MAGNETISM DURING THE SEVENTEENTH CENTURY

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The development of electricity and magnetism after the publication of Gilbert's landmark work can be summarized in the following manner. The publication of On the Magnet appears to usher in a golden age for the magnetic philosophy. But, Gilbert's achievement is surprisingly limited in scope. The golden age of magnetism is over almost before it begins; a victim of a rapid change in scientific fashion that rejects the Gilbertian magnetic philosophy.

There is a continuation of the theories of natural magic and sympathy which persists until the end of the century. Concurrent with this, there is a shift towards a more rational theory of magnetism based on a corpuscular interpretation of magnetism. The materialist or corpuscular theories have the objective of supplanting the Aristotelian theories, which were identified with the magical, occult and animistic theories of the middle ages. Theories of electrical attraction continue to be based on the idea of effluvia. Towards the end of the century, there are new discoveries that shift emphasis away from magnetism towards electricity. The main story is clearly a struggle between the occult ideas, which become closer to the ideas of natural magic, and the materialistic interpretation. Both of these approaches eventually are discarded by the success of the Newtonian action at a distance philosophy.

The century ends with a bitter irony. The mechanical experimentally based magnetic philosophy successfully drives its aristotelian opponent from the field of battle, but it is a hollow victory. Experiments performed with vacuum pumps reveal that the magnetic force is transmitted through the walls of the pump and through the void. This result shakes the foundations of the theory so violently that interest in magnetism nearly disappears during the eighteenth century. Another ironic factor is the rising interest in electricity. This supplants the experimental interest in magnetism so effectively that one can say the eighteenth century is the golden age of electricity. The era of magnetic philosophy is over by the end of the seventeenth century.

The Persistence of Natural Magic

It is a surprising and curious fact that the belief in the ideas of natural magic and astrology persisted almost up to the end of the seventeenth century. This is remarkable because of the definitive experimental refutations that were published by Gilbert at the beginning of this century. There are many examples that could be cited. One of the more interesting is Alexander de Vicentis who published a book which opposed astrological beliefs and the concept of occult virtues and qualities which were fundamental tenants of natural magic. This book which appeared in 1634 shows the author is either completely ignorant of William Gilbert's book, or incapable of understanding its contents. The odd aspect is that the stated intention of the book is to oppose the views of astrology and belief in the occult virtues and qualities. Given this background we are surprised to find the following opinions in de Vicentis' book wherein he states that:

"The magnet did not attract iron by such [occult] virtue but by reason of a likeness in temperament which depended on manifest qualities. This was proved by experiment. For, if the magnet was smeared with garlic, it would no longer attract iron, because the garlic prevented the species of the stone from being represented to the iron as it was-rather quite differently, since garlic is destructive to iron, making it rust and deteriorate if it is anointed with garlic juice. The magnet turns towards the poles, because there are mountains of iron and magnet there, as sailors testify."[1]

This argument so strongly resembles the argument of Henry of Langenstein that one suspects he is copying from Henry's book. The basic flaw is that it was proved experimentally by Cardan, Porta and Gilbert, that garlic has no effect on the action of the magnet or the compass. However, we see the persistence of this false belief along with the old idea that the compass points towards mountains made of iron and the magnet. The author can be excused for being ignorant of the change of the declination, which clearly showed that the direction towards which the compass points is constantly changing, because this discovery was not announced until the following year. His resistance to Gilbert's explanation shows that Gilbert's work did not have sufficient influence to alter the old ideas.

In 1621, Jean Bapiste van Helmont published in Paris a book that seems more in the realm of natural magic than experimental science. De Magnetica is a medical book on the magnetic cure of wounds. This is a subject that Gilbert roundly criticized and ridiculed. Van Helmont is clearly a follower of Paracelsus, but the many disproofs of Paracelsian ideology regarding magnetism did not deter Van Helmont. His approach to magnetism is within the spirit of natural magic. He tells us that magnetism:

"... is an unknown property of a heavenly nature, very much resembling the stars, and not at all impeded by any boundaries of space or time... Every created being possesses his own celestial power and is closely allied with heaven...the spirit is everywhere diffused; and the spirit is the medium of magnetism...it is not the spirits of heaven of heaven and of hell which are masters over physical nature, but the soul and spirit of man which are concealed in him as the fire is concealed in the flint." [2]

Van Helmont was clearly familiar with William Gilbert's On the Magnet which he praises by saying:"no man ever writ more judiciously or experimentally". But, he persists in saying that:

"The loadstone onely by the affriction of Garlik, amits its verticity, and neglects the pole...The reason, because Garlik is the loadstones proper Opium, and by it that spirituall sensation in the magnet is consopated and layd asleep..."[2]

Despite the many disproofs of the garlic story, belief in its truth continues with Van Helmont.

Van Helmont's book clearly shows his understanding of the difficulties regarding magnetism. These facts persuade him to believe in the spiritual nature of the magnetic force. One of his more convincing "proofs" is the following:

"Doth not the needle of the Mariners compass, through a firme glasse, closely sealed up with melted soder (in which there can be no pore or cranny discovered) steer it self to the Artik pole?... wherefore the same numericall *accident* streaming in one continued *radius* from the loadstone into the *aer*, passes through the glasse, and perhaps goes as farre as to touch the pole itself..."[2]

Van Helmont is convinced of the spiritual nature of the magnetic virtue. This belief leads him to a position that is closer to natural magic than the rational materialism that is the developing fashion of the century.

The Baconian Reaction to Gilbertian Magnetical Philosophy

Sir Francis Bacon is considered the father of experimental scientific philosophy in England. His works mark the origin of the new fashion of inductive science based on experiment. But, there is more than an experimental approach. There is also a determination to interpret all natural phenomena mechanistically. This is the aspect that dooms Gilbert's magnetical philosophy in England.

One reason that the publication of On the Magnet failed to initiate a golden age of magnetism, is the extremely severe criticism that was leveled against it by Francis Bacon in his famous controversial condemnation in the following words:

"Gilbert has attempted to raise a general system upon the magnet, endeavoring to build a ship out of materials not sufficient to make rowing pins of a boat."[3]

The language that is used is clearly not ambiguous, Bacon is condemning Gilbert's magnetical philosophy. This condemnation has puzzled historians who are confused as to why Bacon would attack one of the finest examples of a philosophy which he advocates. The explanation is clear, Bacon disagrees with Gilbert's hypothesis that the earth is a giant magnet, and finds his Aristotelian explanations unacceptable. Bacon dislikes the magnetical philosophy and delivers a polemic against it.[4]

Bacon's polemic was persistent, unremitting, and extensive. His negative comments appeared in many of his works. One can be certain as well that he used all opportunities, private conversations, personal letters, and published works, to castigate Gilbert's magnetical philosophy. Bacon set out to cast Gilbert's work as an example of false scientific method; an example of error to be avoided. He compared him to the alchemists in disparaging terms:

"Another error...is, that men have used to infect their meditations, opinions, and doctrines, with some conceits which they have most admired, or some sciences which they have most applied...So have the alchymists made a philosophy out of a few experiments of the furnace; and Gilbertus, our countryman, hath made a philosophy out of the observations of a loadstone."[4]

Bacon's polemic against Gilbert has provoked considerable debate among historians of science, in their efforts to understand its motivations. Why does Bacon attempt to derisively deny to Gilbert any claim to experimental philosopher, when his book is a model of the new approach which Bacon champions? [4,5]

Unfortunately, there was a grain of truth in Bacon's criticisms, which was best revealed when he said of Gilbert, that he has "not unscientifically introduced the question of magnetic force" but that "he has himself become a magnet; that is he has ascribed too many things to that force, and built a ship out of a shell". Here Bacon means that Gilbert's magnetic philosophy overreaches what can be proved by his experimental demonstrations. Frankly, one can see why this criticism made sense. The idea that the magnetic force of mother earth caused it's rotation seems to be a pure Copernican fantasy. The arguments presented to support it were weak and the connection to the demonstration experiments that Gilbert claimed proved it were unconvincing.

On the other hand, Bacon resisted the thesis that the earth was fundamentally magnetic. Today this seems absurd, and totally hardheaded, because the discovery of the magnetic dip offered indisputable proof of it. But, Bacon seems to have objected fundamentally to the idea that the earth had a soul or animate force within it, which was the source of it's Copernican movements; ie, rotation and revolution. When this idea was extended to the entire universe so that all the planets, moons, and stars had animate souls, we can see why Bacon opposed Gilbert's magnetic philosophy.

