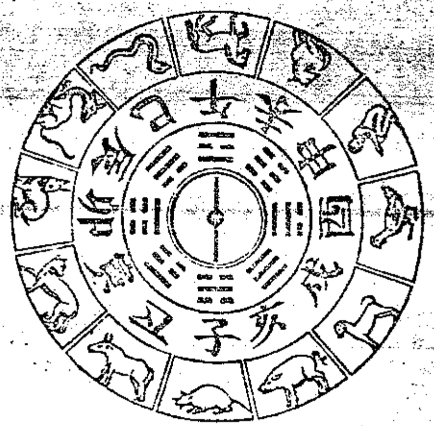
Magnetnadel mit japanischer Kreisteilung.

§ 197. Im Dienste der Seefahrer [illegible]

63

8. Jahrhundert n. Chr. auf ihren langen Seefahrten von Kanton über Ceylon bis zum persischen Golf ihre Schiffe mit Hilfe des Kompasses gesteuert haben. Im 13. Jahrhundert war in der chinesischen Marine der Kompaß allgemein in Gebrauch. Eine im Jahre 1297 erschienene chinesische Schrift gibt nämlich den Kurs der Schiffe durch die Richtung der Magnetnadel an.

Fig. 161.



Chinesische Kreisteilung.

In demselben Jahrhundert war der Kompaß auch in den Mittelmeerländern bekannt, und das Gerücht von demselben war mindestens ein Jahrhundert früher nach Frankreich gedrungen, denn er wird in einem Gedichte von **Guyot de Provins** aus dem Jahre 1190 erwähnt. Es ist daher nur eine Sage, wenn erzählt wird, **Flavio Gioja** aus Pasitano bei Amalfi habe am Anfang des 14. Jahrhunderts den Kompaß erfunden und in Europa eingeführt. Wenn er überhaupt irgendwelche Verdienste in dieser Richtung hat, so mag es wohl sein, daß er den Kompaß auf den neapolitanischen Schiffen eingeführt hat. Wenn man aus diesem Grunde sein Andenken geehrt hat, so ist dies sehr erklärlich, da die Einführung des Kompasses die Entwickelung der Seefahrt außerordentlich gefördert hat.

§ 198. Die Entdeckung, daß sich die Magnetnadel in die Richtung von Norden nach Süden stellt, muß alsbald weitere Entdeckungen zur Folge gehabt haben. Die Chinesen bestrichen das Ende der Nadel, welches nach Süden deutet, mit roter Farbe. Sie waren also darüber im klaren, daß die beiden Enden der Nadel voneinander wesentlich verschieden sind, daß es immer dasselbe Ende ist, welches nach Süden deutet. Diese Eigenschaft der Nadel führte später dazu, daß man das nach Süden gerichtete Ende den Südpol, das andere den Nordpol nannte.

Selbstverständlich wußten die Chinesen, daß beide Pole Eisen anziehen, aber zugleich haben sie jedenfalls auch beobachtet, daß die beiden Pole zueinander ein ganz eigentümliches Verhalten zeigen. Wenn man nämlich zwei Richtungsnadeln nebeneinander hat, kann man wohl schwerlich übersehen, daß die beiden Südpole und ebenso die beiden Nordpole sich gegenseitig abstoßen, während ein Südpol und ein Nordpol sich einander anziehen. **Gleichnamige Pole stoßen sich ab, ungleichnamige ziehen sich an.** Es gibt also nicht nur eine magnetische Anziehung (Wirkung des Magnetpols auf Eisen), sondern auch eine magnetische Abstoßung. Dieses merkwürdige Verhalten ...

fig. 38 The origins of the compass: Magnetite spoon resting on a polished bronze plate. (*The Chinese characters which are engraved on the plate have been omitted.*)

The Compass

The origins of the compass must be sought in the attempts by Chinese diviners to foretell the future from the direction in which a spinning spoon came to rest. Chinese spoons have a short handle and are balanced about a central point. A south-pointing spoon made of magnetite and pivoting on a polished bronze plate is mentioned in the *Lun Hêng* ('Discourses weighed in the Balance', A.D. 83). It is also depicted on a bas-relief dated A.D. 114, which is kept in the Zürich Museum (*fig. 38*). Floating or pivoting magnetic needles are mentioned in ninth- to twelfth-century texts and were used for land surveying. It seems likely that sailors took over the compass from the Fu Kien geomancers. In 1125, a floating compass was carried during a voyage to Korea.

From Than Chhiao's 'Book of Transformations' (*Hua Shu*), written about 940, we know that four sorts of lenses were known at the time. The high Sung official, Shen Kua, was familiar with the camera obscura and the compass, and produced an artificial magnet by cooling a small trough of molten steel with its axis lying in a north–south direction. He also appreciated the significance of fossils. He prescribed naphtha as a substitute for wood-fuel and hence as a measure against deforestation. His writings on pharmacology, in particular, show how greatly knowledge of natural history had advanced over the past.

Reproduced from Ref. 4,

Besides, they are compelled to break out through the water
dispersed, and then they come together on reaching the surface.
This is like the spring of Aradus in the sea,[29]
sweet and fresh, which dispels the salty brine around it,
and here and in other places too, the sea provides
welcome refreshment for the thirsty mariners
by spurting forth fresh water right amid the brine.
This is the way the particles of fire burst forth
through that other spring, until they reach the tow
and when they meet there, or on the torch's body,
they easily catch fire straightway, for the tow itself
and also the torch have many seeds of fire in them.
Have you not seen how, if you begin to bring a wick,
newly extinguished, to a burning night-light, it kindles
before it touches the flame, and likewise with a firebrand?
And many other things, when only touched by heat,
will blaze into fire before the flame itself can touch them.
This is what we must suppose takes place in the spring.

Next I shall explain by what decree of Nature
iron is caused to be attracted to that stone
called by the Greeks a *magnet* from its origin,
since it is found in the land of the Magnesians.
Men think it miraculous, because it makes a chain
of individual little rings that hang from it.
Sometimes you can see as many as five or more
hanging in succession, and swaying in the breeze,
each one clinging to the one above, and deriving
each from the other the magnet-stone's mysterious power.
So powerful is the attraction of this magnet-stone.

In matters of this sort, many facts must be established
before you can give the reason for the thing itself,
and the approach must often be quite circuitous:
therefore give heed with all your powers of concentration.
In the first place, from everything that we can see[30]

[29]An island off the Phoenician coast. Cf. Pliny *N.H.* ii, 227.
[30]Lines 923-935 = iv, 217-229 with slight variations.

there is a perpetual stream of particles
striking the eye, and these are the cause of all our vision.
And from some things there is a constant flow of odors,
as cold from rivers, heat from the sun, and spray from the ocean,
which eats away and erodes the walls around the seashore.
And sounds and voices travel incessantly through the air.
Again, a salty tang will strike us in the face
when we walk along the beach; and when wormwood is mixed
in our presence, we can sense the bitter taste.
So from all things there is a flow of particles
and these are diffused and spread about in all directions;
there is no delay or interval to the flow,
since we constantly can feel them, and at all times
we see them and we smell them and we hear the sounds.

Now let me repeat how porous all things are
(a fact which I have explained already in Book One),[31]
for an understanding of this is of great importance
in many respects, especially in the subject on hand,
which we are about to discuss. First we must understand
that there is nothing that does not consist of atoms and void.
In the first place, in rocky caves, we find the roofs
are always dripping and exuding drops of water.
Sweat, moreover, oozes from all parts of our body,
and hair grows on our chin, and over all our limbs.
Food is dispersed into the veins, building and feeding
the extreme parts of the body, even the fingernails.
Cold and also heat are felt to pass through bronze,
and we feel the same sensation in gold and silver
when we hold full drinking-vessels in our hands.
And sounds and voices fly through the dividing walls
of houses, as do smells and cold and fiery heat,
which can even penetrate the strength of iron.
And even heaven's breastplate that surrounds the world[32]

[31]Cf. i, 329 ff; 348 ff.
[32]There is a gap here, probably containing something like:
"is penetrated by all kinds of elements"
This passage has been much emended, lines transposed, etc.

sickness at the same time, coming from outside,
and tempests from the earth and sky, respectively,
can easily penetrate into the sky and earth,
since nothing that exists is altogether solid.
Besides, not all the particles that are thrown off
from various objects, have the same kind of effect
on sensation, or on the substances they meet.
The sun, for instance, bakes the earth and hardens it,
but it melts ice, and its burning rays make the deep snowdrifts,
piled up high on the lofty mountains, thaw and melt.
And wax is liquefied by contact with its heat,
and fire likewise makes bronze melt and gold dissolve,
but it shrivels skin and flesh and makes them contract.
Water hardens iron that has been in the fire,
but it softens skin and flesh made hard by heat.
Wild olive is a delicacy for bearded goats,
as if it were dipped in nectar and ambrosia,
but nothing has more bitter leaves for human beings.
Pigs will flee from marjoram and shrink from perfumes,
for that which is to us a pleasant restorative,
is the most deadly poison to the bristly pig.
But filthy mud which is for us so very loathsome
is a source of great delight to these same swine,
so that they never weary of wallowing in it.

There is another matter which must be explained,
before we can approach the topic under discussion.
Since different objects have many different pores and channels,
these must also be endowed with different natures,
inasmuch as each thing has its own nature and channels.
For living creatures are endowed with different senses,
each of which perceives its own and proper object;
for sound we perceive with one sense, and taste with another,
and the smells of various odors with yet another.[33]
Furthermore, we know that some things go through stone,

[33] Lines [illegible] = 995-996, and are rejected by all edd.

while others pass through wood, and others still through gold,
and yet another finds its way through glass or silver.
The former transmits images, the latter heat,
and the same thing transmits different atoms at different speeds.
Clearly it must be the nature of the passages
that makes for this variety, as I have shown,
due to the varied forms and textures of different things.

Now that all these matters have been well established
as a preparation for further argument,
the rest is easy: to deduce from these the reasons
for the phenomenon of the attraction of iron.
First, the Magnet-stone must send great quantities
of atoms, in a current which beats upon the air
bombarding all the space between the stone and the iron.
When this space is empty, then a void or vacuum
remains in the middle, and straightway the atoms of iron
rush forward to fill this vacuum, tangled all together
so that the ring itself will follow in a body.
Indeed, no other substance is so tightly packed
by the intertwining of its component atoms
as the strong and chilly roughness of iron's nature.
No wonder, then, as I have said, if a cluster of atoms
from the iron cannot move into this vacuum
without the whole ring's body following upon it.
And this is just what happens: it follows till it reaches
the Magnet-stone, and clings to it by invisible bonds.
This happens in any direction where a vacuum exists,
whether it is above or below or on the sides:
the nearby atoms move at once to fill the space.
For they are bombarded from the other directions
and cannot rise into the air of their own accord.
To this must be added an auxiliary factor—
another movement that facilitates this action—
namely: as soon as the air that is in front of the ring
is rarefied, and all the space is evacuated,
it follows then that all the air behind the ring
pushes it and propels it forward from behind,

For air is continuously bombarding every object,
but in this case it actually propels the iron
because of the vacuum which is ready to receive it.
This air of which I am speaking slips into the spaces
of the iron and pushes on the particles,
propelling them as the wind propels our ships and sails.
And all things must have this air within their bodies,
since they are all of porous texture, and the air
surrounds, envelops, and is adjacent to all things.
This air, which is hidden in the iron's inmost depths,
is agitated and is in perpetual motion
bombarding the ring, of course, and moving it from within.
And the ring must be propelled in that direction
in which it has started on its path towards the vacuum.

But sometimes the iron is repelled by the stone
and it tends to flee and follow in succession.
I have even seen some rings from Samothrace
dancing, and iron filings in a brazen bowl
jump about when the Magnet-stone was placed beneath them,
so eager was the iron to escape from the stone.
When the bronze is interposed, discord is created,
because, no doubt, the current from the bronze has come
and occupied the open channels in the iron,
and then the current from the stone comes in and finds
all the iron's pores are full and it cannot swim through
as it did before, so that it must strike and buffet
the iron with its stream, and thus it repels the iron,
driving away, through the bronze, what normally it attracts.

But you must not be surprised if the Magnet's power
does not have the strength to propel other things as well.
For some are firm because of their weight, as gold, for instance,
and others, because their texture is so very porous
that the current is unopposed, and they cannot be pushed:
wood is a good example of this sort of substance.
But the nature of iron is between these two,
and when it receives bronze atoms, then it follows

But there are other examples of this kind of attraction,
and it is easy to think of many instances
of substances that attract each other, but nothing else.
For stones can be cemented by nothing except mortar,
and wood is joined together only by bull's glue,
so that the wood will sooner crack and split wide open
that the bull's glue will relax its tenacious hold.
The juice of grapes will easily mix with fountain-water,
which heavy pitch and lighter olive oil cannot do.
The brilliant hue of Tyrian shellfish mingles only
with wool, so that it cannot ever be separated,
not even if you try to bleach it with Neptune's ocean,
nor if the sea tried to wash it out with all his waves.
Again there is only one thing that can solder gold[34]
and bronze can only be joined to bronze by using tin.
Other examples can be found, but to what purpose?
For there is no need of such roundabout explanations,
nor is it necessary to belabor the point,
for many things may be explained in a very few words;
when the textures of objects mutually correspond,
so that one thing's empty spaces fit the full parts
of the other, and *vice versa*, the best link is made.
And some objects are linked together as if by rings
or hooks, in a sort of coupling, as is the case
when we see what happens with iron and the Magnet.

Next I shall explain the nature of diseases
and whence the force of the deadly sickness comes together
making storms of destruction for men and animals.
First, I have shown that there are many elements
which are necessary to support our lives.
But there also must be many that fly about
bringing death and disease. When these have gathered by chance
or accident, the sky is disturbed, and the air is sick.
Now, all these dread diseases and these pestilences

Extract from Lucretius: De Rerum Natura. with Translation by W. Whewell. Ref. 7.

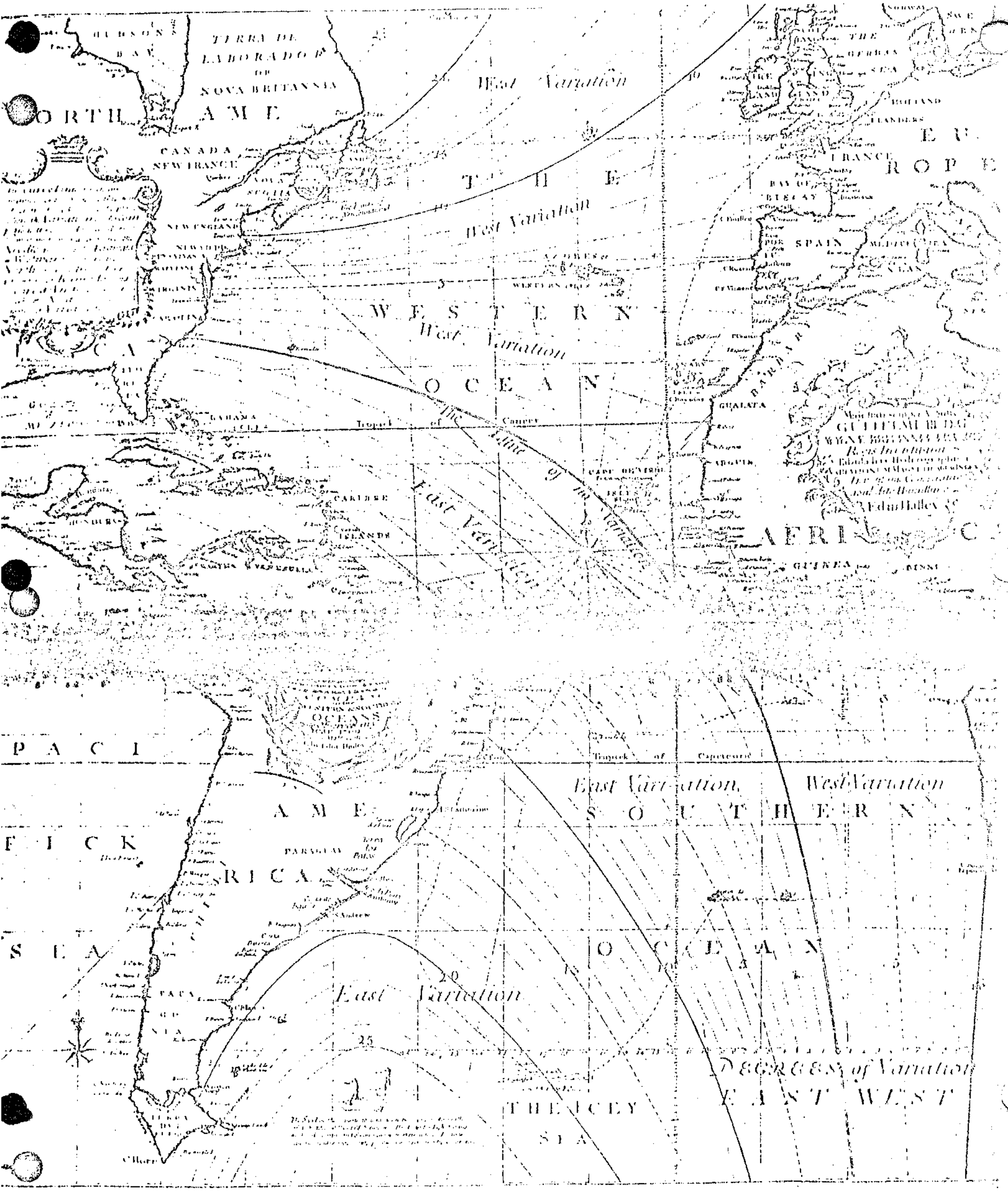
Effice, ut interea fera munera militiai
Per maria ac terras omneis sopita quiescant.
Nam tu sola potes tranquilla pace juvare
Mortales; quoniam belli fera munera Mavors
Armipotens regit, in gremium qui sæpe tuum se
Rejicit, æterno devictus vulnere amoris;
Atque ita suspiciens tereti cervice reposta,
Pascit amore avidos inhians in te, Dea, visus,
Eque tuo pendet resupini spiritus ore.
Hunc tu, Diva, tuo recubantem corpore sancto
Circumfusa super, suaves ex ore loquelas
Funde, petens placidam Romanis, incluta, pacem.

LUCRET. i. 31.

O charming Goddess, whose mysterious sway
The unseen hosts of earth and sky obey;
To whom, though cold and hard to all besides,
The Iron God by strong affection glides,
Flings himself eager to thy close embrace,
And bends his head to gaze upon thy face;
Do thou, what time thy fondling arms are thrown
Around his form, and he is all thy own,
Do thou, thy Rome to save, thy power to prove,
Beg him to grant a boon for thy dear love;
Beg him no more in battle-fields to deal,
Or crush the nations with his mailed heel,
But, touched and softened by a worthy flame,
Quit sword and spear, and seek a better fame.
Bid him to make all war and slaughter cease,
And ply his genuine task in arts of peace;
And by thee guided o'er the trackless surge,
Bear wealth and joy to ocean's farthest verge.

(Compare this translation with the corresponding part of the previous translation:) Ref. 4, p. 3.

Therefore, goddess, grant a lasting grace to my words,
and meanwhile cause the brutal works of war to cease,
to sleep and to be still, on every land and sea.
For you alone can bless mankind with tranquil peace,
since it is mighty Mars who is the Lord of War
and all its brutal works, and he often lies in your lap,
entirely conquered by the eternal wound of love,
and looking upward with his shapely neck bent back,
he feasts his avid eyes upon you, hungry for love;
his breath is hanging upon your lips as he reclines.
And you, O goddess, bend over him as he lies there
upon you holy body, and shed your honeyed words,
and for your Romans, glorious goddess, seek placid peace.



…ey's earliest chart of the magnetic 'variation' (or declination — see p. 1) for the Atlantic Ocean, showing also the course of his ship, the *Paraore* … in which, between 1697 and 1701, he made the magnetic observations that form the basis of this chart. Probably published in 1701. This was …

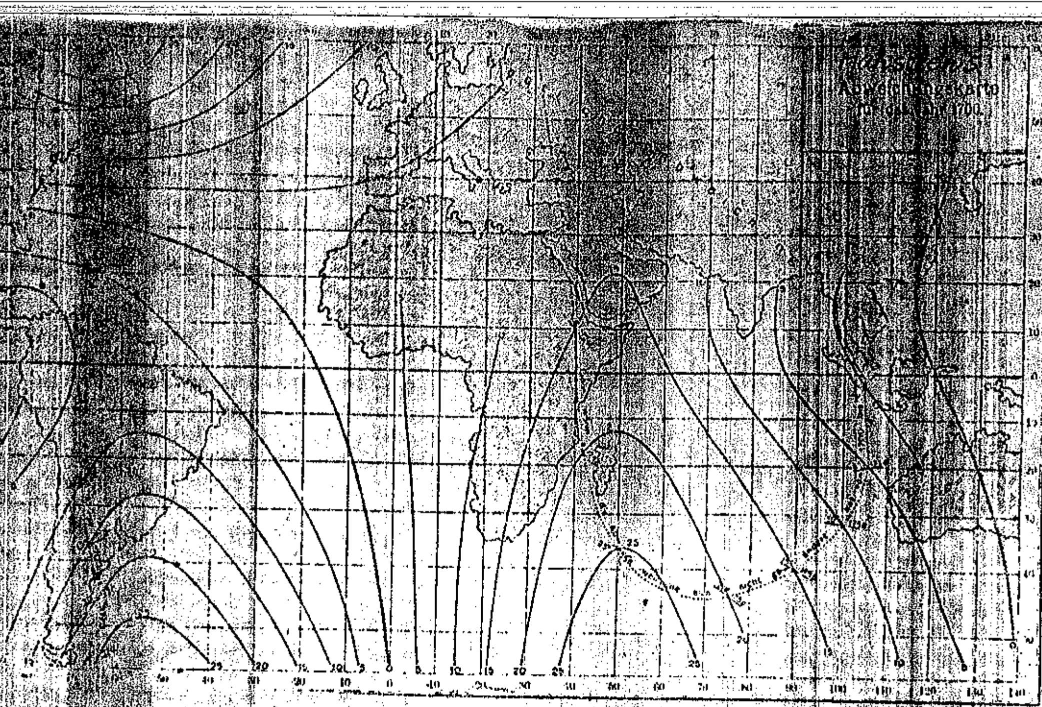
Isogonic lines for:

(a) 1700

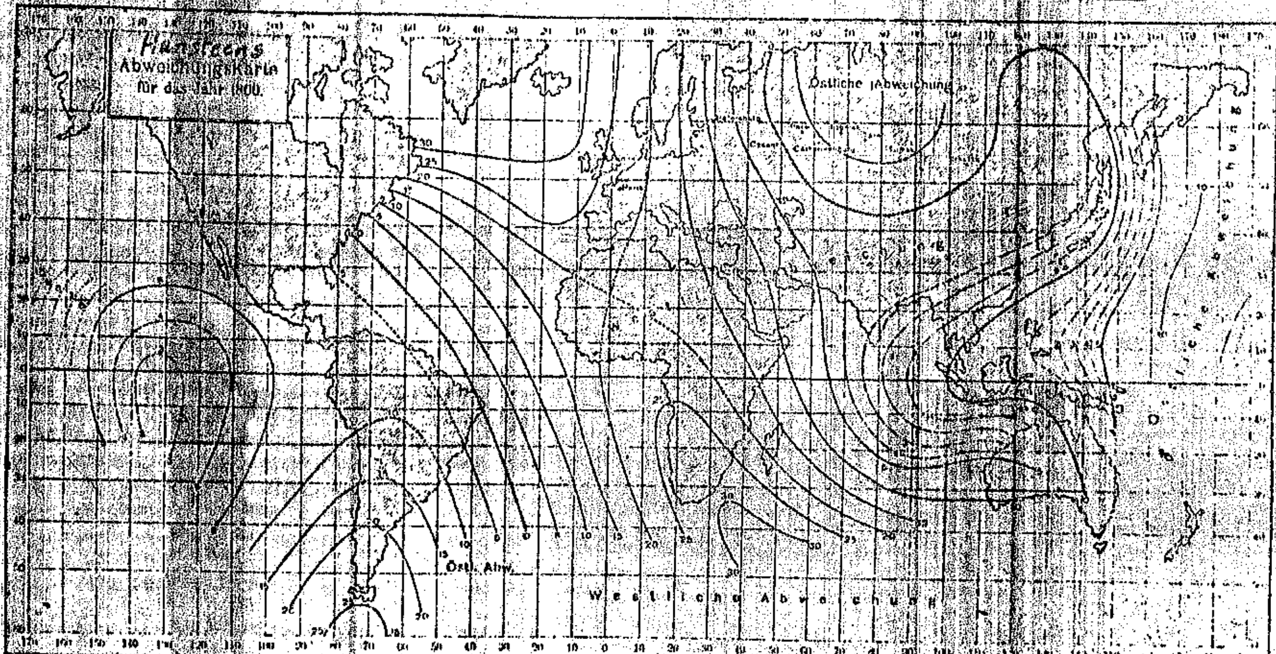
(b) 1800

(c) 1922

(a) from Ref. 3, p. 230



(b) from Ref. 5, p. 231



(c) from Ref. 1, Vol. 1, p. 98

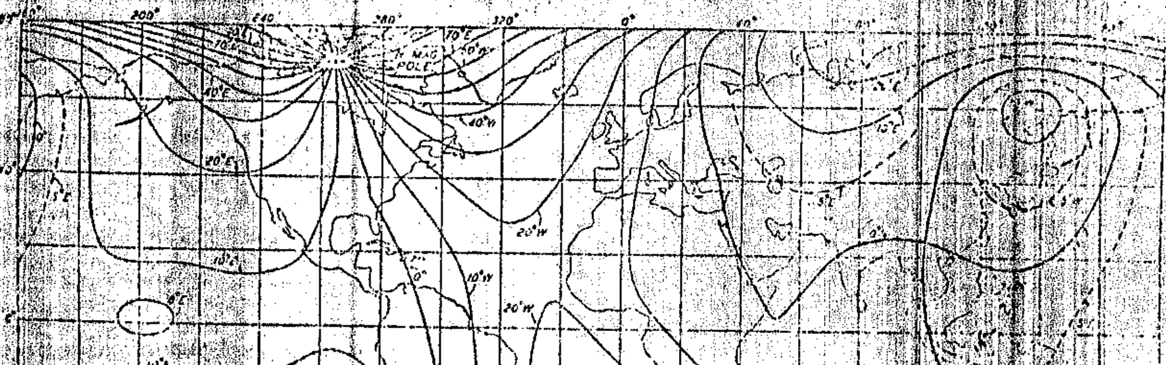
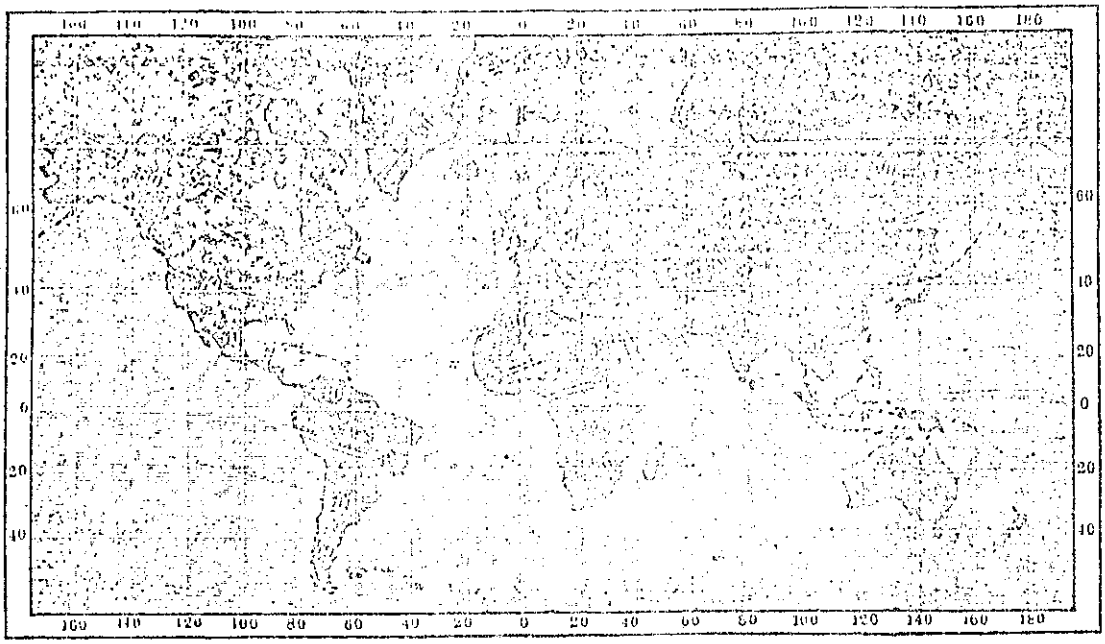