Another reason is that Gilbert's theory of magnetism is fundamentally Aristotelian. When we examine it carefully, we see that essentially it is an immaterialist theory of secondary occult qualities. As presented by Gilbert, it is greatly enhanced by the fundamental idea of the orbitus virtus or sphere of influence, and his magnetic demonstrations which clearly show how this magnetic influence is propagated and acts across space. But, his rudimentary field theory was still Aristotelian in its vocabulary, and maintained the fundamental idea of the form. What Gilbert contributed was a series of demonstrations combined with an attempt to develop a new magnetical vocabulary. Gilbert's new magnetic vocabulary was excellently suited to his rudimentary field theory, but when he sought to discuss the fundamental nature of magnetism, he was forced to return to the old fashioned concepts of the scholastics, which Bacon sought to overthrow.

Ultimately Bacon opposed Gilbert's ideas because Gilbert was fundamentally out of tune with the new scientific philosophy advocated by Bacon. Gilbert's methods were old fashioned. He expressed himself in terms that were fundamentally scholastic and Aristotelian. This was the approach which Bacon sought to supplant. Hence, Gilbert's work was flawed and provided an example of bad philosophical method. The result of Bacon's polemic was unfortunate. In England Gilbert's magnetical philosophy didn't take hold. The result was a rising interest in mechanical and corpuscular theories of magnetism, consistent with the mechanical theories of electricity. This gives us insight as to why Gilbert's experimental work in electricity was fruitful. It was based on a materialistic effluvial theory. His immaterial magnetic theory was stillborn, and we should not be surprised that magnetic science makes little progress for another two hundred years.

It is ironic that the publication of On The Magnet stimulated English interest in materialistic theories of magnetism. This was clearly a reaction against the traditions of natural magic and aristotelian philosophy. The new effluvial theories of magnetism are clearly a return to the theories of Empedocles, Democritus, Epicurus, and Lucretius. These theories were clearly doomed from the beginning because the experimental facts were inconsistent with them. Gilbert clearly understood this and proposed an immaterialistic theory of the magnet as a result. But, the builders of the new science were intent upon building a new scientific philosophy upon the foundations of mechanism. The result was a fruitless effort, which upon failing resulted in a declining interest in magnetism.

Thomas Browne's Pseudodoxia Epidemica

In 1646 Sir Thomas Browne published an important, but today little known, scientific work that continued the Gilbertian-Baconian tradition of Elizabethan English science. Inspired by Bacon's program for a comprehensive catalog or "calendar of old errors". Brown's answer to Bacon's plea for a catalog of errors was the Pseudodoxia Epidemica: or Enquiries into Very many received Tenants, And Commonly presumed truths, commonly known as An inquiry into Vulgar Errors. The book devotes each chapter to a common, vulgar error. Book II, Chapter 3, addresses the common errors of the lodestone and magnetism. Brown's work is also famous as the first work in English to use the word electricity in describing the attraction of amber.

Brown's inquiry was in the tradition of Elizabethan English science pioneered by Robert Norman, William Barlowe, Mark Ridley, and William Gilbert. Their approach was to use experiments to test time honored beliefs regarding magnetism. Brown's work continued this tradition. In his chapter on the lodestone, he describes a number of vulgar errors which he personally tested by experiments. He also describes other errors: natural, historical, medical, and magical. It is fascinating to read. Particularly the medical errors, some of which Brown is not sure are true or false.

Browne begins his discussion of magnetism with "a very hard paradox" which will seem to be a great absurdity, when he makes the claim that there is no attraction due to the lodestone. Browne says that there is no attraction of a lodestone for iron as commonly supposed. Browne explains with the definition of "Magnetical attraction" given by Ridley which defines attraction "...to be a natural incitation and disposition conforming unto contiguity, an union of one Magnetical Body with another, and no violent haling of the weak unto the stronger. And this is also the doctrine of Gilbertus, by whom this motion is termed coition, and that not made by any faculty attractive of one, but a Syndrome and concourse of each: a Coition always of their vigors, and also of their bodies, if bulk or impediment prevent not." Simply put, the magnetic attraction between a magnet and iron is a mutual attraction of each for the other. Here is the basis of Newton's third law of motion that action and reaction are equal and opposite. But this law would not be invented by Newton for many years. Did he study Browne's book during its formulation? We can not say. However, Browne's book was very successful and was widely read. It was republished in many editions during the nearly thirty year period from 1646 to 1672.

Browne dispenses with many of the old tales, the fable of the garlic, the fable of the diamond, as well as the fables of Paracelsus. He affirms they are false. He also refutes a modern fable that heat destroys the attraction of the magnet for iron and steel. He says that it is false what "..hath formerly deceived us, that a lodestone will not attract an Iron or Steel red hot." While Gilbert clearly showed that heat destroyed the magnetic power of the lodestone, it did not destroy the magnetic nature of the iron which was attracted to it. Besides fire there were a number of ways to destroy the power of a lodestone. One was to place it near another more powerful stone, which could

“...in a short time enchange its Poles; or being kept in undue position, that is, not lying on the meridian or else with its poles inverted, it receives in longer time impair in activity.”

Browne’s chapter continues with a discussion of errors in magnetic history, medicine and magic. He ends with a brief mention of the fundamental ideas of Gilbert’s magnetical philosophy that motions of celestial bodies are due to magnetism. “Many other magnetisms may be pretended and the like attractions through all the creatures of nature. Whether the same be verified in the action of the Sun upon inferior bodies... whether the flux and reflux of the Sea be caused by any Magnetism from the moon...might afford a large dispute”. Hence for Browne, Gilbert’s magnetic philosophy remained merely an interesting unproved hypothesis. Browne also ignored many other of Gilbert’s discoveries. Most significant is his complete failure to mention the experiments which form the basis of Gilbert’s rudimentary field theory, and in particular Gilbert’s concept of the orb of virtue. Apparently, the field theory concept was beyond the grasp of even the very best educated English savants of the seventeenth century.

Galileo’s Researches in Magnetism

In continental Europe, Gilbert’s work was received with more enthusiasm. Kepler attempted to incorporate it into his theory of the solar system. Galileo admired the experimental aspects and performed his own researches. Vincenzio Viviani who liked to style himself as “the last disciple of Galileo” describes some of Galileo’s magnetic experiments:

”towards the end of 1604 he had completed a long study of the properties of the loadstones, and after many and varied experiments had found a sure way of arming any given stone so as to make it sustain a weight of iron 80 to 100 times greater than could be supported by the stone unarmed-a result which had not been reached by any investigator up to that time”.[6]

It is believed that Galileo may have been performing experiments in magnetism prior to the publication of <u>On the Magnet</u>. Professor Favaro of Padua, a biographer of Galileo, tells us that:

”our philosopher had been engaged on these studies for a considerable time, if not to a date anterior to the issue of Gilbert’s book, certainly very soon after, when he verified all the experiments of the English philosopher and instituted new ones of his own.”[6]

It is certain that publication of Gilbert’s book stimulated him to active research in magnetism, because we have letters written in the immediately following years which describe Galileo’s experiment with loadstones. These experiments resulted in one sure demonstration of a repulsive effect of magnetism, known as superposed magnetism. This is described in a letter written in 1608.

“I have also observed in this stone another admirable effect which I have not met with in any other, namely, that the same pole repels or attracts the same piece of iron according to distance. Thus, placing an iron ball on a smooth and level table, and quickly presenting the stone at about a one finger’s distance, the ball moves away and can be chased about at pleasure. But sharply withdraw the stone to a distance of about four fingers, the ball now moves towards it, and with a little dexterity can be made to follow it about. It never approaches nearer than one finger, at which distance repulsion ensues."[6]

The experimental result occurs because the iron ball does not consist of a pure iron, which always exhibits an attraction towards the magnet.