FIG. 1a. Isogonic lines for 1922

ı) from
ef. 5.
233



Inklinationskarte für 1860.

from
r. 1.
100

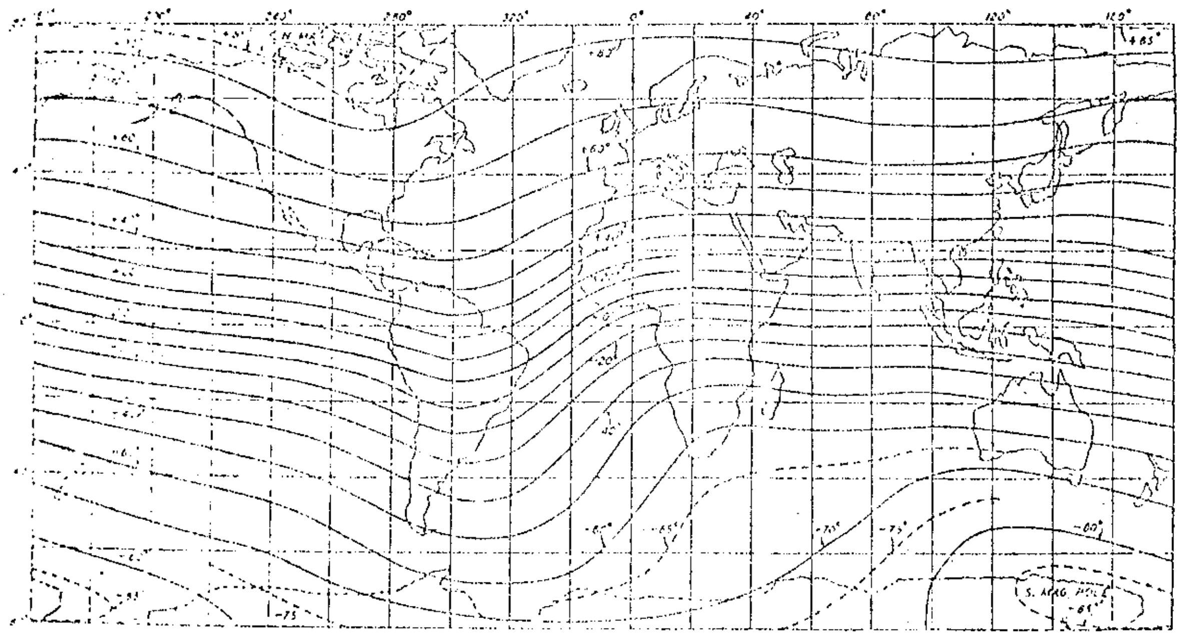


FIG. 3. Lines of equal inclination (I) for 1922

From the Philosophical Transactions of the Royal Society
1775

EXPERIMENTS ON THE DIPPING NEEDLE, MADE BY DESIRE OF THE ROYAL SOCIETY,

BY

THOMAS HUTCHINS.

REDDE, FEBRUARY 16, 1775.

At Moose Fort in Hudson's Bay, September 8, 1774, lat. 51° 20′ North, long. 82° 30′ West from London, variation 17° West.

80° 25′	The index placed West.
80 15	
80 35	
79 0	
80 30	The Index placed East.
81 25	
80 13	
81 13	
79 10	The poles reversed, index East.
80 45	
79 50	
79 10	
79 10	The index placed West.
80 25	
79 45	
80 5	

The observations were made on shore. So remarkable difference between them, when I was expecting quite the reverse, surprized me as much as the increased inclination of the needle from observations made nearly in the same parallel of latitude in London. I endeavoured, by drawing a magnetical meridional line with chalk, and paying the greatest attention to keeping the instrument perfectly steady and horizontal, to render

At Albany Fort in Hudson's Bay, September 14, 1774, long. 82° 30′ West, lat. 52° 22′ North, variation 17° West.

°	′
80	13
80	25
79	37
79	55

I made a trial of the instrument at this place, but having lost the slip of paper on which I had noted the experiments, I was dubious whether I should insert the above or not. I can only recollect these four, and am not positive which way the index stood; however, I remember that the mean of all the observations I made was something less than 80°. Time will not permit me to repeat the operation during the ship's stay in these parts; I must therefore defer it to a future period. During the winter, I shall have frequent opportunities of amusing myself this way; and the respect I bear the Royal Society, makes every service I render to that illustrious body an additional happiness to

Their devoted servant,

Albany Fort,
September 17, 1774.

THOMAS HUTCHINS

From Ref. 1. (Vol. 1. p. 101)

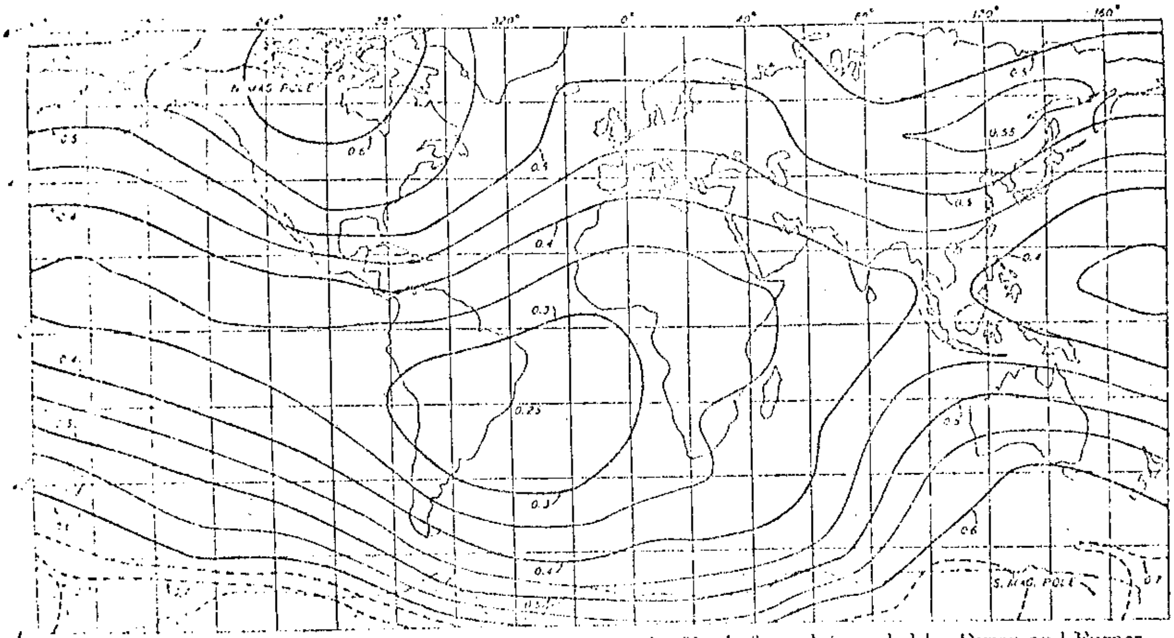


FIG. 4. Lines of equal total intensity (*F*) for 1922. (Drawn by Ennis from data scaled by Dyson and Furner from British Admiralty charts)

From Ref. 1. (Vol. 1. p. 106)

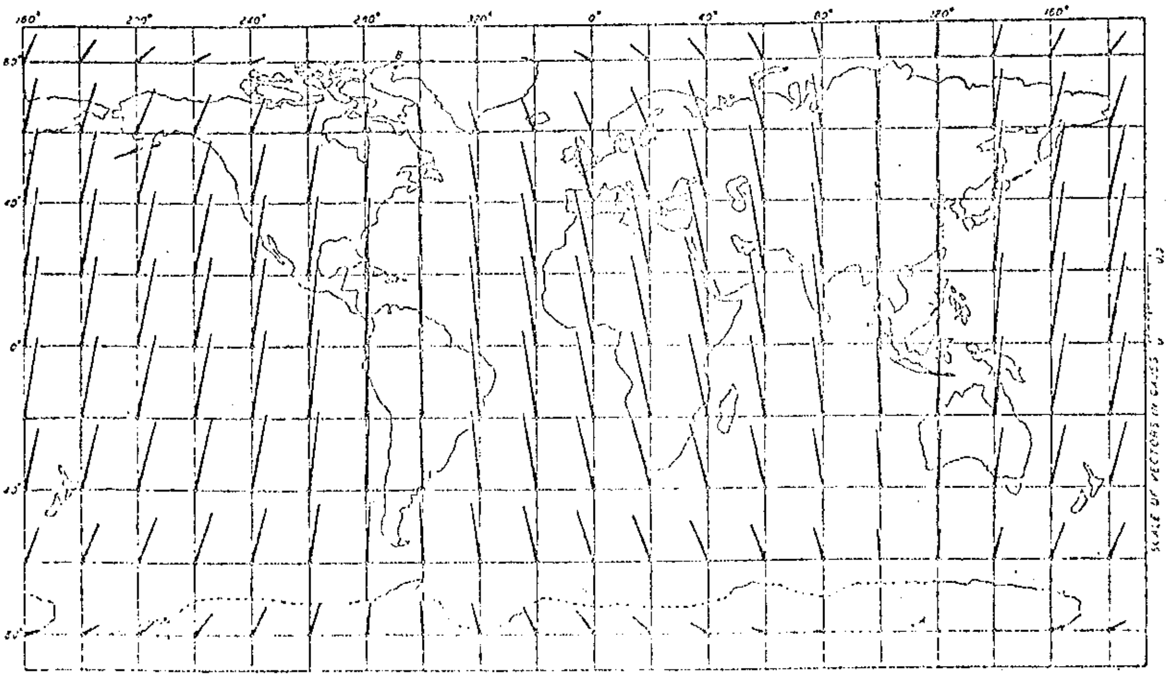


FIG. 8. Vectors showing at different points on the earth the magnitude and direction of the horizontal magnetic force corresponding to the field F_1 of the central dipole, or the field of uniform magnetization, that most nearly approximates to the earth's field F

Fr ef. 1. p. 220

(a)

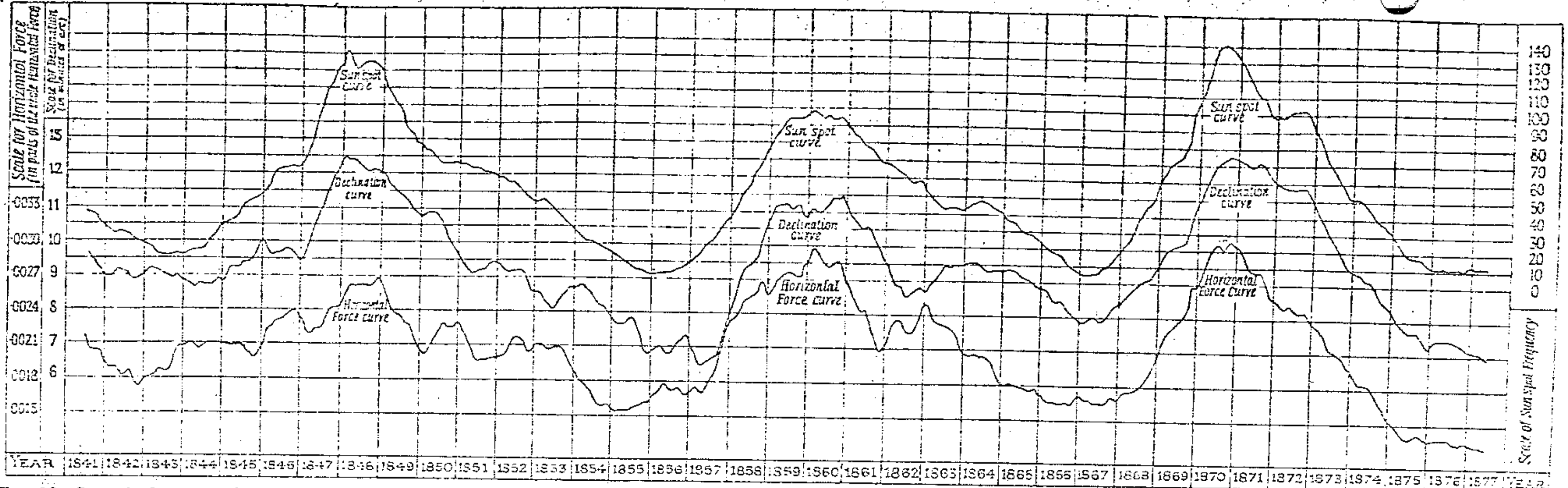
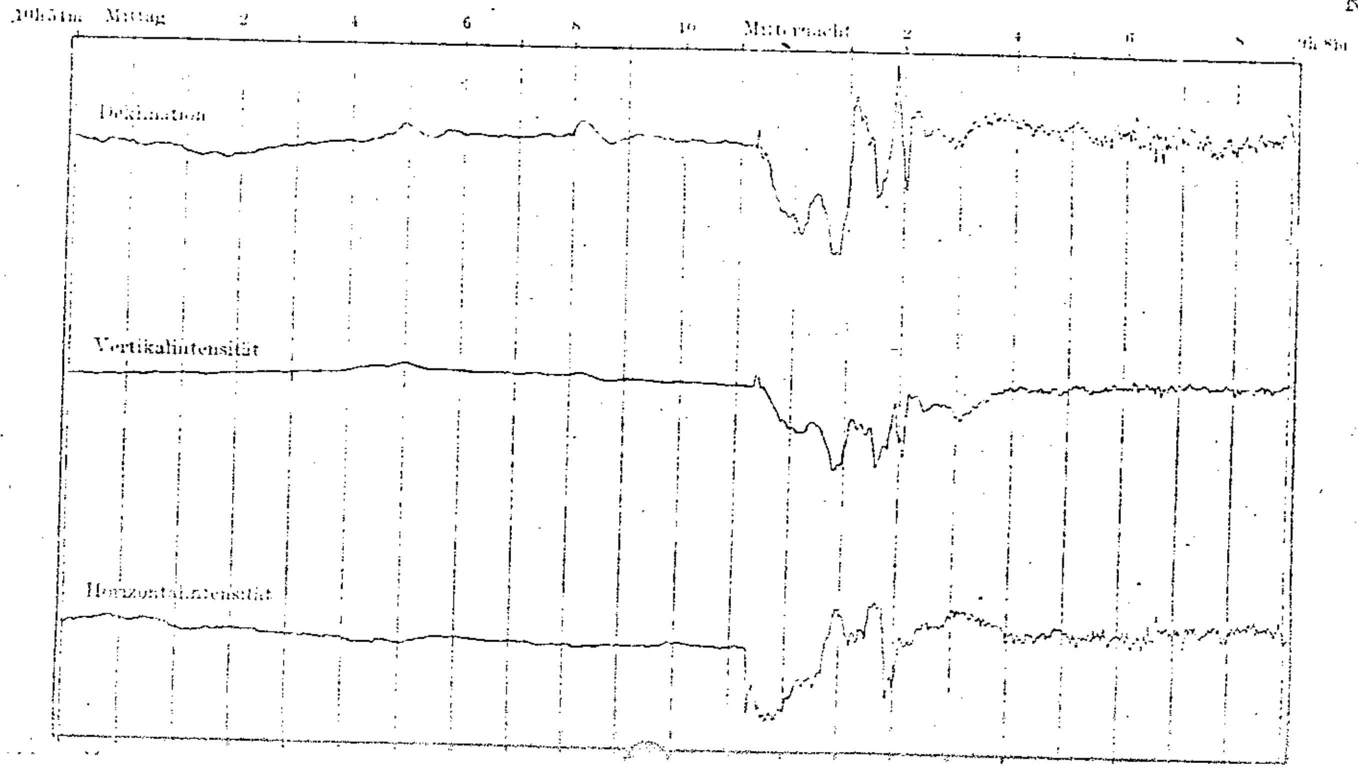


FIG. 10. Smoothed curves of sunspot frequency (Wolf numbers) (top) compared with the corresponding curves showing the variation in the daily range of declination (middle) and horizontal force (lowest) at Greenwich, 1841–77 (after Ellis)

(b)

Ref. 5. p. 245



From Ref. 12.

PERMANENT MAGNETS

by Joseph J. Becker

New alloys of cobalt with rare-earth elements have magnetic properties so superior to those of former materials that they constitute virtually a new class

Hidden somewhere inside a great variety of electrical and electronic devices is a permanent magnet, and often not one but several. The only magnets most people ever see, however, are the ones that hold the refrigerator door closed or that catch the lid of a freshly opened tin can. Hidden though they may be, magnets exert a large influence on the design and performance of every device in which they are used. The more powerful the magnet for a given size is, the smaller it can be for a given job. (The old-fashioned telephone receiver was not given its elongated shape so that it would be convenient to hold but to accommodate the long tungsten-steel magnet needed to make it work.)

Within the past few years a new class of materials for making permanent magnets has been developed, based on cobalt and some of the rare-earth elements. The improvement over other materials is so great that the cobalt-rare-earth magnets stand in a class by themselves. In terms of their resistance to demagnetization the new materials are from 20 to 50 times superior to conventional magnets of the Alnico type, and their magnetic energy is from two to six times greater. As a result the cobalt-rare-earth magnets should eventually find their way into applications for which other materials could not even be considered.

Elements that are ferromagnetic, such as iron, cobalt and nickel, have atoms in which one electron shell contains fewer than the maximum number of electrons. In such unfilled shells there are one or more unbalanced electron spins, giving rise to a small magnetic moment and making the atom itself a tiny magnet. Ordinarily in a large collection of such atoms the atomic magnets point in various directions and cancel one another. If a sample of ferromagnetic material is placed in a magnetic field, however, the individual atomic magnets tend to line up so that when the sample is removed from the field, it retains a net residual magnetism, with an observable north and south pole. The total mag- [illegible] of a piece of material is elementary atomic magnets. If all the atomic magnets are parallel and pointing in the same direction, the magnetization in that direction reaches its saturation, or maximum, value.

Magnetic materials are traditionally divided into two categories: "hard" and "soft." A hard material is difficult to magnetize and demagnetize; thus it is what one ordinarily wants in a "permanent" magnet. A soft material has the opposite property: it is easily magnetized and demagnetized. The softer the material is, the better it is suited to certain electrical devices, such as a transformer, in which the magnetization must be reversed many times per second.

. . . . . .

The mechanism that makes a magnet hard can be described theoretically in terms of magnetic "domains." It was proposed as early as 1907 and demonstrated experimentally in the 1930's that ordinary ferromagnetic materials are subdivided into the microscopic regions called domains [*see illustration on page 93*]. Within each domain the individual atomic magnets are parallel; whichever way they happen to point determines the direction of magnetization of that domain. The boundaries between domains are not fixed but can move in response to a magnetic field. They move in such a way that domains whose magnetization is in the direction of the field grow at the expense of the others. The total externally measured magnetization, which is the sum of the domain magnetizations, thus increases. The motion of domain boundaries can cause large changes in magnetization.

To make a magnetic material soft, the motion of domain boundaries should be made as easy as possible. Soft magnets are characteristically fabricated from a material with a uniform structure, free from inclusions and annealed to relieve strains. For a long time it seemed logical that hard materials should have directly opposite properties. Thus early carbon steels were quenched to produce a structure called martensite, consisting of a [illegible]

The Alnico alloys, introduced in the late 1930's, owe their magnetic properties to the metallurgical precipitation of a finely dispersed intercrystalline second phase.

Around 1950 several investigators (including the French physicist Louis Néel, who is sharing the 1970 Nobel prize in physics for his many contributions to magnetism) proposed a new theory for the design of hard-magnet materials, arguing that if ferromagnetic particles were made small enough, there would be no room for domain boundaries. Coercive forces might be very high because reversal of magnetization would have to take place by rotation of magnetization of the entire particle, which should be more difficult than the displacement of domain boundaries. The size of the particles needed to implement this new theory depended on the material selected. For iron the size could not exceed a few hundred angstroms, comparable to the dimensions of a medium-size virus. Ideally the particles should be highly elongated to make rotation of the magnetization still more difficult.

Ingenious efforts to prepare such particles have led to useful materials, but their properties fall far short of the spectacular predictions made by some early proponents of the fine-particle theory. Irregularity of particle shape appears to be the fundamental stumbling block. Perfectly smooth, elongated particles of the right dimensions might still produce coercive forces approaching 10,000 oersteds, as the theory predicts, but no one knows how to make them.

As hopes for this particular theory faded, attention shifted to another way crystalline materials can resist magnetic rotation. All ferromagnetic crystals are anisotropic, meaning that the magnetization prefers to follow certain crystallographic directions—the "easy" axes—and energy is required to rotate the magnetization to some other direction. The magnitude of the anisotropy varies widely from material to material. If a material could be found combining large anisotropy with a reasonably large magnetization, it might qualify as a good hard-magnet material if it were also in fine be limited only by the value of the anisotropy. Furthermore, there were theoretical reasons for believing that the effective particle size would be large enough for it to be achieved simply by grinding the bulk material. This line of reasoning had for several years guided a search for anisotropic materials among the intermetallic compounds of iron, cobalt, manganese and nickel with a variety of elements such as boron, phosphorus, germanium, aluminum and tin. Some of the materials turned up were interesting but not really outstanding.

Then in 1966 Gary Hoffer and Karl Strnat of the Air Force Materials Laboratory published some remarkable measurements of a single crystal of an intermetallic compound containing five atoms of cobalt for each atom of yttrium: Co_5Y. The material has a substantial magnetization value and an anisotropy several times larger than that of any previously known material. Its anisotropy is so high that its resistance to demagnetization could conceivably be as high as 200,000 oersteds, or more than 100 times the value of typical Alnico materials.

Initial experiments with bulk quantities of Co_5Y, however, were disappointing. Not only was the material difficult to prepare but also attempts to increase its coercive force by mechanically reducing it to small particles seemed to be self-defeating. The coercive force would rise to about 2,000 oersteds and then fall again with further grinding. Evidently the grinding was deforming the crystal structure so much that the inherent anisotropy was being destroyed.

The author, working at the General Electric Research and Development Center, and the Air Force group collaborated closely in an investigation of Co_5Y and related compounds. It had been known for some years that compounds analogous to Co_5Y could be prepared by substituting lanthanum or other rare earths for yttrium. In 1967 we jointly announced that the cobalt-samarium compound Co_5Sm developed far higher coercive forces than any of its near relatives and that it looked extremely promising even at that early stage.

The pace of development has been very rapid since then, with studies going forward in many laboratories. The fabrication of good magnets requires the solution to a number of basic processing problems. Once the material is reduced to a powder of favorable size it must be aligned by a strong magnetic field so that done the powder must be compacted into a dense form. This final and important step can be accomplished either by mechanical pressure or by a sintering process. Both have been successful.

The Philips Research Laboratories in the Netherlands, the Raytheon Corporation and General Electric have all announced the successful fabrication of cobalt-samarium permanent magnets with an intrinsic coercive force of from 10,000 to 30,000 oersteds and with a maximum energy product of from 16 million to 20 million gauss-oersteds. Such intrinsic coercive forces are some 30 times higher than the forces found in typical Alnico alloys, and the maximum energy products are about three times as great. This represents a remarkable amount of progress since the original discovery of the anisotropy of Co_5Y in 1966.

As one might expect, the new materials are still expensive. At the moment, using laboratory quantities of pure metals, the raw-material cost of cobalt-samarium magnets is around $40 per pound. Even at this price there are applications where the superior performance of the new magnets is well worth the cost.

Rare-earth elements are not really very rare, however; the chief cost in their preparation is in separating them from one another. One effort to reduce the cost of rare-earth magnets involves using rare-earth mixtures, called "mischmetal," in place of pure elements in combination with cobalt. Mischmetal, the mixture of rare-earth metals that results from reducing the mixed ore, has long been used as a deoxidant in steelmaking and, more familiarly, in flints for cigarette lighters. In this form the rare earths cost only a few dollars per pound. Up to now, however, efforts to make good magnets with mischmetal have not been successful.

. . . . .

There is no satisfactory theory that links the magnetization process in the rare-earth materials to their composition. We do not know why cobalt-samarium develops permanent-magnet properties that are so superior to those attainable with, say, cobalt-praseodymium or cobalt-cerium, even though they are chemically, metallurgically and magnetically similar in basic properties.

. . . . .

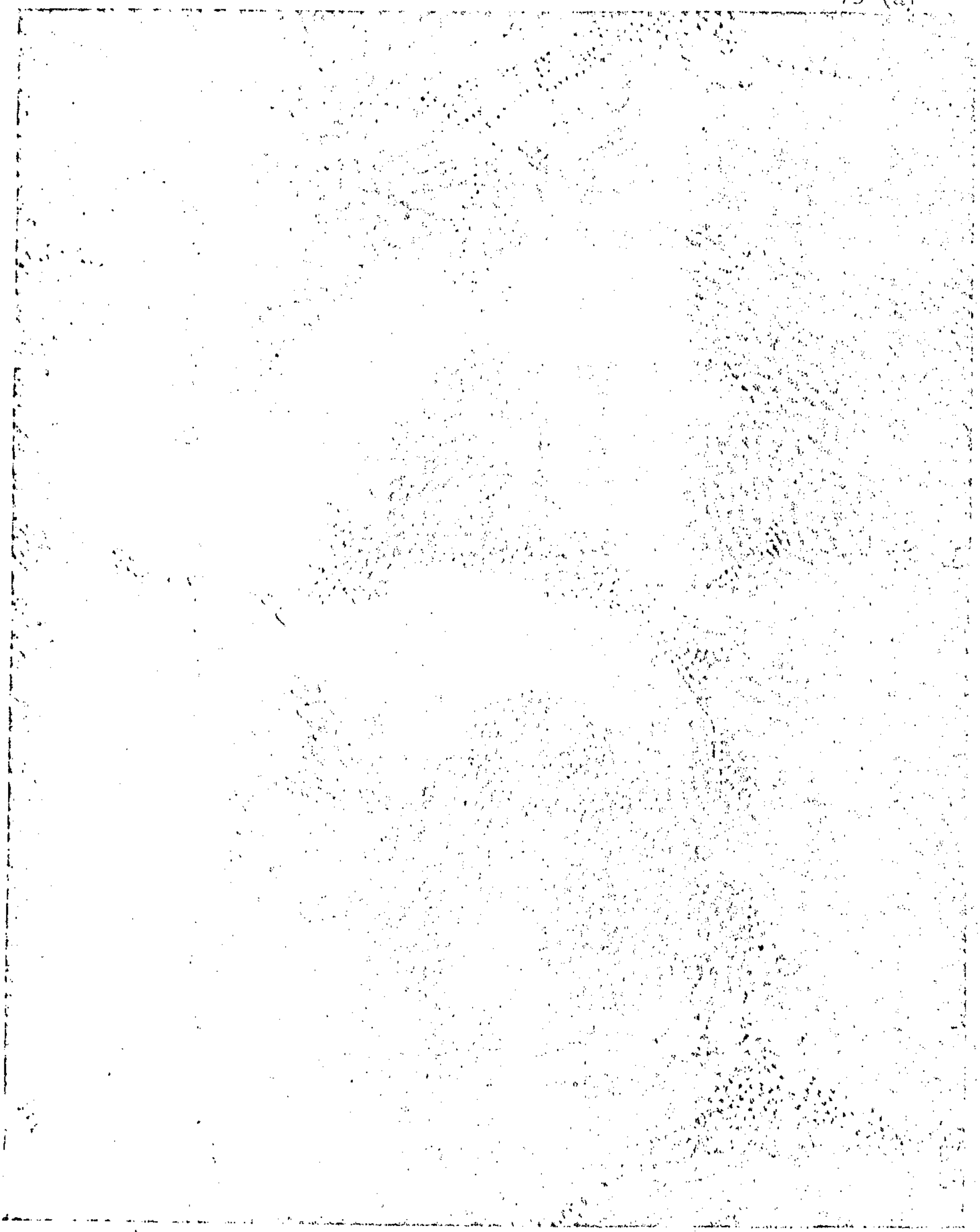
I have already mentioned one promising use for materials with high intrinsic coercive force: large permanent-magnet electric motors. What other applications can one see in the future?