It is clear that Galileo admired Gilbert's work and endorsed his theory. In a letter to the Grand Duchess Cristina he refers to Gilbert in the following positive manner:

> "From the work of that 'grandissimo filosofo', so exhaustive of its subject and so full of evident demonstrations, there can be no question that our earth in its primary and universal substance is none other than a great globe of loadstone."[6]

Galileo further supports Gilbert's conclusion in his Dialog on the Chief Systems of the World, published in 1632. But, this endorsement by Galileo did not lead to a wide acceptance of Gilbert's magnetical philosophy in Italy.[7]

Galileo's role in the history of magnetism points toward an important aspect of his scientific program. There is no evidence that Galileo understood the ideas that William Gilbert developed in his work. Galileo seems to have been attracted towards what today seems to be the least relevant phenomena of magnetism. He did not investigate the phenomena of magnetic induction and seems to have been completely oblivious to the idea of the field which Gilbert had developed to a rudimentary form. Galileo does not seem to have seen the mathematical possibilities within Gilbert's work. If we are to conclude that Galileo was a great man. His inability to grasp the truth of magnetic phenomena is puzzling. We can understand it only in terms of his inability to accept the existence of an immaterial force. He was unable to bring magnetism within his materialist system of thought, and hence it is relegated to a minor role in his program. A role which emphasizes experiments that do not reach towards a depth of understanding of the phenomena.

Galileo is not a great figure in the history of electricity and magnetism. His importance lies in his modest interest in performing magnetic experiments and his endorsement of Gilbert. However, Galileo did not publish his experimental results and did not develop theories of electricity and magnetism. What we know is principally contained in the Dialog on the Chief Systems of the World, which is not experimentally detailed or extensive. His interest inspired the interest of his students. One of them, Benedetto Castelli attempted a theory of magnetism which was described in a treatise written in the form of a 32 page manuscript letter around 1640, but this was not published until 1883.

Castelli's Theory of Magnetism

In the year 1639, Benedetto Castelli developed a theory of magnetism which he composed as a short treatise in the form of a letter. Titled "Discorso sopra la calamita". The letter was discovered in manuscript form among some other papers by Galileo in the eighteenth century and eventually published in 1883. Although the author considered the work merely a preliminary study that was incomplete and unsatisfactory for publication, the Discorso is interesting. Despite the fact that Castelli claims to eschew Aristotelian notions, the magnetic theory of the Discorso resembles the Aristotelian notion of the propagation of magnetism through a medium. The document is also important as the first example of a theory of magnetism which uses elementary magnets to account for magnetization of iron.

Castelli's theory is based upon metaphysical principles which resemble Gilbert's magnetic philosophy. His first principle is the assertion that what is predicable for the earth and the loadstone is also true for those microscopic particles which are beyond sensible perception. He asserts that microscopic elementary particles exist that are magnetic. This argument by analogy is based on his acceptance that the earth is a giant loadstone, as Gilbert claimed. Hence it follows for Castelli that any part of the earth possesses the property of magnetism just as Gilbert asserts as well. So the earth is composed of material which is magnetic because any part of the earth, no matter how small, is "true, genuine, and conatural" with the loadstone of the earth.

So far Castelli has not asserted anything which is not present in Gilbert. Castelli's contribution consists in an explanation of why some earthly bodies such as iron become magnetized. Along the way he presents a theory of the propagation of magnetism through a medium. The idea is based upon the concept of minute elementary magnets which are in a normal state of disorder and confusion. Magnetization consists of bringing these into an ordered state. The concept employs the idea that the microscopic particles are tiny loadstones.

Castelli explains magnetization of iron in the following way:

> "Let there be a body throughout which are disseminated very many and very minute corpuscles of loadstone. Let such corpuscles be disordered with respect to the principle ends, i.e. the Northern and Southern [poles], but let the majority, if not all of these corpuscles be easily moveable and predisposed to be reordered by a weak force, and, once reordered, to maintain such ordered disposition. When such a body touches either the Northern or the Southern pole of a piece of loadstone it will acquire the magnetic virtue so definitely that the end of the body which has touched the Northern pole of the loadstone will acquire the Southern virtue, and the other end, without further touching, the Northern virtue, and the body will orient itself in perfect fashion toward the same poles of the great loadstone, and it will also have the strength to communicate the [magnetic] property to other bodies of the same nature..."

Castelli defines the resulting magnetization of iron as magnetic "in the first degree or sense". This magnetization occurs as follows:

> "...as the Northern pole of the loadstone touches one end of the body...the nearest magnetic corpuscles disseminated in the latter unite with those in the loadstone by joining their Southern poles with the Northern poles of the former. Likewise will all other succeeding corpuscles do, and thus, without further contact of the end of the body with the pole of the loadstone, all the corpuscles spread out within the body will come to orient themselves with their Southern poles toward the same end of the body, and with their Northern poles in the opposite direction. Thus will the body become magnetic..."

Magnetization in the first degree does not occur instantaneously, the iron body must make contact with the loadstone:

"...for some little time, at least as long as two or three or even more beats of music...so as to give time for the ordering of those disseminated magnetic corpuscles..."

As an extension of this idea, Castelli explains that magnetization by magnetic induction can take place without having the loadstone physically touch the iron, it merely needs to be within the sphere of influence of the loadstone.

The theory of magnetization also was accompanied by a theory of demagnetization, which was necessary to explain why the iron lost its magnetic property when separated from the loadstone. Here Castelli's ideas are less convincing. He tells us that the body loses its magnetic virtue when some of the corpuscles

"contests the force of the others", with the result that the corpuscles "become disordered and confused. Hence neither the Northern nor Southern poles can operate and the virtue is abated and extinguished".

The process can occur over time, due to natural corruption and decay, or due to heating, or melting of the iron such that its "particles no longer conserve exactly their legitimate and ordered orientation".

Castelli's magnetization in the second degree is the mechanism that allows propagation of the magnetic virtue. Substances magnetized in the first degree retain their magnetization for an indefinite or protracted period of time and can magnetize other bodies. Magnetization in the second degree is impermanent and is retained only as long as the magnetizing body is kept near to the magnetized body. The basic idea is that for magnetization of the second degree, the particles are easily and quickly brought into alignment. He describes this as follows:

"Let very small corpuscles of loadstone be disseminated and scattered throughout the substance of a body, but confusedly and without order with respect to its constitution. Let such corpuscles, however, be very easily moveable, if not to say instantaneously. Or let them have the propensity to arrange themselves in the first constitution [i.e. to align themselves]...Now, if inside such body a piece of loadstone is immersed, the body will acquire the magnetic virtue and will conserve it for as long as the loadstone is present. Once it is removed the body loses that virtue. We shall call such a body magnetic in the second sense or second order."

The key part is the following explanation of how the magnetization takes place. Here the idea of propagation of the magnetization is latent in the theory. We see this because the magnetization occurs progressively throughout the body.

"...as the end N is the Northern pole of the loadstone, it must be that all the corpuscles scattered through the body...unite with their Southern Poles toward the Northern pole of the loadstone starting with those that are closer and contiguous with it. In consequence their Northern poles are at the farther ends, and to these Northern poles the Southern poles of successive corpuscles will unite. and thus by and by the corpuscles of loadstone scattered throughout the body...will orient themselves. In this way as the body...acquires Northern and Southern poles it is magnetized. However, were the loadstone removed, because of the propensity {to be easily moved], or because of some other cause, those corpuscles return to confusion and disorder hence the virtue is lost."

The decreasing strength of the magnetization with distance is explained by a diminution of virtue with distance as follows

"... as the corpuscles which are nearer to the loadstone become oriented, it must be that the power goes on decreasing by and by the farther away the corpuscles are from the loadstone until it finally vanishes completely."

The payoff is the ability to explain why the magnetic virtue is able to act at a distance. The explanation reminds us of the propagation of an occult quality. Castelli tells us that magnetization can occur without direct contact by making the medium an active agent capable of magnetization as a body of the second kind. Hence the air for Castelli is a magnetic substance capable of magnetization to the second degree. It is a beautiful theory, but its similarity to the Aristotelian idea of a secondary occult quality probably doomed it. These ideas were clearly out of favor by the time that Castelli composed his Discorso. This explains why he felt that the theory was incomplete and that more time was needed to work upon it.

Although Castelli's Discocso was not published, it is certain that it was circulated and read by members of the Galileo circle in Italy. Castelli was an important member of that community. He had assisted in Galileo's study of sunspots. In 1667, Giovanni Alfonso Borelli, a student of Castelli's, published a treatise on mechanics, De vi percussionis, which presented a brief discussion of magnetism. This discussion is believed to be a modified version of Castelli's theory. The main modification introduced by Borelli, is the introduction of a magnetic effluvia or vapor from the loadstone to replace Castelli's propagation of magnetism through the air. Borelli explains magnetization of iron by supposing that

"..one must postulate that in the iron there are innumerable active and spirited particles. These particles, however, are disposed in a very confused manner, all intertwined in a variety of ways so that not all their Northern poles point in the same direction but are all confusedly mixed...it is necessary to imagine that when the iron is brought near the loadstone and within its sphere, which stems from the exhalation of the vapor of the loadstone, just as by the process of stirring up, the magnetic particles which are within the interstices of the iron are stirred up and turned, and once loosened and set free...they direct their poles in proper orientation toward the pole of the loadstone..."