. . . . .

The fact that like poles of a magnet repel each other is the basis of many suspension devices that are virtually frictionless. In many watt-hour meters, for example, the rotating shaft is suspended in a magnetic bearing, because any friction in the meter would tend to make it read too low. The moving-coil meter, widely used for measuring current and voltage, reflects the design changes that have been brought about as the maximum energy product of magnets has increased over the past several decades [*see illustration above*].

The ability of permanent magnets to support large loads without physical contact may one day be exploited in suspension systems for high-speed trains. Fanciful as such a scheme may sound, it has the great virtue that permanent magnets consume no power and thus would provide a fail-safe system. If one wanted to support a 10-ton car with ferrite magnets (cont) . . . .
would need two sets of magnets, one under the car and one in it, with a combined weight of perhaps 4,000 pounds. If cobalt-samarium were used, the combined weight of it needed to hold up a 10-ton car would be only 1,000 pounds. It is assumed in both calculations, of course, that the weight of the magnetic unit in the car has to be supported along with the weight of the car itself. Thus the ferrite magnet would have to support a total weight of 11 tons, whereas the cobalt-samarium would have to support only 10.25 tons.

These calculations are no more than rough estimates. Many other suspension schemes for high-speed vehicles are under consideration. Compared with air cushions or electrodynamic systems, however, this one has the virtue of simplicity. Its practicality would depend on the economic production of miles of permanent-magnet track at a cost not greatly exceeding that for steel rails. This is at least conceivable for ferrites, perhaps hardly so for cobalt-rare earths or some of their descendants. In any case the implications for the permanent-magnet industry of a demand for magnetically repelling railroad track are quite staggering.



MAGNETIC-DOMAIN STRUCTURE in many ferromagnetic materials can be made visible with polarized light. In this micrograph of one of the new permanent-magnet materials, cobalt-samarium, each region with a particular type of pattern is a grain in the casting. When polarized light is reflected from the polished surface, the plane of polarization is rotated slightly one way or another, depending on the direction of magnetization within each domain, and this can be converted into a pattern of light and dark areas. Within each grain the dark and light regions are oppositely magnetized. In the grains with a cogwheel pattern the direction of magnetization is roughly perpendicular to the surface, alternately in and out. The cogwheels are hexagonal because the crystal lattice of cobalt-samarium is hexagonal and the domain boundaries of the material prefer certain orientations. The micrograph, which is shown here at an enlargement of 500 diameters, was made by Curtis [illegible]

From Ref. 13.

PHYSICS. By PROFESSOR S. DEVONS, F.R.S., Columbia University, New York.

THE SEARCH FOR THE MAGNETIC MONOPOLE

MAGNETIC MONOPOLES IN CLASSICAL AND QUANTUM THEORY

THE concept of the magnetic pole in the development of the scientific study of magnetism is time-honoured indeed. It already appears in the extraordinary investigations of Peregrinus (1269), and although the later, and more celebrated, Gilbert's *de Magnete* (1600) deals somewhat scornfully with Petrus Peregrinus' "celestial poles" as "things from abroad and afar as are dear to them and the object of longing," yet the magnetic pole, albeit modified, persists right through to the modern epoch of physics; is either exploited or blasphemed in most contemporary textbooks; and, most recently of all, is being searched for with the full armoury of modern physical techniques. Withal, it does not (yet?) exist.

The contemporary view of the *classical* aspects of the matter are expressed well enough by Maxwell himself, to whom indeed this view largely owes its origin and inspiration. Thus: "The ends of a long thin magnet are commonly called its Poles. In the case

of an infinitely thin magnet, uniformly magnetised throughout its length, the extremities act as centres of force, and the rest of the magnet appears devoid of magnetic action . . . (although) . . . in all actual magnets the magnetisation deviates from uniformity so that no single points can be taken as poles" [1]. The extremities of the long thin magnets act as "poles" and the interaction between the poles is accurately described by Coulomb's Laws. The essential difference between electric and magnetic poles is stated explicitly by Maxwell: "In every magnet the total quantity of magnetism (reckoned algebraically) is zero" [2]. This vanishing of the net amount of magnetism, even for the smallest magnetic particle, is at first related to a hypothesis that "magnetic fluids," initially present and unseparated in the molecule in equal quantities, cannot in the process of magnetisation "pass from one molecule to another" but can only be separated within the (assumed *indivisible?*) molecule [3]. Later Maxwell finds that even this limited concept of the magnetic pole (separated magnetic fluid) is less plausible than the Amperian hypothesis according to which "magnets derive their properties from electric currents circulating within the molecules . . ." [4]; and, although the latest experimental evidence which Maxwell is able to quote (1873) is insufficient to establish the "existence of these molecular currents . . . to the rank of a demonstration," it is clear that he has little doubt in accepting the Amperian hypothesis in favour of any other that would involve even the limited existence for magnetic poles. In brief then Maxwell himself accepted the essential dissymmetry in the elementary sources of electric and magnetic forces, notwithstanding that he himself was responsible for the very field equations which display the remarkable symmetry of the electric and magnetic fields. Many of Maxwell's successors have been more hypnotised by this symmetry than Maxwell himself!

The later developments of atomic physics and its repercussions on the atomic-molecular interpretation of electric and magnetic phenomena do, of course, greatly modify the original Amperian conjecture, although in the basic respect that they confirm the profound difference between the primary electric pole and magnetic dipole (or equivalent dipoles) Ampere and Maxwell are essentially vindicated. The electron with electric charge (pole) and magnetic moment (dipole) is the basic (and simplest) source of electromagnetic phenomena: other "elementary" particles provide similar (although more complex) sources. From the viewpoint equally of classical electromagnetism and present-day microscopic interpretation of electric and magnetic phenomena (including the properties of the individual particles themselves) the elementary dissymmetry of electric and magnetic phenomena is acceptable even if, perhaps, it remains inexplicable in terms of any fundamental "principle."

The inclusion of isolated magnetic poles (magnetic monopoles) into classical electromagnetism, whilst not called for to explain observed phenomena, introduces no difficulties in principle; indeed the occurrence of such poles might be viewed as further enhancing the already pleasing symmetry of the field equations. The situation is otherwise in quantum theory. In a remarkable paper published in 1931 [5], Dirac examines the consequences of postulating the existence of magnetic monopoles alongside the already existing electric charges (poles) whilst at the same time retaining the basic axioms and interpretation of quantum mechanics. In the prefatory remarks of this paper, entitled "Quantised Singularities in the Electromagnetic Field," Dirac addresses himself to some of the (then) "most fundamental problems in theoretical physics awaiting solution, *e.g.* the relativistic formulation of quantum mechanics and the nature of the atomic nuclei (to be followed by more difficult ones such as the problem of life)." To grapple with such formidable problems there must be used methods commensurate with the tasks and Dirac suggests, at least as a possibility, the search for and formulation of abstract, logically consistent theory first, with identification of a correspondence between theory and actual phenomena to follow.

In this particular work there is some hope, at the outset, that light will be shed on the mysterious "fine-structure constant" ($e^2/\hbar c \simeq 1/137$), and although this remarkable dimensionless constant is not "explained," a result only a little less remarkable is obtained. It is demonstrated that to satisfy the requirements of quantum theory, electric charges and magnetic monopoles can only coexist if both are quantised, the one in integral units of electricity "e" (as observed), and the other in integral units of g (magnetic monopole), with e and g related by: $eg = \frac{1}{2}\hbar c$.

If we accept, as we must, the observed fact that the quantised e has the value given by (approximately)

$$e^2 = \frac{\hbar c}{137}$$

then the "possible" magnetic monopoles are of charge $n.g$ (n integer), given by:

$$g^2 = \frac{n^2}{4} \cdot \frac{\hbar^2 c^2}{e^2} = n^2 . \frac{137}{4} . \hbar c$$

Just as the elementary electric charge is, when expressed in natural units, $\hbar c$, small, the elementary magnetic charge is large in these units. Thus complete symmetry of magnetic and electric fields and sources, as might be conceived in classical theory, is still elusive: even if magnetic monopoles exist, their properties, both quantitative and, in effect, qualitative, would be remarkably different from those of electric charges of electronic size.

The conclusions of Dirac appear to be the inspiration of the subsequent investigations, both theoretical and experimental, of magnetic monopoles. Examinations of more detailed and up-to-date sophisticated aspects of the theory do not seem to have modified Dirac's conclusion in any essential way. Experimentally, the increasing energy available from particle accelerators and improved techniques of particle (including "monopole"!) detection, have encouraged a number of investigators to search for magnetic monopoles either in the products of high-energy nuclear collisions or in the cosmic radiation and its secondary products produced in the atmosphere. Before describing these attempts, and their outcome, it is appropriate to discuss briefly the physical properties and behaviour of any such postulated particles.

Properties of Magnetic Monopoles

The outstanding feature, indeed the only definitely predicted property, of the magnetic monopoles is their large magnetic charge, and hence their very large electromagnetic interaction. Speculatively, this large interaction also suggests a large rest mass: *e.g.* if one assumes a "classical radius" for the monopole, then the smallest mass for such particles (corresponding to unit monopole charge, g) is about two and one half times the proton mass (2·4 GeV). It is also usually assumed that magnetic, like electric, charge is conserved so that magnetic monopoles will be produced only (if at all) in pairs, + and − or N and S. Furthermore since, clearly, there is no appreciable number of monopoles (of either polarity) in normal matter, monopoles, at least those of lowest mass, will be stable.

An energetic magnetic monopole will ionise very heavily a gas through which it passes, comparable in this respect to a fission fragment. The ionisation is, however, velocity-independent at high energies, and amounts to some 12 MeV energy loss per centimetre of air at N.T.P. After losing most of its energy and suffering numerous elastic or quasi-elastic scatterings it will reach "thermal" energies after passage through some 1 gm/cm² of matter or less, and then moves diffusely until it collides with solid material. The behaviour of a magnetic monopole in solid matter is a much more complex and uncertain matter, although certain features seem very likely. Malkus [6] showed that a single electron and single monopole cannot exist in a bound state. (Indeed, for a bound state there must be *some* electric field.)

However, between a complex atom and a magnetic monopole there would be short-range diamagnetic, repulsive forces and longer-range attractive paramagnetic forces, these latter arising from electrons in unfilled shells. In a non-ferromagnetic solid, it seems likely that the Dirac monopole would be loosely bound with an energy of the same order or rather less than typical molecular binding energies (of the order of a few electron volts). In the case of bulk ferromagnetic materials larger energies and forces are involved. Since the ionisation energy loss of a monopole is of the order 8 GeV per gm/cm^{-2} of material, even an energetically moving monopole will soon be reduced to "rest" and then be "captured" if it impinges on solid material of any bulk. A slow ("thermalised") monopole will be captured by a solid near the surface: in a fluid it would be expected to diffuse through the medium at a rate dependent on the viscosity of the medium, the temperature, and the extent to which the monopole forms a bound cluster with neighbouring molecules. All these detailed atomic-molecular properties are relevant to the problem of detection of possible monopoles; they have been studied by a number of investigators [10, 12] sufficiently to enable reasonable interpretations of the experiments to be made.

The nuclear interactions of the hypothetical monopoles are quite unknown: bound nuclear-monopole states may be possible although this seems unlikely. In nuclear collisions of sufficient energy it is expected (or hoped!) that pairs of monopoles (N + S) would be produced, although the cross-section for such a production process can hardly be guessed. The least speculative possibility would be the photoproduction of monopole pairs by virtue of the large electromagnetic interaction (g). But just because the electromagnetic interaction is so large the normal type of calculation cannot be made reliably, so that even in this, the most definite case, the theoretical prediction provides only a rough guide to experimental design and interpretation [12].

If a mass for the monopole is assumed, then one can, of course, readily calculate the minimum particle energy, for example in a proton-proton collision, necessary to produce a monopole pair. Thus with 30 GeV protons the maximum monopole mass is 2·9 GeV, *i.e.* somewhat greater than the speculatively "predicted" value of 2·4 GeV. For the pair of 2·4 GeV monopoles to be produced in the field of a single nucleon, a gamma-photon energy of 17 BeV would be required, but this same photon could produce a pair of monopoles each of mass 5·6 BeV if a coherent process involving the whole of a complex carbon nucleus were involved. All these energies are in the range now attainable by particle accelerators, and, of course, particles of such energies are present in, and produced by, cosmic radiation.

Perhaps the most conspicuous feature of the monopoles with the large charge g is their acceleration in a magnetic field: in a uniform field of H gauss the monopole acceleration corresponds to a gain (or loss) of energy of $20 \times H$ MeV/cm! On account of these large forces the magnetic fields that can be produced in the laboratory can be, and in all experiments have been, used to extract monopoles from solid or liquid material in which they might have been "captured." For example, a field of some 600 gauss at the surface of a liquid (oil) and much larger (pulsed) fields of the order 50 to 100 kilogauss at the surface of ferromagnetic materials have been used and assessed as adequate to extract monopoles imbedded near the surface of the material or, in the case of the liquid, those which move to the surface under the influence of the magnetic field within the liquid.

Experimental Search for Monopoles

The first search—and like all subsequent ones it was fruitless—was made by Malkus in 1951 [6]. The equipment was extremely simple. A current carrying solenoid was mounted vertically so that any magnetic monopoles existing in, or produced by, cosmic radiation and diffusing through the atmosphere would be sucked by the magnetic field of the solenoid into an evacuated tube mounted inside along the length of the solenoid. At the end of the tube were mounted suitable photographic emulsions in which the tracks produced by the accelerated monopoles would be readily observable. Now if monopoles of cosmic-ray origin existed and were strongly bound after coming to rest in the earth's crust then a flux of monopoles of 1/cm^2/sec would cancel the earth's magnetism in about one month. Assuming a constant flux for 10^9 years implies then a flux of less than 10^{-10}/cm^2/sec. On the other hand weakly bound, and therefore easily diffusing, monopoles would not produce such dramatic effects, but would be readily detected in the apparatus used. The lack of any observed monopoles in the experiment indicates a cosmic-ray flux of less than 10^{-10}/cm^2/sec without the above restrictions. If monopoles are produced by cosmic-ray particles of sufficient energy in the atmosphere, an upper limit for the cross-section for this process can be estimated to be some $3 \cdot 10^{-35}$ cm^2.

Much lower limits have been obtained more recently by use of particle accelerators. The principles of the methods are all much the same. Either the sought-for monopoles are allowed to enter a photographic emulsion or other detector directly from the point where they might be produced (*i.e.* where the high-energy proton beam strikes some appropriate target); or the monopoles "produced" are stored in one of a series of different materials, and then later extracted by a powerful magnetic field, which also imparts sufficient energy to the monopole so that its detection poses no problem.

The first experiments of this sort were made by Bradner and Isbell, 1959 [7], using 7 GeV protons provided by the Berkeley Bevatron. Pulsed magnetic fields of up to 200 kilogauss were used to extract monopoles "stored" in polythene. Owing to the limited energy available only monopoles of mass 1 GeV could have been made and for such monopoles the production cross-section (proton-proton) was shown to be $\lesssim 10^{-40}$ cm^2, if monopoles were strongly bound (3–20 eV), and a rather poorer limit ($\lesssim 10^{-37}$) for binding energies less than 3 eV (no monopole "storage" in this case).

Experiments with protons of higher energies (27–30 GeV) have been made in the past couple of years, using the facilities at Brookhaven National Laboratory, New York, and CERN, Geneva, Switzerland. The methods used are similar in all the investigations. In some experiments the monopoles are captured in solid material and subsequently extracted by poweful magnetic fields—an arrangement which is sensitive even if the binding energy in solid material is large. In one experiment [10] the capturing takes place in liquid (oil) and the monopoles are dragged through the liquid out of the surface and then accelerated, *in vacuo*, all by the use of appropriate magnetic fields. These fields also serve to focus the particles on to the sensitive region of the detector. In several of the experiments monopole pairs produced by secondary gamma-radiation, as well as those produced directly in proton-nuclear collisions of the primary beam, would have been detected if present. In no case was any positive evidence of monopole production recorded, so that only upper limits for the cross-sections for their production (or lower limits for the monopole mass) can be estimated. Typical figures are:

σ (proton-nucleon)	Monopole Mass Limits	Magnetic Charge	Other Features	Ref.
$\lesssim 10^{-40}$ cm^2	<1 GeV	g	binding energy in polythene between 3 and 20 eV	[7]
$\lesssim 10^{-39}$ cm^2	$\lesssim 2.8$ GeV	$0.3g$ to $4g$		[8]
$\lesssim f\omega \times 10^{-40}$	$\lesssim 2.94$ GeV	g	binding energy (in various materials) greater than 0·6 eV and less than ~ 40 eV	[9]
$<1.5 \cdot 10^{-40}$ cm^2	$\lesssim 2.9$ GeV	g	insensitive if rather special and improbably large binding energies exist	[10]
$<10^{-36}$	<2.9 GeV		σ for photoproduction (coherent)	[10]
$<10^{-34}$			σ for photoproduction (nucleon)	[10]

By way of comparison one theoretical estimate [12] of the gamma-nucleon photoproduction cross-section for monopole pairs is in the region 10^{-32}–10^{-34} cm^2, for a monopole mass of 2–3 proton masses.

The most recent monopole search reported [12] looks for such particles trapped in meteorites or magnetic outcrop on the earth's surface, a method suggested earlier by Goto [11]. The results of these investigations are in a sense complementary to the accelerator investigations. These latter provide pretty strong evidence for the absence of monopoles of mass less than some 2·9 GeV, but do not of course say anything about possible higher mass monopoles. These could be in evidence in cosmic-ray processes. Any but extremely high energy monopoles entering the atmosphere should be slowed down to a terminal drift-velocity in the earth's magnetic field and if they reach the earth near a region with strongly ferromagnetic properties the concentration of the magnetic field there would help funnel the monopoles into the ferromagnetic material, where they would be trapped. The forces on a monopole embedded in or near the surface of a ferromagnetic substance have been estimated [12], and these provide a basis for calculating the magnetic field necessary to extract a monopole so trapped. For a monopole of unit strength g, this field is some 50–60 kilogauss for iron, and about 17 kilogauss for magnetite. Due to saturation effects these figures are barely changed if the monopole strength is, *e.g.*, $2g$ rather than g.

In the experiments, a large pulse-solenoid was used, in situ, over the rock-face (outcrop areas in the Adirondack Mountains, New York, U.S.A.). The maximum field attained was 170 kilogauss at the centre of the solenoid and 60 kilogauss at the surface of the rock. If monopoles were trapped in the rock they should be [illegible]dily extracted, accelerated in the magnetic field and [illegible]lly recorded in the photographic emulsion detector used. In the meteorite examination an essentially similar system was used, and small samples could be introduced right into the solenoid (~100 kilogauss) itself.

To interpret the results it is necessary to estimate the time during which the rock (or meteorite) has been exposed to a postulated monopole flux. From considerations of the rate of erosion of the rock surface a figure of 300 years is used in this case (for the meteorite a speculative figure of 5×10^8 years is used). The negative results obtained in the rock investigations confirm the accelerator observations: they are less sensitive if the monopole mass is ~2·5 GeV, but extend the range up to the region of 10 GeV. The existence of monopoles of the mass in the range of 10 GeV or higher is not excluded by any experiments made so far.

Conclusions

No experiment has so far yielded any traces of evidence for magnetic monopoles of the type predicted by Dirac. Of course *no* experiment whatever can *disprove* their existence conclusively. Perhaps the weakest point of most of the experiments and arguments is the guess made of the mass. One could hardly be surprised if the mass turned out to be, say, an order of magnitude greater than is given by simple conjectural numerology, and if such were the case all existing searches would indeed have yielded a negative result. (A much *lower* mass for the monopole seems unlikely for theoretical reasons, as well as experimental ones; *e.g.* if monopoles with a mass of the order of the π-mass existed, their "virtual" pair creation would have to be included in the calculations of such quantities as the "Lamb Shift" and magnetic moment of the electron and muon. Agreement between theory and experiment here, without monopole pairs, speaks against their existence.)

Dirac, in the conclusion of his original investigation, suggests that, since it has been shown that a magnetic monopole is possible, then "under these circumstances one would be surprised if Nature has made no use of it." Needless to say the absence of monopoles —and future experiments may well confirm what is already suggested—would not be the first example of a surprise afforded by the contrariness of Nature. It would be disappointing indeed if the simple coexistence of magnetic monopoles and electric charges, which is sufficient to quantise both quantities, turned out to be unacceptable only because it did not conform with experimental observation. (From the viewpoint of "economy" in Nature the existence of only a *single* monopole is all that would be necessary to quantise all electric charge: the search might then be described as that for *the* magnetic monopole—with prospects of success that seem anything but rosy!) If future investigations do indeed further confirm the absence of magnetic monopoles then one can hardly continue to chide Nature for its foolishness in not accepting such an excellent opportunity. Rather, their absence may conceal (or reveal ?) a principle even more important than their presence might have demonstrated. Certainly if the presence of magnetic monopoles could be shown to be highly improbable, one should review again the arguments concerning symmetry of electric and magnetic phenomena which stimulated their theoretical postulation. Possibly this symmetry is more illusory than real.

References

1. Maxwell, J. C., *A Treatise on Electricity and Magnetism*, Third Edition (1891), Part III, Art. 373.
2. Maxwell, J. C., *ibid.*, Art. 377.
3. Maxwell, J. C., *ibid.*, Art. 380.
4. Maxwell, J. C., *ibid.*, Art. 833.
5. Dirac, P. A. M., *Proc. Roy. Soc. A.*, 133, 60 (1931).
6. Malkus, W. V. R., *Phys. Rev.*, 83, 899 (1951).
7. Bradner, H., and Isbell, W. M., *Phys. Rev.*, 114, 603 (1959).
8. Fidecaro, M., Finocchiaro, G., and Giacomelli, G., *Nuovo Cim.*, X, 22, 657 (1961).
9. Amaldi, E., Baroni, G., Bradner, H., Hoffman, L., Manfredini, A., Vanderhaege, G., and de Carvalho, H. G., *Proceedings, Aix-en-Provence International Conference on Elementary Particles*, 1961, Vol. 1, p. 155.
10. Purcell, E. M., Collins, G. B., Fujii, T., Hornbostel, J., and Turkot, F., *Phys. Rev.*, 129, 2326 (1963).
11. Goto, E., *J. Phys. Soc. Japan*, 10, 1413 (1958).
12. Goto, E., Kolm, H., and Ford, K. W. Preprint (1963).

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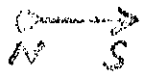
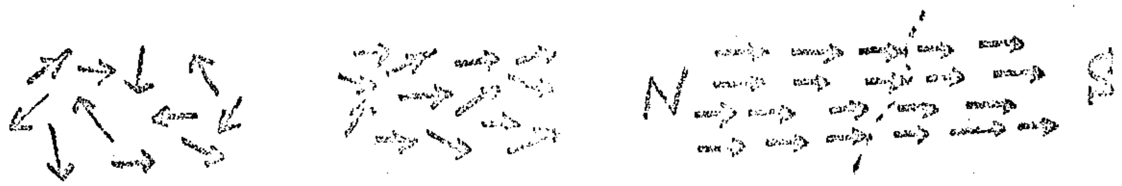
Appendix

Interpretation of some of Gilbert's results,
(using contemporary concepts)

Magnetization & Verticity or bipolarity. This is an essential feature of all magnetic or magnetized bodies; a geometrical symmetry which results from some ordering of the constituent elementary parts. These elementary parts -- atoms or groups of atoms -- may be represented, formally: as a small magnet with bi-polarity, thus:



In a normal unmagnetized, macroscopic piece of matter innumerable such elements are arranged in random orientaion (a); but

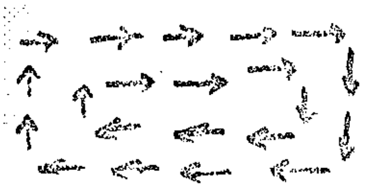


(a) (b) (c)

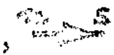
in magnetized matter there is some ordering, (b), which "ideally" would be complete alignment, (c). One end of such an object would be the S (or N-seeking) and the other N (or S-seeking).

This alignment of the "elements" might be more-or-less permanent -- as in a loadstone, or a hard-steel needle, or temporarily induced by some external (magnetic) influence. In either case the actual alignment (degree of magnetization) is the result of all the forces on all the elements combined, and each element is subject not only to "external" influences but the combined influence of all the neighboring elements.

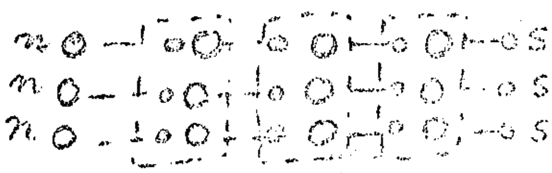
What makes some materials able to retain magnetism "permanently", others to a high degree, if only "temporarily" and others only very weakly? This involves a wide range of questions -- some quite intricate, involving both sophisticated aspects of individual atomic structure and of the whole arrangement of these atoms in solids. If one thinks, naively, of the simple elements themselves as just "permanent" magnets, free to turn in any direction, then the most likely result would be (since N attracts S): for the elements to form closed arrays with no net polarity. But the



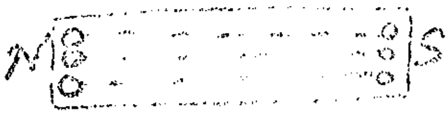
balance of forces in a magnetized solid is much subtler than this. We simply remark that certain materials, in particular physical form, can possess this property of permanent magnetization. (especially materials containing iron, cobalt, nickel). If such a "permanent" magnet is broken each part will (normally) show bi-polarity thus:

Forces The element of magnetism is a "dipole",  ; we may (inprecisely, but as was quite common for a long time) picture a dipole as two poles (one N or Boreal, the other South or Austral) separated by a small but finite distance:

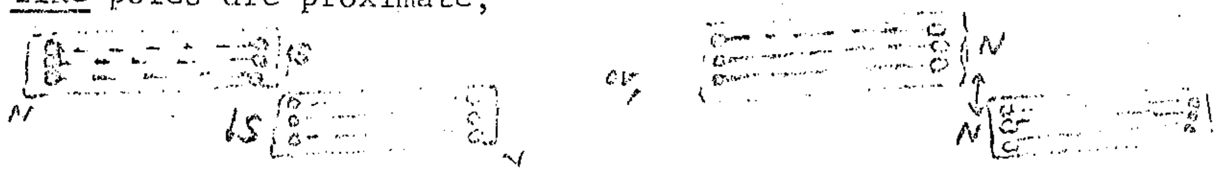
A long magnetized body (e.g. a "magnetic needle") would be interpreted (ideally) thus:



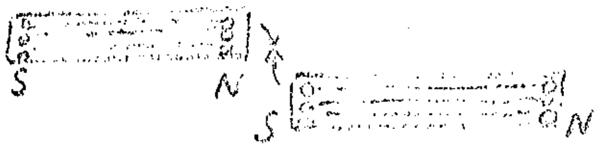
Now the contiguous N and S poles inside the material "cancel" and, as far as external influences are concerned we can replace the object with:



i.e. a pair of poles separated by the whole length of the object. Working with such objects we can observe experimentally that when two like poles are proximate,