This is not Castelli's theory, but we see that Borelli has borrowed Castelli's ideas and combined them with the currently prevailing magnetic theories. The ironic aspect is that for the modern reader, Castelli's theory has more of the ring of truth to it than the improvement offered by Borelli.

The Aristotelian Reaction to Materialism

Modern histories have tended to make the error of including the Aristotelian theories of magnetism within the magical and animistic interpretations. This error derives from the new scientific fashion of the seventeenth century, which lumped all these ideas into the same category. In England, the new experimental approach to science advocated by Francis Bacon, tended to prefer a mechanistic approach based on material causes. In France, there was also shift towards the new mechanistic philosophy within the context of Cartesianism. These efforts to mechanize the magnetic theories of attraction were not designed to discriminate between magical and Aristotelian theories of magnetism. This is because these theories were all immaterial involving a hidden cause. The new modern approach which presented itself as a rational, experimentally based, philosophy of truth, therefore lumped all of their opponents into the same category, painting them all with the same brush of old fashioned outworn, erroneous, and false ideas. Only the new materialist interpretations escaped this negative connotation.

However, there were significant differences between the scholastic theories based on Aristotelian concepts and the ideas of magic and animism. Time and again, as we saw in the chapter on the middle ages, the scholastics stressed the rational and anti-magical aspects of their occult explanation. However, the negative meaning took hold. The word occult now means magical as a result of the efforts to associate it with irrational conceptions. The main problem with the Aristotelian conception was an inability to provide a specific cause for motion. This weakness also existed within the materialist theories, but these were seen as the new approach to science; a modern rationalist approach based of the new enlightened method of scientific reasoning. It was not realized that these ideas had previously been found unable to satisfy the experimental facts. So the materialistic theories of the Greeks were revived, by the new thinkers who did not realize that they were reinventing the failed theories of the Greeks.

This resurrection of materialism was not acceptable to the doctrines of the Aristotelians and it is not surprising that the champions of the anti-materialistic view would be found among the Jesuits. The Aristotelian reaction is led by a Jesuit priest Niccolo Cabeo of Ferrara. His most important work was published in 1629 with the latin title Philosophia magnetica in qua magnetis natura pentus explicatur. This is know in english simply by the shortened title: The Magnetic Philosophy. It is an important book, because it extends Gilbert's Aristotelian theory of magnetism and his primitive theory of electrical attraction. It is an important work on magnetism, but it is far better known for its experiments in electricity. The most important result being the claim to be the first observed instance of an electrical repulsion.

Niccolo Cabeo, who is also known by his latinized name of Cabeus, was born in Ferrara Italy in 1585 and died in 1630 at the age of 45. He was educated at the Jesuit College of Ferrara. He was a product of the catholic education system which excelled at identifying and promoting intellectual genius. From 1622 until his death he was engaged in experimental physics. He wrote two books. The second which was published in 1629, just one year before his death, is one of the most important books of the seventeenth century devoted to magnetism and electricity. In this book, Philosophia magnetica, is the first attempt to discover the mathematical laws governing the propagation of magnetic force. He showed that at every point within Gilbert's orbis virtus, the force has a fixed magnitude and direction. Niccolo Cabeo is important because, following Gilbert, he is the next great man to study and develop a field theory of magnetism.[8]

According to Cabeo's Aristotelian metaphysical theory, every material substance consists of a union of two elements or principles, matter and form. Matter is permanent and in all circumstances unchanging, while form is the variable principle of change. What we see in the world as motion and change is the result of the alteration of the form, not the matter of substance. When placed is the presence of a piece of iron, the iron experiences an alteration or change in its underlying form. This change becomes more pronounced or intense as the magnet is brought closer and closer to the iron. The particular effect of the alteration of the form of the iron is to cause it to exhibit magnetic poles and it is these magnetic poles which cause the movement of the iron according to the law of attraction of like for like and the law of repulsion of unlike poles. Hence the iron is drawn to the like pole of the magnet and repelled by the opposite pole.

To understand Cabeo's theory, we must return to the ideas behind the Aristotelian explanation of magnetism. The salient feature is that it is a very primitive field theory. Prior to Gilbert, the idea that qualities were transmitted without a medium for the transmission was developed by the scholastic philosophers. Henry of Langenstein having developed the most formalistic theory. There was a recognition that there was a common property shared with light and heat; the ability to transmit its quality across space without contact. This idea we call propagation, transmission, or communication of energy. There are two aspects which were only dimly perceived by the philosophers in early history. The first, is the ability to communicate the property or quality over a large distance. The primary example of this being light from the sun, moon, and stars, and heat from the sun. The second being the influence or action of the magnet and amber in attracting objects over relatively short distances. We now understand these to be two different aspects of electromagnetic fields. The Aristotelian approach was to argue, by analogy to the qualities of heat and light, that magnetism was a quality propagated in space by a hidden or occult means. This is a conception familiar to us as a propagation of force by the electromagnetic field. The difficulties arose in separating this concept from the theories of magic, astrology, and sympathy advocated by the spiritualists.

Understanding Cabeo's role in the development of magnetic ideas requires that we see his effort in terms which clarify the nature of the transmission of the magnetic force. Unfortunately, electrical attraction was not included within this program. Little was known, and just as Gilbert and other predecessors had done before him, Cabeo attempted a materialistic theory of electrical attraction. It is an important step because it begins the debate on the nature of electrical attraction which proceeds during the seventeenth century.

Cabeo's theory of magnetism is a thoroughgoing Aristotelian approach in the spirit of the middle ages. His main contribution is to clarify the theory, in light of the experiments of William Gilbert. Hence Cabeo's contribution is to strengthen the Aristotelian theory by clarifying or extending it. The basic ideas of the Aristotelian theory can be divided into the following main considerations. First, the theory is a field theory, although the idea of the field is unformed and not specifically defined. Cabeo rectifies this deficiency by incorporating Gilbert's orb of virtue or sphere of influence into the concept. In doing this, he addresses the second main problem; why does the iron react to the loadstone?

Cabeo dutifully emphasizes that the magnetic action is not spiritual in the sense used by the animistic, magical, astrological and sympathetic theories. Here he is following in the path of Henry of Langenstein, who stressed the same thing. The action of the magnet is a natural process. It is analogous to the action of gravity. Cabeo considers that the action of the compass is as natural as the fall of heavy bodies towards the center of the earth. This is due to an intrinsic motive quality possessed by the loadstone. This quality is not defined. Cabeo does not have the solution for this problem, but he understands the second aspect of the problem needs clarification.

Cabeo considers that iron is magnetized through imitation or reception of the magnetic quality from the loadstone. As such, magnetization is an accident, as loss or reversal of it clearly demonstrated. Magnetization takes place through an agent which is neither an emission of particles nor a transport or local movement of the magnetic quality. Rather, the magnetic quality propagates through the medium of the sphere of influence of the loadstone just as light and heat. The fact that iron is magnetized without contact shows that there is a resonance between the loadstone and the iron in the manner of the consonance between strings: when one of them is plucked the other receives the vibration.

This theory is not complete, but it attempts to resolve the ambiguity of the Aristotelian approach. This is accomplished in two parts. The first by defining that the action is transmitted by the sphere of influence. The second was to define why only iron is attracted. The idea of a resonance through the sphere of influence is an attempt to clarify this problem. We see that resonance clarifies why the action is specific only to iron, and the sphere of influence defines the character of the region of the action in space. Cabeo is clearly moving towards a way of relating the field theory of Gilbert, which addresses the magnetic action on the versorium and iron wires, with the attractive force. The idea is hampered by the lack of a mechanical theory of force and its action which was not developed until the following century.

By the second half of the century, the materialist approach to magnetic science was gaining ground primarily through the efforts of Descartes and Gassendi. This of course provoked a response from the followers of Cabeo. Cabeo's Aristotelian magnetic theory was extended by Vincent Leótaud, a French Jesuit mathematician who lived from 1595 to 1672. Father Leótaud was professor of mathematics. In 1668, he published a book on magnetism titled <u>Magnetologia</u>. Its significance is that it:

> ”was the first to have considered magnets as aggregates of small elementary magnets with equal directions, though earlier experiments on breaking magnets ought to have suggested this hypothesis long before.”[9]

Leótaud specifically set out to extend Cabeo's magnetic field theory. He rejects the animistic astrological, and occult (magical) theories as well as the materialist ones developed by Descartes and Gassendi. Leótaud saw the hooked atoms and threaded particles as absurd conceptions. He viewed magnetism as a property of certain bodies to move and to orient themselves with respect to one another. The activating force or power was conceived as an immaterial or nonsubstantial property which propagated in a sphere like heat and light. The property of magnetism resembled light in its effect of being intensional. The property of intensity, the ability to carry force or power, like “visible images, light, or, equally, like the various influences that celestial bodies exert upon things down here on the Earth.”

Leótaud urged that this magnetic power was drawn from the earth, and was not inherent within the loadstone:

”For if a loadstone is not oriented in concordance with the Earth, its magnetic property is lost; or at least it is lessened [while] fragmented loadstones show that the magnetic property is unique, simple, and homogenous, and occupies the whole magnetic body.”

This is not very clear until we consider what he is aiming at. Leótaud is thinking that the magnetic power is drawn from the earth as a gigantic magnet. This power is communicated to magnets but its effectiveness depends on their orientation. Improperly oriented magnets do not possess the power and unless all the individual portions of a loadstone are properly ordered, the magnetic power is not present within its sphere of influence.

Here we find the first intimation of the idea of magnetic domains. This is one reason why Leótaud’s ideas have attracted the interest of historians of science. But, Leótaud doesn’t really have this in mind. He is aiming at two basic facts. He wants to explain why iron is not magnetic until it approaches the sphere of influence of a loadstone, and to develop a field concept that explains why the magnetic action appears at the poles as opposed to uniformly distributed in space.

Leótaud’s theory appears to be based on a single experiment which brings to his mind the idea that magnets derive their power from the earth, and without this, the resulting power is impotent. The experiment consists of taking a loadstone and filing it down into small particles of loadstone dust. These are then packed into a paper tube with the following result as Leótaud says:

”...we do not observe any phenomenon of orientation because of the disorder of the loadstone particles, and it is in reason of this same disorder that we must explain how iron is deprived of magnetic property until it suffers the influence of a loadstone which gives to all its particles the property and energy along the same orientation.”[10]

Leotaud interprets this as the explanation why iron is not magnetic. When it is removed from its vein within the mine, smelted and then poured into a mould, its particles are like the loadstone power win the paper tube. They are disordered. But then when a magnet is brought near, they again receive the power to attract.

Leotaud also applied this idea to the mathematical calculation of the sphere of influence.

”Leotaud disagrees with both Gilbert and Cabeo on the thesis that the poles of a loadstone are not merely points of the resultant magnetic forces of the whole magnet, but also the natural loci from which the magnetic force spreads out in waves. Rather, Leotaud argues, the magnetic force is spread out in all directions from every point of the loadstone taken as a small, elementary magnet. The loadstone poles, he continues are but the loci of the resultants, or integration in our modern view, of the forces of all such elementary magnets.”[10]

The Materialist Theories of Magnetism

The second half of the 17th century was an era of attempts to liberate all physics, from the grip of the occult ideas and Aristotelian philosophy. Natural philosophers, they can't be called physicists yet, of the 17th century were struggling to invent modern ideas. The watchword of these moderns was experimental mechanism. The new mechanical sciences of Galileo, Descartes, and Newton were candidates to overthrow the occult, but they were in their infancy. Primary among these mechanical ideas were theories relying on the mechanism of material effluvia. The interesting aspect of these is their similarity to the old ideas of the Greeks. As we have seen, magnetism was resistant to the ideas of material or corpuscular emanations, a fact well understood before Gilbert. Magnetism was a paradox that defied material explanation; but the enthusiasm for the new mechanistic approach to science urged the mechanists to attempt a new interpretation of magnetism.

The new materialism was a repetition of already familiar pattern of changing intellectual fashion. Just as during the tenth and eleventh centuries there was a surge of interest in Aristotelian knowledge, followed in the fifteenth century by a surging interest in neo-Platonism, Hermeticism and natural magic, in the seventeenth century the intellectual fashion was a mechanical materialism. This was based on a resurrection of the ideas of Democritus, Epicurus and Lucretius through an interest in the work of Lucretius.

Prior to the decline of Rome, Lucretius poem, De rerum natura, was not widely circulated, but it was preserved and copied into the collections of the Christian monasteries. The renaissance obsession with the rediscovery of classical knowledge resulted in its recovery and publication. In 1418 Poggio Bracciolini discovered a copy, which was eventually published in 1473. This was followed by another edition published in 1563, which was based on an earlier manuscript version. There was a surge of interest in the work, and by 1600 there were as many as thirty editions in publication. The work inspired controversy. It provoked reactions, both positive and negative. [11]

The resurgence of interest in Lurcetius is interesting. His work had never been popular, but in light of the surge of superstition, and the resulting reaction against witchcraft and the witchcraft trials, which stained the fourteenth and fifteenth centuries, we can understand the new fashion as a reaction against the excesses of magic, superstition, and the catholic church. Turning towards Lucretius and the Epicurean tradition was a natural reaction, because it represented the contrary philosophical approach. Its mechanical rationalism was devoid of any astrological, magical, hermetic, or spiritual elements. Its purely mechanical non spiritual naturalism represented a danger to the church as well as to the Aristotelian magnetic philosophy, because it lumped the occult qualities, such as heat, light, and magnetism into the same superstitious category.

In England, there was a dissatisfaction with the magnetic theory of Gilbert because of its Aristotelian and animistic elements. We have already seen how the bitter opposition of Francis Bacon began undercutting the Gilbertian magnetic philosophy at the beginning of the century. However, there were no really well developed theories which were brought forward to supplant the Gilbertian ideas. The English were occupied with their civil war. During the restoration period of the second half of the century there was a resurgence of science marked by the establishment of the Royal Society, founded in 1660 with a charter from Charles II. Materialists contented themselves with an experimental program which sought to undercut the nonmaterialist approach by eliminating its occult, animistic, and vitalist elements. This was motivated by the Baconian approach which urged extensive experimentation before building new philosophical systems.

On the continent, the situation was different. The attempts to build a materialist theory of magnetism began earlier. Here the natural philosophers attempted to build new philosophical systems upon the foundation of materialist mechanism. The most successful was the system of the famous French philosopher Renee Descartes. In Italy, the Galilean school also attempted the development of magnetic theory, but in a more modest manner that was not successful.

The most important materialist theory was developed by Descartes. It is characterized by an ambitious hubris, which sought to create a comprehensive mechanical philosophical system deduced using only mechanistic principles. The Cartesian approach developed from the ideas of Issac Beeckman, a Dutch school teacher and administrator, who had a particular interest in natural philosophy. In 1618 he met Descartes, who was then serving in the army of the Protestant Dutch Republic. Descartes who was interested in mathematics, learned mathematical natural philosophy from Beeckman. An innovative approach for the time.[12]

Born in 1588, Issac Beeckman's career is an example of the materialist fashion that styled itself as the new modernism. He is significant because his thought stands at the apex of the new fashion. He is a teacher to the intellectual giants of the new modernism: Descartes, Gassendi, and Mersenne. Beeckman was the prototype of the new natural philosopher. He was very well educated, skilled in the practical arts, advocated mathematics, performed experiments, and was a critical thinker. He developed his materialism from Hero of Alexandria and was interested in the mechanistic materialism of Lucretius.[13]

Beeckman's career reflects this combination of backgrounds and his interest in experimental science. His philosophical approach was mechanical, and his association with Descartes is beleived to have influenced Descartes toward mechanical natural philosophy. He was interested in astronomy and accepted the Copernican astronomy. Beeckman's primary philosophical notion was the idea of inertia. By 1613, he had rejected the notion of animate soul or form as the cause of motion. He beleived that when there is no impediment to motion there is no reason why velocity and curvature of movement should be altered. He anticipated Galileo's discovery of the law for free fall. In 1618 he had successfully worked out the law for freely falling bodies accelerated in a vacuum and obtained the correct relation between time and distance. In 1627, Beeckman became interested in magnetic experiments after reading Gilbert's <u>On the Magnet</u>. Beeckman rejected Gilbert's Aristotelian magnetic philosophy, because he objected to Gilbert's idea of an animate magnetic soul in the heavens. He described it as "unworthy of a philosopher", a statement which reminds us of Francis Bacon's opinion.[13]