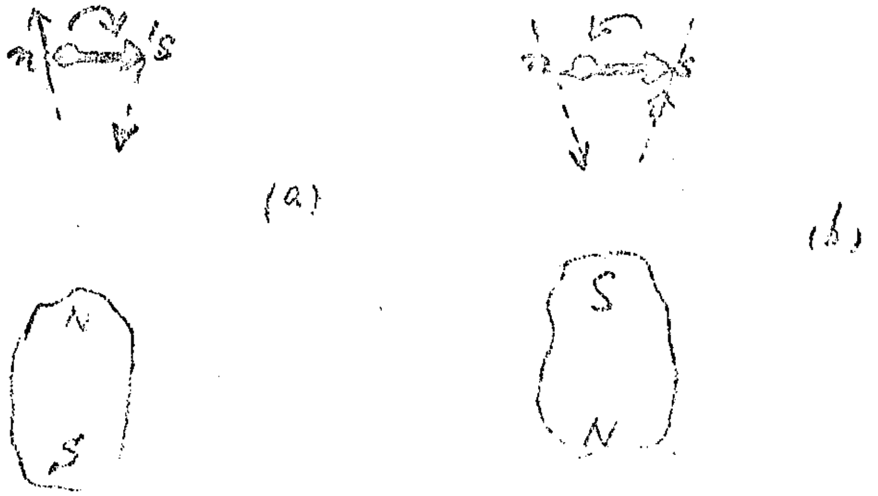


their mutual influence suggests repulsion. In the arrangement where the proximate poles are unlike we observe an attraction:

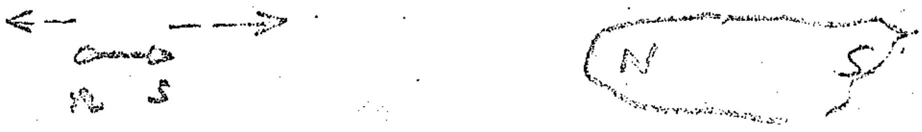


(Notice that there are always four pairs of poles SS, NN, NS, SN; but in this particular configuration we attribute the mutual forces (and motions) to the closest pair. Instinctively we assume that forces decrease as distance increases. Actually a detailed study of such arrangements -- by Coulomb, some 200 years after Gilbert, showed that the law of forces interpreted as due to poles was an "inverse-square law".)

Now if we have one (small) magnetic needle (cf. Gilbert's versorium) a long distance away from a magnet thus:



We see that although the prominent forces (from the N in (a) and the S in (b)) may be equal and opposite at the two ends of the needle, there will nevertheless be a resultant torque, turning the needle (clockwise in (a), counter clockwise in (b)). If the two ends n, s are not equidistant from the large magnet then there will be, also some residual force. viz., where



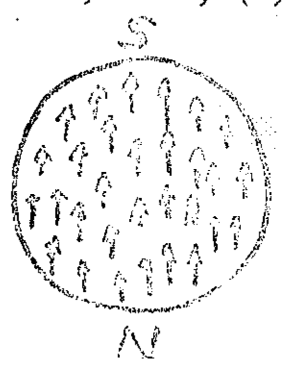
the attraction of N on s is greater than the repulsion of N on n. (In the case of a pivoted needle, translational forces are balanced by the forces exerted by the pivot, i.e. translational motion is suppressed; so that only the turning motion is exhibited.)

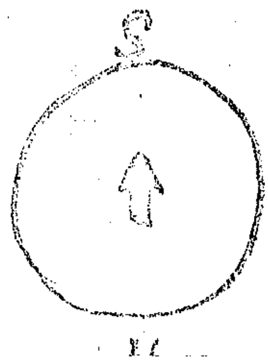
Expressed formally: In a uniform magnetic field (or some other cases of special symmetry) there will be only turning forces on a dipole. If the field is non-uniform there will also be (generally smaller) translational forces.

When we are dealing with the earth as a magnet the dimensions are sufficiently large that over a laboratory range of distances, and à fortiori over the extent of a magnetic needle, the magnetic field can be regarded as uniform.

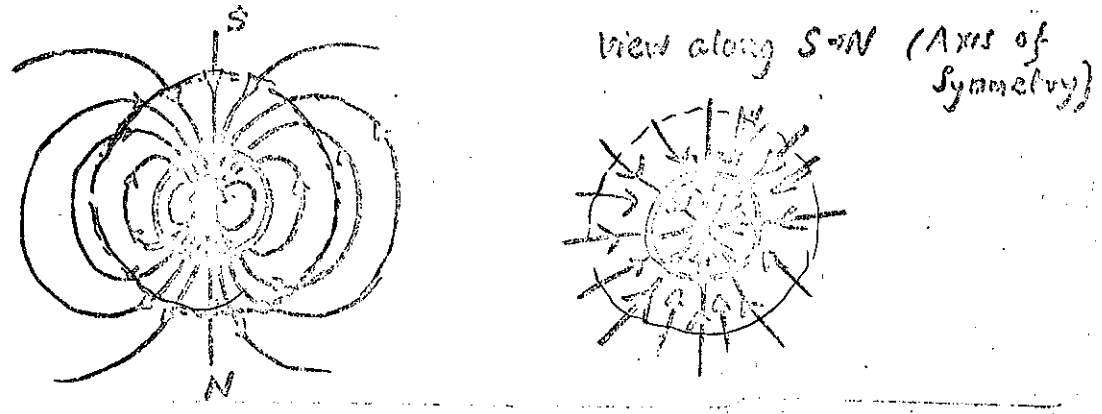
The Terrella The ideal terrella is one which is uniformly magnetized, i.e. each "element" is magnetized to the same degree and with the same orientation, thus, (a):

(a)





Now it is a remarkable feature, readily demonstrated with present day analysis, that the external influence of such a magnetic configuration is identical with that of a single dipole (of apropriate magnitude) located at the center;(b). Both produce externally -- what in formal language is magnetic dipole field, whose lines of force are as shown:



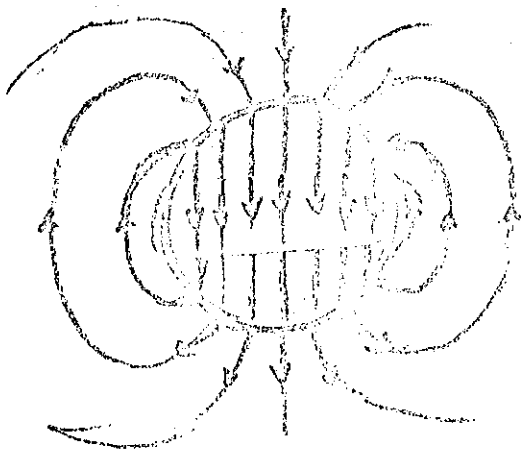
These "lines" indicate the direction which a freely pivoted magnet would assume in the neighborhood. In measuring declination and inclination (or dip) we measure -- at the surface of the sphere, respectively the projection of these lines on to a local horizontal (tangent) plane, and on to a meridional plane. The diagram gives examples of both: in the case of declination the particular view is a tangent plane at the N-pole.

A magnetic field which can be represented in this simple way -- as a pure dipole field -- has a most important property: the field pattern is the same for all (concentric) spherical surfaces (e.g. the dotted circles shown in fig.). This is the essence of Gilbert's discovery (pp. 293-298 and pp. 304-307). However Gilbert's attempt at a geometrical construction to reproduce this pattern (p. 293) is only approximately correct (For example: the dip-angle at latitude 45° is not $22\frac{1}{2}^{\circ}$ as Gilbert's construction gives, but $26\frac{1}{2}^{\circ}$.)

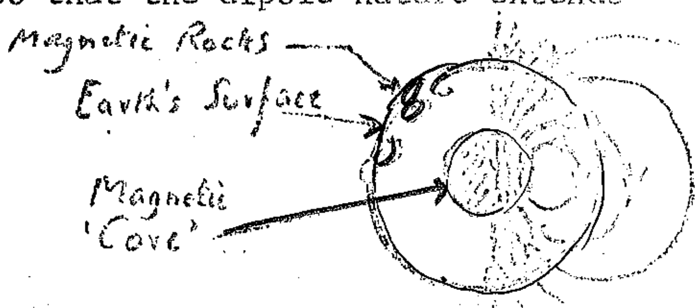
† See also diagram p. 12

But the general idea of a pattern which is the same at all distances -- but simply becomes weaker -- is correct. It is an example of a very general principle of mathematical physics: the analysis of a field into its "multipole" components, each of which preserves its own, characteristic pattern indepently of radial distance. Here we deal with the pure dipole-pattern. (If there were more than one multipole involved -- as would be the case in less "ideal" representations there would be no such simple property of radial independence.)

<u>The Earth's Magnetism</u> Inside the earth, the field need not in any way resemble a pure dipole. <u>If</u> the earth were made of uniformly magnetized material -- as is the terrella- then the field would be:



We cannot enter here seriously into the question of the real nature and origin of the Earth's magnetism. Current ideas attribute to some sort of giant convection currents in the <u>core</u>, so that the dipole nature extends -- although modified locally by



(Schematic Core-Model)

magnetic materials -- somewhat below the earth's surface. This would be the modern equivalent to Gilbert's ". . . inner parts of the earth [which] are in union and act in harmony, and produce direction to north from south." (D.M. p. 184)

Notice that there is a reversal of the field when we move, equatorially, from the region which is the source of the field to the region outside. It is this question which Gilbert is trying to probe when he discusses the relationship between the orientation of a piece of magnetic rock inside the earth, and the position it would assume when freely suspended just outside the surface.

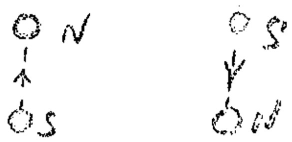
The Nature of the Magnetic Elements The picture of the magnetism of a macroscopic object as arising from the coordinated ordering of many constituent elements leaves open the nature, size, shape, etc. of these "elements". Are they atomic, molecular, microscopic, sub-microscopic? Is there some specific magnetic stuff ("magnetic fluid") of two forms (boreal and austral?) And are the two fields always associated in equal and opposite amounts? Until very recently (this century) most such questions could only be answered -- or even asked -- in a formal way, since the whole atomic concept and hypothesis was itself largely formal, with no physical indications of the size or nature of the atoms (whether of philosophy or physics or chemistry). We now know of magnetic "elements" of a great variety of sizes and forms, ranging from the basic "particles" -- electrons, atoms, molecules, and "domains" of which, in ferromagnets can be up to visible dimensions. The situation can be far more complicated than one simple stage of ordering which relates to the primary elements (electrons, say) to the whole body. There are patterns within patterns; arrangements of arrangements, a whole range of scales and levels of ordering.

How these are manifest in a particular practical way depend on many factors: the physio-chemical nature of the material, the history of its formation (e.g. in the earth's crust), solidification, heat and mechanical treatment (annealing, drawing, pressing, rolling, etc.). These matters as well as scientific comprise a whole field of technology.

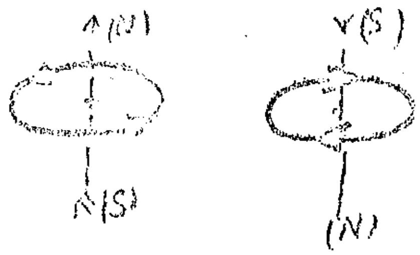
Magnetism and Electricity In the foregoing discussion we have discussed magnetism essentially on the same scientific basis as did Gilbert -- as a distinct phenomena, sui generis. This does not of course properly represent our contemporary view. Since 1820, when the magnetic influence of the galvanic-electric current was discovered by Oersted, electricity and magnetism have developed as parts of a more comprehensive science: electromagnetism. Magnetism is not only a manifestation of some "intrinsic" magnetic properties of the atoms, or molecules/materials: it is a universal accompaniment of electric currents on any scale microscopic, macroscopic, or cosmic. The "element" of the magnetism of currents is best represented by a small "loop" of current (a); macroscopic currents can be regarded as formally equiva-

(a) (b) (c)

lent to an array of such elements (b); magnetism of materials as a physical array of such elements. (c). The basic "verticity" or bipolarity of magnetism now assumes a quite different interpretation. It is no longer regarded as the invariable association of two elements of opposite polarity (the point and the tail of an arrow); but rather as the "two-sideness"-- a clockwise and counter clockwise circulation, associated with circulation of a loop, which are opposite when viewed along the axis from the two sides.



Bi-polarity(as pictured in terms of two "fluids", Boreal & Austral)



Bi-polarity of current-loop: Above counter clockwise; below clockwise, or vice versa.

Bipolarity is an ineluctable feature of the "current-loop" picture. It is an added feature of the "two-fluid" picture: one can for example postulate that both (N) and (S) "stuff" are present equally in all atoms/molecules, but that although some separation -- on the atomic/molecular scale of dimensions -- may be effected, no forces are able to effect complete separation

The basic bipolarity of the earth's magnetism is, today, attributed to (complex) circulating currents in the earth's interior, rather than to the result of a great ordering of magnetic elements, like a lump of magnetized iron.

As late as 1880 James Clerk Maxwell writing about the nature of magnetism asserts that there is no experimental evidence which clearly favors one or the other interpretation of the bipolarity of magnetism, in contrast to the essential mono-polarity of electricity. Even today there is a certain mystery about the difference. Is magnetism always bipolar? Is it possible to discover somewhere in nature, or to "create" magnetism in monopole form? Many attempts to "find" magnetic monopoles have been made in the past decade or so. So far none have been successful (Ref. 13.)

Part II Laboratory Notes

Even a quick glance at Gilbert's De Magnete will show what a great variety of experiments on magnetism can be performed with quite simple instruments -- at least when these are chosen perceptively and used with imagination. The laboratory equipment assembled, although not identical with Gilbert's, is in principle similar; it can be used to demonstrate and elucidate many of the intrinsic properties of magnetism itself and of the Earth's magnetic influence.