Beeckman's magnetic philosophy was mechanistic. He wanted only explanations which "put things as it were sensible before the imagination." The idea of an "internal magnetical force" as the motive power for rotation of the earth and revolution of heavenly bodies conflicted with Beeckman's concept of motion due to inertia in empty space. Further, Beeckman beleived only in action by contact and rejected the notion of an attractive magnetic force. Beeckman's magnetic theory conceived an "apparent attraction" of iron to the magnet as a result of subtle spirits or corpuscles which emanated from the magnet. During the act of streaming towards the iron, the stream of emanations reduces the air pressure between the iron and the magnet, with the result that the air pressure on the opposite side of the iron pushes it towards the magnet. This explanation reminds us of the Lucretian theory of attraction. It conceives the action mechanically in order to avoid the concept of attraction, which Beeckman rejects on philosophical grounds. Renée Descartes and another of Beeckman's students Pierre Gassendi later adopt this explanation as the foundation of Cartesian mechanical magnetism.[13,14]

The Cartesian Materialist Philosophy

The magnetic theory of Rene Descartes is the zenith of magnetic science in the seventeenth century. It ranks with the work of William Gilbert in terms of its importance. It represents the single most important modern theory of magnetism based on a mechanical mechanism. It marks a crucial stage in the development of a mechanical philosophy of nature.

Descartes significance lies not only in his magnetic theory but in the principles upon which this theory is founded. Descartes was the first philosopher in modern times to attempt the construction of a natural philosophy upon the mechanistic principles of the new modernism. He was an exponent of a new epistemlogical rationalism based on the assertion that all knowledge of nature can be deduced logically from first principles, with a certainty that was unquestionable and indubitable. This certainty or precision in the truthful accuracy of deduced knowledge followed from the precise truth of mathematical knowledge which Descartes held to be genuine universal knowledge. This new element was another feature of the new modernism. A belief in the power of the mathematical deductive method to achieve truth in natural knowledge. This knowledge owed its certainty to the inexorable truth of mathematically derived proof. Hence, natural truth would be as valid as the theorems of mathematics and would not depend on experiments or observations.

Descartes coupled the idea of mathematical certainty with the doctrine that all aspects of the external inanimate world can be regarded as an automatic mechanism, and that it is possible and desirable to imagine a mechanical model for every physical phenomenon. This ambition was based on the false conception that the fundamental first principles were known to Descartes, and that their application was merely a process of mathematical deduction. But, Descartes was not an experimenter or observer of nature, his first principles were not based on them. Huygens judgement of Descartes natural philosophy succinctly summarizes the result:

> "Descartes who seemed to me to be jealous of the fame of Galileo, had the ambition to be regarded as the author of a new philosophy, to be taught in academies in place of Aristotelianism. He put forward his conjectures as verities, almost as if they could be proved by his affirming them on oath. He ought to have presented his system of physics as an attempt to show what might be anticipated as probable in this science, when no principles but those of mechanics were admitted: this would indeed have been praiseworthy; but he went further, and

claimed to have revealed the precise truth, thereby greatly impeding the discovery of true knowledge."[15]

Descartes idea of nature as an automatic machine was a lasting idea that still influences physical thought. But, he failed to understand the idea that true knowledge of nature can only be obtained through observation and experiment.

A second major flaw in Descartes philosophical system was his rejection of the concept of force as a cause of motion. We saw earlier that Isaac Beeckman rejected the notion of an attractive force in magnetism. Descartes adopts this same viewpoint and attempts the construction of his system of natural philosophy without the notion of force, which he believed had no place in physics. His attempted physics would be based only on mathematical principles as he tells us in the <u>Principles of Philosophy:</u>

"I do not accept or desire any other principle in Physics than in Geometry or abstract Mathematics, because all the phenomena of nature may be explained by their means, and sure demonstration can be given of them."[16]

Here he is insisting that only the principles drawn from geometry and mathematics will be admitted into his system. This, of course, is not the case, because he must introduce some assumptions regarding nature in order to describe it mathematically, but we see the underlying reason that force is excluded as an explanatory concept. Only the sure and certain principles of mathematics can be trusted.

The concept of force is excluded by Descartes and Beeckman because it implies or carries with it an occult conception. Force is either an unseen entity or a fictitious appearance. It is a fundamentally Aristotelian conception. Force as a cause of motion, implies that it is a potential quality. It causes alteration of quality in order to cause motion. Descartes program is to rid natural philosophy of all these suspect notions. Since force appears as an occult or Aristotelian cause it has to be excluded from the new mechanical philosophy. Descartes tries to exclude and abolish it, using it as a fictitious appearance not as a physically real conception. This program is a major source of difficulty, because it results in a physics based only on a kinematics of matter based on vortex motion without any dynamic principles; an approach that was doomed to fail.

Descartes founded his physics upon the principle that apparent force can only be communicated by pressure or impact of a material body. This required that all of space must be filled with matter. But, this matter was not like the ponderable matter of the earth, it was a subtle matter that filled space and transmitted forces. This idea is the first appearance of the concept of the aether. This aether, or subtle medium penetrated all ordinary matter as well as the space in the heavens. The circulation of the vortices of aetherial matter accounted for the motion of the sun, moon and planets, as well as the transmission of light and heat from the sun and stars. Descartes magnetic theory was founded upon this idea of space as a plenum filled with aether, but his magnetic matter was not the same as the aether, it had its own peculiar nature.[17]

The Cartesian magnetic theory was based on the classical Greek theories of emanations and pores, suitably modified and extended to fit within the Cartesian system of natural philosophy.

Descartes conceived magnetic vortices consisting of emanations or streams of corpuscular matter which circulated through the pores of the magnet and iron. The cartesian magnetic particles partook of the vortical motion as if they were long chains of circulating streams. The movement of one particle was followed by that of its neighbor each taking the place of the other with no empty space or void between them.

The Cartesian magnetic vortexes had the very desirable feature that they were observable by spreading iron filings around a loadstone. An experimental procedure which was described by Gilbert. This observation may have motivated Descartes magnetic theory. He identified the pattern formed by the iron filings, a pattern of circular tubes, with the vortices of magnetic particles.[18]

The explanation of magnetism required three different theories; one for the orientation of the compass, one for the attraction and repulsion of different magnets, and a third to explain the attraction of a magnet for iron. However, all three were fundamentally founded upon the same basic assumptions of circulating vortices of particles and suitably arranged pores. It is in the mechanism of the penetration of the vortices through the materials that the theories offer different mechanisms.[19]

Consider first the orientation of the compass towards the north and south. This theory was based upon the conception of the circulating vortices oriented parallel to the axis of rotation. There were two streams of suitably grooved particles, one grooved for a right handed twist and the other with a left handed twist. The pores of the earth were conceived as forming long passages oriented roughly north-south so that the particles moved through them parallel to the axis of rotation. The pores were conceived as long channels suitably grooved to accept the circulating particles. There were two circular streams, one circulating from north to south and the other oppositely. Particles circulating in the two different directions possessed opposite or contrary twists in their groves, hence even though they had opposite twists they were able to enter the pores of the earth. Particles which were intercepted by loadstone or magnetized iron exerted a pressure upon it which caused it to turn in the direction so that its grooved pores were aligned with the circulating streams. This idea assumed that the magnetic material was predisposed to the magnetic vortices by having grooved channels oriented in a single direction. Later in the discussion of the magnetization, the explanation of how these oriented grooves are formed will be given.

The theory of the attraction and repulsion of magnets required that the explanation account for both kinds of apparent forces. The mechanism which he uses reminds us of the theory of circular thrust and the explanation offered by Lucretius. But, Descartes was unable to utilize the action of the void or vacuum as the ancient Greeks had, this required a slightly different approach. The basic elements are familiar. A stream of screw shaped grooved particles emanating from the magnet, corkscrew pores which are provided with a means of accepting or rejecting the emanations, and a mechanism whereby the action of the streams upon the pores causes a resulting motion. The major new element introduced by Descartes is a way to provide mechanisms for both the attractive and repulsive motions.

When two magnets were brought together with unlike poles facing each other, Descartes asserted that the emanations of both magnets were able to easily enter the pores of the opposite magnet, because the pores were properly disposed to receive the emanations. The flow of the magnetic particles in easily entering the opposite magnet and returning to the source would complete the circular vortex. This mechanism of vortex flow forced out the air between the magnetic poles. The air moving in a vortex in the manner of a circular thrust moved around behind the magnets and drove them towards each other. When like poles faced each other, Descartes asserted that the magnetic particle flows from the magnets were unable to pass into the pores of the opposite magnet. This resulted in a repulsive force because of the pressure created by the opposing streams of magnetic mater. This occurred because as Descartes said upon being unable to pass into the opposite magnet the streams of matter "must have some space between the two loadstones through which they can pass."

To explain why the pores were unable to accept the emanations in the repulsive case, Descartes said that the pores were fitted with projections which acted like one way valves. They allowed the magnetic matter to pass in one direction but not the other. These projections or filaments, which projected into the corkscrew grooved pores would lie flat when the magnetic particles passed in one direction but would ruffle up and block the flow in the other direction.

Descartes mechanism for the attraction of iron towards a magnet relied on an extension of the mechanism used to explain the attraction of two different magnets. The same elements were used, but the nature of the pores in iron was conceived differently. The pores of iron, Descartes said, contained projecting filaments arranged randomly in a disordered chaotic manner. When a loadstone was brought near the iron, the streams of magnetic grooved particles would enter the grooved pores of the iron and force their way along the channels because of the momentum of the magnetic flow. This forced the projecting filaments to arrange themselves to accept the direction of the magnetic particle flow. This process of magnetization would then be followed by the mechanism of attraction as the air was forced out from between the magnet and iron and then moved around by the circular thrust and pushed them together.

This explanation sounds similar to the modern idea of domains, which are properly oriented by the application of a magnetic field to make the iron become magnetized. Descartes theory was the first to explain why the iron became magnetized, a process used to make compass needles. When subjected to the magnetizing flow for a long time, the projecting filaments within the pores of the iron would lose their flexibility, and become oriented in one direction. The iron became magnetized and acted as a loadstone or compass needle. The filaments became oriented so that the grooved channels were suitably disposed to receive the magnetic particles from the stream of particles within the earth's magnetic vortex. The magnetic needle would gradually lose its magnetism as the filamentary projections returned to their original positions. The theory could explain why different materials possessed different susceptibilities for magnetization by the hypothesis of different flexibility for the projecting filaments. This was an important new innovation.

The reader may find that the explanatory mechanisms offered by Descartes are not convincing. His contemporaries also were not completely convinced, with the result that there were many different variations of Descartes magnetic theory created in the years following its publication.

The theory has the major weakness that three different mechanisms are required to account for the three different forms of magnetic action. These theories are not consistent and appear to be contradictory.

One obvious contradiction of the theory is immediately apparent. It is the same one that plagued the classical Greek theories. The mechanisms for attraction and repulsion appear absurd, because if we accept the mechanism for attraction, the mechanism for repulsion can not work. It should also result in an attraction, because the dense streams should force the air out from between the magnets in both cases. The mechanism for the alignment of the compass also seems unreasonable, because there is a different mechanism to accomplish this, the force of the vortex streams in the grooved channels, versus the use of the pressure of the air or streams of magnetic particles. One wants to know why different mechanisms are required. Why doesn't the same mechanism work for all the types of magnetic action? This explains why the Cartesian magnetic theory was not successful. Ultimately its failure doomed magnetic theory itself. Since the new science demanded a mechanical explanation, the failure of all attempts to construct this kind of theory eventually resulted in frustration, resignation, and a loss of interest in magnetic theory.

Elaborating Classical Magnetic Mechanism

While René Descartes was developing his system of natural philosophy from first principles, a different approach was developed by the French priest, philosopher, scientist, and mathematician Pierre Gassendi. Gassendi was born in 1592 and died in 1655. He has been described as "not a very good physicist, a bad mathematician... and a rather second rate philosopher."[20] Gassindi's primary strength was his ability to communicate ideas through his writing and through demonstration experiments. He was "the best philosopher among the writers and the best writer among the philosophers."[21] His main contribution was to construct a theory of atomism which was acceptable to Christianity by suitable modification of the classical atomism of the Greeks.

Gassendi's approach to natural philosophy was restrained and more practical than the flamboyant egoistic approach of Descartes. Gassendi took the pragmatic approach of adopting an existing mechanical philosophy and adopting it to conform with the fashion for natural philosophy of the seventeenth century. His approach was to embrace the atomistic philosophy of the classical Greeks, and modify it to satisfy the objections of the church and contemporary critics. The result was a successful atomic theory which satisfied the times. But its deficiency was that it did not rectify the known deficiencies of atomistic theory. In the case of magnetism, Gassendi adopted the theory developed by Lucretius. Hence Gassendi's magnetic particles, which were very small, possessed handles or hooks. Attraction occurred because these hooks captured the iron. The theory rejected Descartes notion of space as a plenum, filled with subtle matter. Gassendi reasserted the old doctrine of atomism. The universe consisted of atoms and the void, with all of nature arising from the motion of these atoms in the void, their movements and combinations explaining all the phenomena of the world.

Gassedi's magnetic theory is presented in <u>De motu</u> published in 1642, and in the <u>Syntagma</u> published in 1649. Gassindi's theory of magnetic attraction envisioned a form of magnetic effluvia consisting of tiny magnetic particles with hooks or handles. Gassendi imagines that the particles are interconnected by the hooks so that the stream of particles forms small rigid rods, taut cables or chains of particles which enter the porous iron. Once inside the iron the streams become disordered by refraction like light traversing a transparent body. This disorder entangles the chains of magnetic particles with the matter of the iron and so permits the magnet to pull the iron towards itself.

Repulsion is accomplished by an attraction of opposing poles. So, according to Gassedi, there is no repulsion, because it is only apparent. When two loadstones are positioned so that two like poles are facing each other, there is an attraction to the poles upon the opposite end of the loadstone. This causes the loadstones to turn around so that the unlike poles are facing. But, this action is resisted or opposed by the attraction of the attraction of the second pair of poles. So the action of the north pole of loadstone one towards the south pole of loadstone is balanced by the opposing attraction of the north pole of loadstone two for the south pole of loadstone one. The result, according to Gassendi is that the two loadstones only appear to repel each other. There is no repulsive force, only a frustrated attraction.

Here we see a significant difference between the Cartesian approach and the Gassendian. The characteristic approach of the Cartesians is to deny the existence of an attractive force. So the magnetic action must result from a transfer of force by contact of physical particles. This contact can only occur by impact, and not by an attraction. Thus we see that repulsion by a pressure of subtle particles is the basis of the Cartesian approach. Gassendi takes a different approach. He appears to deny the pressure of repulsion and asserts that attraction is the primary mechanism.

Gassendi also offered a theory of magnetization to explain why a loadstone is magnetized. The idea seems to be based on the concept than iron consists of magnetized atomic corpuscles. The magnetization is effected by an alignment of the corpuscular bodies from the normal disordered state. When the magnetic particles from the earth enter the iron they change its state such that

“Its insensible and very minute particles or corpuscles are ... pulled apart, drawn together, inverted turned both in position and in orientation in reason of which they are inclined to turn differently than before.”

The process also explained why a loadstone which is broken in half always forms a new pair of north and south poles. Before a stone is broken, half the particles point towards one side and half towards the other. When the stone is broken, half of the particles in each fragment keep their original orientation while the other half turn to the opposite direction. The magnetization of an iron needle which is stroked or touched by a loadstone is accomplished as follows

“An iron needle whose particles are indescriminantly and confusedly turned attains an orientation such that half of them point toward one side, half towards the opposite.”

Although the nature of the magnetic corpuscles is ambiguous, the idea resembles the modern theory of domains.

Gassendi’s approach to the concept of gravitational attraction, which Descartes denies, is to compare it to magnetic attraction as Gassendi does in the following:

"...we can understand it from the here adjoined example of the magnet: let us take and hold in the hand a small plate of iron of some ounces; if then a most powerful magnet should be put under the hand, we would experience a weight no longer of ounces, but of several pounds. And because we will have to admit that this weight is not so much innate to the iron, as impressed [in it] by the attraction of the magnet placed under the hand; thus also where we deal with the weight of gravity of a stone or of another terrestrial body, we can understand that this gravity is in this kind of body not so much from itself [its own nature] as from the attraction of Earth that is below it."