Listed below is a sample of suggested experiments. It is not intended to be an exclusive or exhaustive list. Other experiments will no doubt suggest themselves, and simple apparatus may be devised to do these. References below are to pages in De Magnete which are reproduced in Section 7. Note Gilbert's remark, in the preface: (p. xlix)

> We have set over [in the margin] against our discoveries and experiments larger and smaller asterisks according to their importance and subtility. Let whosoever would make the same experiments, handle the bodies carefully, skilfully and deftly, not heedless and bunglingly; when an experiment fails, let him not in his ignorance condemn our discoveries, for there is naught in these Books that has not been investigated and again and again done and repeated under our eyes. Many things in our reasonings and our hypotheses will perhaps seem hard to accept, being at variance with the general opinion; but I have no doubt that hereafter they will win authoritativeness from the demonstrations themselves.

1. Preliminaries (pp. 26-27 & 47-48)

Take any of the pivoted magnetized needles to a place in the laboratory as far as possible from any iron. (Hopefully the iron/steel in the building itself will not vitiate your observations. This is a problem Gilbert did not have to contend with!) You will observe that one end of the needle points consistently in the direction roughly north. This end, which should be marked identifiably, is the "North-seeking", "South", "Austral" or "marked" end. (The opposite end is called the "South-seeking", or "North", "Boreal" or "unmarked" end.) This needle will be used for reference purposes throughout the experiments.

In place of the needles provided, you can use any piece of loadstone, and place it on a wooden float in water. It will assume a particular orientation. The northerly part can likewise be "marked" for reference. Alternatively "magnetize" a steel needle or piece of hard-iron, and by means of a cork (e.g. p. 93) allow it to float. Again a north-seeking "marked" end can be identified and used as s reference. (N.B. The needle must be of "hard" steel and well-magnetized. Otherwise its magnetism may be reversed it is later used in a particular juxtaposition with a strong magnet. If in doubt, retest the needle in the chosen "isolated" position.)

Remember that whenever you observe magnetic forces, the earth (and its magnetic influence) is always present!

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1. Polarity (pp. 23-25)

Explore the orientation of a "marked" compass needle placed at different points near a piece of loadstone. (Ideally one would use a needle ("Magnetized versorium") pivoted so as to move in any direction -- as seems to be implied in the figure on p. 25. The actual (conventional) compass needles turn freely essentially only in the horizontal plane. This clearly limits their proper use, and the interpretation of their orientation.)

Look for regions where the needle is most strongly affected (e.g. where it vibrates most rapidly.) Observe whether, in these regions it is the North or South end of the needle which points toward the stone. Mark their areas accordingly by the appropriate letter, (S,N). The center of such a region is called a pole. How many such poles do you find? How many S and how many N? How is the needle oriented when placed near a pole? You can also investigate the "polar" properties by using a needle pivoted on a horizontal axis ("dip" needle). You can also keep the needle in a fixed place, and move the loadstone underneath it.

Similar observations can be made of any piece of loadstone or any of the magnetized objects provided, or on pieces of iron you can make magnetic. Is there any general conclusion about polarity? If the object examined has just two poles (one N and one S), the line joining may be called the magnetic axis. The object exhibits simple bi-polarity, or verticity. How is this axis related to the orientation of the magnetic object when it is floated (or suspended freely)?

2. Artificial Magnets (pp. 133, 155/8, 192/6)

A piece of unmagnetized iron or steel may be made magnetic by contact with (or by stroking with) a loadstone or other magnet, such as the much stronger magnets made of a special modern alloy of Aluminum, Nickel and Cobalt (Alnico). (There are other methods available nowadays.) Examine the polarity of these artificial magnets, and how this is related to the polarity of the magnet used. Examine the polarity of an iron wire magnetized by touching the mid-point with a strong magnet. Can you explain this? Cut in two pieces an iron wire which has been magnetized and observe the polarity of the parts.

3. <u>Attraction, Repulsion, and Turning</u> (pp. 155/6, 301/2, etc.)

When the poles of several objects (preferably simple bipolar ones) have been identified you can examine the influence of proximate poles N and S, N and N etc. For example you can float two pieces of (marked) loadstone on water and observe their mutual influence, or you can use pivoted magnetic needles, or magnets and loadstones suspended by thread.

The mutual interactions may now be formulated in terms of attraction/repulsion of like/unlike poles. On the other hand, a small magnetized wire or needle, mounted on a cork so that it just floats (cf. p. 302), turns but does not move translationally, if it is placed where <u>only</u> the Earth's magnetic influence is present. Now bring a strong magnet. What happens? What is the characteristic feature of magnetism: turning, or attraction/repulsion?

4. <u>Transmission of Magnetic Influence</u> (pp. 106, 107, 132, 140)

Examine the effect of interposing between a magnetic needle and a loadstone or magnet, a flame, a sheet of paper, wood, copper, etc, a sheet of soft (annealed) iron. (All this is significant by way of contrast with <u>electical</u> phenomenon.)

5. <u>Some Physical Properties</u>

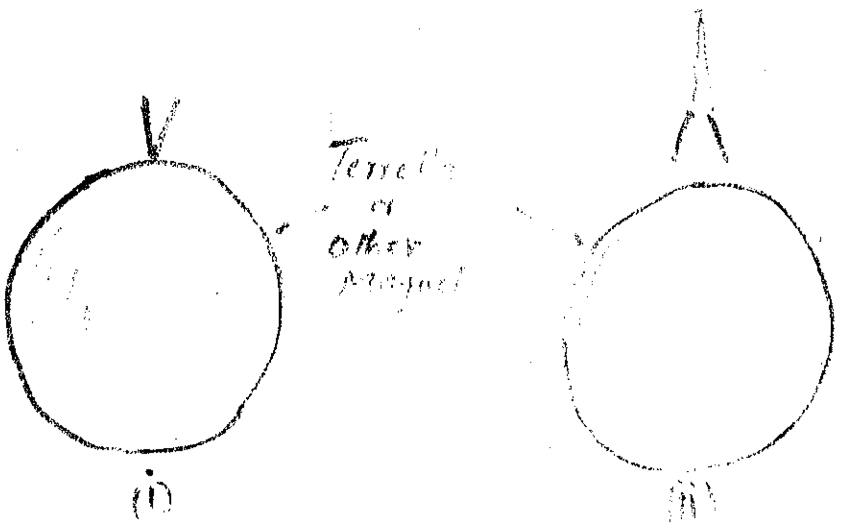
(a) Examine the effect in a magnetized steel/iron wire of heating it red-hot. Does the magnetism return when the wire cools down? (p. 189)

(b) Does breathing, moistening, rubbing by hand change the magnetization? (pp. 106, 189)

6. Induced Magnetization

(a) (p. 68, 50) Use a piece of soft (annealed) iron wire. Is it attracted to a magnet? Can you produce effective repulsion? When floated (using the cork technique) does it take up a special orientation? Can you observe (and describe) a difference between this case, and that of the hard steel magnetized needle?

(b) (pp. 202, 203) Place two short pieces of soft iron wire



as in (i) or suspend them as in (ii). Describe and explain what you observe. (See also p. 160)

(c) (p. 134) Place a compass needle a few inches away from a magnet and observe (qualitatively) the vibrations of the needle. Now place a soft iron sphere S near the needle. Are the vibrations now more or less vigorous?

7. Loadstones Inside and Outside the Earth (p. 187)

A piece of loadstone is separated from a large lump, and then suspended freely. Does it now take up the same orientaion as it had when it was part of the larger piece? Could the magnetism of the small piece be the result of induction by the larger one?

8. Exploration of the Earth's Magnetism

Gilbert's ideas on magnetism were shaped by two major influences: first, the accumulated , and rapidly growing, information about the behavior of the compass needle , (and later the dip-needle), as garnered from the observations and reports of numerous navigators and explorers; secondly, from his own "laboratory" observations. Some idea of the former has been presented in preceeding pages. It could be made more vivid by making a wide-ranging series of terrestial measurements, but this has obvious practical limitations. As a substitute (!), (and using the hindsight of subsequent knowledge) a simple, rough model of the main features of the present day magnetism has been constructed. It is possible to explore this in the laboratory, and then compare the results with recorded terrestial observations.

We recall an essential difference between the earth and the model, vis-à-vis the behavior of a compass needle or dip needle. The deployment and behavior of any "balanced" needle on earth is governed by two factors: Gravity, which always acts to the center of the earth; and magnetic forces, which vary from place to place. In our model we can simulate the latter but certainly not the former! Whatever model we use, when we explore it magnetically, gravity will always act vertically downwards -- towards the floor. However we can largely compensate for this handicap by exploiting the fact that we can turn our model earth in any desired orientation, and thereby reproduce, effectively, at each place "on earth" the appropriate response.

(a) Declination (or Variation) The compass needle moves in a horizontal, i.e. tangent plane; the pivot-axis is vertical (towards the earth's center). Hence on our model: Use the compass needle centered over the top of the earth. It's pivot-axis is vertical, and points towards the center -- which now coincides with "downwards". Place any desired point of the model earth under the needle. The angle between the needle and the geographical meridian (north or south) can now be measured. The "sign", i.e. W or E of "true" north (or south) is also significant! (It is most convenient to align the printed scale of the compass along the meridian line at the particular place. These lines are easily recognized on the model globe.) Now the declination can be explored over the whole surface of the globe, and recorded on the blank maps. A "chart" can now be made which displays lines connecting points of equal declination ("isogonal" lines). An alternative representation is to draw an "arrow" to represent the dip-needle direction (the so-called "magnetic meridian") at each point and join up the arrows smoothly (see pp. 69,70 for examples).

(b) Inclination (or Dip) (pp. 285-287, 306-308) The essential features of this terrestial measurement are: first, that the needle is free to move in a plane which passes through the earth's center, and second, that this plane contains the direction in which the (ordinary) compass needle points (i.e. the local magnetic meridian plane). If we wish to use the same instrument as in Part (a) (these are the simplest to make), then we must: first, place this needle on a horizontal equatorial plane (which therefore passes through the center of the sphere); second, turn the globe so that the desired place is adjacent to the needle; and third, orient the globe so that the magnetic meridian is in the horizontal, equatorial plane. In observing "dip" the geographical-astronomical N/S direction is not required -- all that is necessary is a "vertical". This is most conveniently simulated in the model by arranging the "zero" of the compass-scale to point towards the center of the globe.

In recording dip the "sign", i.e. whether "N" or "S" points downwards, is again significant.

Charts of equal-dip lines, ("isoclinals") can be constructed. (Notice that many of the "problems" of representing declination and inclination arise from the attempt to display what are essentially 3-dimensional features on a two dimensional map. This was quite an acute practical problem in the 16/17 centuries -- for cartography and navigation generally, not only for magnetic charts.)

Much later, in the 18/19 centuries, other terrestial charts were constructed showing the variation over the globe of the actual strength of magnetic field (and its variation with time!) Notice that the magnetic force at any place (and time) on the earth's surface is a vector quantity. i.e. it is specified by three magnitudes. In the above experiments -- as in Gilbert's -- only two of these are measured -- two angles: declination and dip.

9. Magnetic Properties of the Terrella (pp. 24/25, 50/51, 235-238)

The magnetic properties of the spherical loadstone can be explored in much the same way as the terrestial model. But there are some differences. On the earth we choose as a coordinate frame-of-reference the meridians and parallels (longitude and latitude). These are determined, essentially, astronimically (axis of rotation, etc.), and can be recognized by geographical features; in both cases independently of magnetic measurements. There is no such obvious frame of reference or convenient landmarks. We can create such a frame from the magnetic properties; i.e. locate the magnetic poles and draw magnetic meridians through these poles. In this case, insofar as the terrella is an "ideal" "uniform" one, the "declination" must be, -- by definition of the meridians -- identically zero. The main point that can be established here is that it is a "good" terrella does permit the magnetic azimuths, poles and equators ("equinoctial line") to be found which are analogous to the astronomical/geographic azimuth, poles, and equator. Gilbert attributes (incorrectly) the actual, terrestial differences between magnetic and geographical azimuths etc., to local imperfections of the earth (pp. 235-238) and his experiments are arranged accordingly: The plausibility of this can be examined experimentally. Set up the large terrella in place of the globe in the supporting cradle. (Use the auxilliary divided circle to facilitate dip measurement.) Now examine the changes in declination or dip produced by adding small lumps of loadstone, or iron, to the terrella. Examine also to what extent the terrella itself is (magnetically) ideal. Obviously merely grinding in spherical form does not assure the proper symmetry: superficial inspection alone may show that the terrella is not made of ideal, uniform material.

You can also attempt to explore -- as Gilbert did -- the magnetism <u>inside</u> the terrella. Use the terrella which is cut up into two parts. Examine the polarities of the separate parts, and of the whole when put together to form an approximate sphere. (The alignment is of course important.) Now examine the polarity between the parts when these are separated. (cf. pp. 204-207) N.B. Again, remember that, particularly since the terrellas are not very strong magnets, all observations depend on the combined influence of terrella and the real earth. (cf. pp. 163-165)

10. Some Questions and Conclusions

Gilbert repeatedly makes the general -- if somewhat vague -- assertion that physical ordering of the elemental parts and the resultant "verticity" (bipolarity) is an essential feature of magnetization. Can you visualize this interpretation for a magnetized (compass) needle? a terrella? the earth?

Turning seems to be more characteristic of magnetic influence than pushing (repulsion) or pulling (attraction). Can you form a picture -- in terms of magnetic elements and forces -- which comprehends both? Is there any distinction between temporarily "induced" magnetism and "permanent" magnetism in this context? To what extent do the experiments suggest a plausible explanation of terrestial compass-needles and dip-circle observations in terms of properties of the earth itself? Is it reasonable to infer that the earth's interior is physically analagous to a loadstone-terrella? If measurements of declination/dip could be made over a sphere of, say, twice the earth's radius, what would they be like? (cf. p. 306) What inferences could one draw from this?

Is the magnetization of loadstone in the earth itself induced by the magnetic influence of the other loadstones in the earth? Do you agree with Gilbert's conclusion that there is a basic, magnetic "core" of the earth, of which the magnetism of loadstone rock is, in a sense, an accidental, superficial, manifestation? (e.g. p. 185)

To what extent is Gilbert's whole picture of the nature of Earth's magnetism destroyed by the subsequent discovery of the change of terrestial magnetism with time?