Gassendi takes the analogy even further, he envisions that gravity acts like magnetic attraction so that each body is drawn towards the earth by little strings or chains that pull upon it. These strings or chains being the same mechanism that he uses to effect the magnetic attraction. The idea evokes an image of field theory because the strength of the attraction is proportional to the number of strings which pull the body.

This shows that, in opposition to Gilbert, Gassendi asserted that gravity not magnetism was the cause of falling bodies. This resulted in a distinction between all bodies which were attracted towards the earth, and iron which was subject to the additional force of magnetism. He performed an important experimental proof that the magnet did not act upon the weight of iron by making it less heavy as had been supposed. Gassendi showed that the force exerted upon an iron body is greater than its own weight when a magnet is placed under it. Gassendi also provided an experimental proof that the magnetic declination was variable over time, a discovery that was also made by Henry Gellibrand in England but is attributed to Gassendi by the French.[21,22,23]

Gassendi's magnetic theory did not offer bold new ideas, he perfected old ones. This was accomplished through his writing and his demonstration experiments. His main experimental discovery was a new method to improve the power of a loadstone. This was accomplished in a manner similar to arming except that the iron was placed inside the loadstone. This was done by boring a hole at the pole along the magnetic axis and inserting an iron rod. The result was that the magnetic power was greatly increased.[21]

Further Cartesian Innovations

During the second half of the century, the atomic theories of Gassendi were more influential in England than in continental Europe, where Cartesian natural philosophy flourished. However, as we have seen, there were obvious problems with Descartes theory of magnetism. These were counterbalanced by its clear superiority in explaining the magnetization of iron and steel. The dissatisfaction with Descartes theory of magnetism did not thwart attempts to rectify the problems. One of the more obvious ways to solve the difficulties was to dispense with the screw shaped magnetic particles moving in opposite directions, while maintaining the idea of pores with filamentary projections. Some theories conceived the magnetic particles as equipped with the projections, rather that the pores. These particles are described as having filamentary projections like fur coats, a charming description, but absurd to conceive as possibly being real. Another idea was to conceive the magnetic particles as bearded grains. The filamentary projections allowed the particles to travel only in one direction. The filaments lying flat or ruffling up and blocking passage in the opposite direction. [24]

In Amsterdam in 1687, Joachim Dalencé published a book titled Traité de l'Aiman or Treatise on the Magnet. This gives a fine summary of magnetic knowledge of the seventeenth century. Dalencé was a French astronomer and physicist. The book gives a theory to explain the experiments on the magnetization of iron and steel. Dalencé returns to the Cartesian conception of pores lined with filamentary projections but discards the screw shaped particles. Delancé conceived a steel knife blade presented to the pole of a strong magnet. The force of the magnetic particles issuing from the magnetic pole would cause the projecting filaments or tiny hairs within the pores of the steel to lie flat. This "stroking action" of the magnetic particles disposed the steel pores to receive additional magnetic matter from the magnet, a process that resulted in the steel becoming magnetized.[24]

Following the manner of Descartes, Dalencé conceived streams of magnetic matter circulating through the earth from pole to pole, and then after exiting, flowing around outside the earth, entering at the poles again. The pores of the earth were conceived as running parallel with its axis of rotation and equipped with the bristly filaments, "garnished with little hairs" as Dalencé says, just as in iron and steel. The same idea was applied to the loadstone. The theory was adapted by Dalencé to explain why the iron caps or armoring of a loadstone increased its attractive force:

"The magnetic matter on leaving the pole [of the loadstone] finds the pores of the iron pole piece so disposed as to facilitate its movement; it therefore passes through the iron cap easily, without being dissipated in any way. Thus the magnetic matter, being united, and in greater quanity, has more power to enter another piece of iron than it had on issuing from the uncapped pole of the loadstone."[25]

The theory was also applied to the explanation of why a loadstone or magnetized iron and steel suffers, "the entire loss of force and virtue." when heated in a fire. This occurred because:

"the heat having changed the configuration of its parts and pores in a manner such that the magnetic matter can no longer pass through it... They are nevertheless capable of being again magnetized, the fire having changed neither the pores nor the configuration of the iron parts, which have remained elongated and suitable for giving passage, as before, to the magnetic matter."[26]

Although the heat of the fire destroys the alignment of the pores of the material, this does not cause a permanent change in their alignment after the material cools down. A result that seems strange and unbelievable. The magnetization of forged iron, when beaten to prolong its length, was explained as caused by the fact that the magnetic matter meets less resistance if it travels along the grain of the beaten iron than in the other directions. Here, Dalencé seems to be saying that, beating iron to lengthen it in a certain direction, causes its pores to align in this direction.

The explanations offered by Dalencé illustrate the advantages and disadvantages of the Cartesian approach to magnetism. The mechanism of the circulating magnetic matter and pores in iron and steel seem to provide good models. But, when we examine them in detail the theory breaks down. Its real advantage is that it explains more than the Aristotelian and occult theories, which do not have a means to explain the magnetization effects upon iron and steel. But, the Cartesian explanations of attraction and repulsion continue to remain contrived, obscure, and difficult to accept.

In 1680 the famous physicist Christian Huygens presented a paper on magnetism before the Paris Academy of Sciences. It illustrates the process of modification that the followers of Descartes were attempting, in order to improve the Cartesian theory of magnetism. The theory presented by Huygens was basically Cartesian in content, but he dispensed with the need for two oppositely moving streams of grooved magnetic particles with opposing twists. In Huygen's model, a single vortex was sufficient. The pores in Huygens model were not equipped with the bristles or filamentary projections. His criticism of Descartes considered that the threaded and grooved magnetic particles were not needed in light of the fact that the filamentary projections within the pores accomplished the same purpose; provide a one-way valve action. He also attempted to dispense with the filamentary projections within the pores. Huygens felt that the same result would be obtained by supposing that the action of the magnetic matter caused a re-arrangement of the particles of the iron so as to form the elongated channels, which allowed the magnetic particles to pass. Huygens also advocated a different model of magnetic attraction. He advocated the notion that the attraction was caused by the tendency of the circulating magnetic vortex to contract into a volume as small as possible, rather than to driving out the air from between the bodies. However, these modifications were not able to successfully resolve the difficulties of the Cartesian model, and Huygens later reverted to a more orthodox Cartesian model.[27]

The difficulty of magnetic theory was its stubborn refusal to be molded into a mechanical model. This placed the mechanists in a dilemma, accept the Cartesian theory or embrace the old occult theories. They failed to see the advantages of the field theories of Gilbert, Cabeo, and Leótaud for this reason. Hence field theory languished as the scientific fashion for mechanical explanation continued to reign supreme into the eighteenth century, carrying the Cartesian magnetic model as advocated by Dalencé along with it.

English Mechanical Magnetism During the 1650's

In England there was a completely different approach to the mechanization of magnetic theory. The English approach was Baconian in its emphasis upon experimentation as opposed to philosophical speculation, by building a new system of mechanical philosophy upon experimentally untested hypothetical first principles. Although they rejected the mistake of Descartes, they were not deflected from the prevailing scientific fashion of materialist mechanism. The English innovation was to couple the mechanical with the experimental to create an experimentally based mechanical philosophy. This was probably a mistake given the extensive experimental progress that had been accomplished by William Gilbert. Bacon's polemic against Gilbert's magnetical philosophical system building, obscured its sound experimental basis. The English should have been more receptive to the adoration of Gilbert as urged by Christopher Wren when he wrote in 1657 that Gilbert should be "adored not only as the sole inventor of Magneticks, a new science to be added to the Bulk of learning, but as the Father of the new Philosophy; Cartesius being but a builder upon his experiments."[28]

The unfortunate fact that the foundations for field theory provided by Gilbert were not extended or exploited by the English, is a mark against their scientific reputations. They were swept up in the enthusiasm for a new anti-aristotelian mechanical approach and failed to see the truth within the Gilbertian field theory.

The approach used by the English mechanizers of magnetism was not to build a mechanical magnetic theory, that had already been done by Descartes and Gassendi, but to perform experiments which supported the claims of these mechanistic theories against those of which asserted the incorporeal action of the magnet. This negative approach was entirely successful, but ultimately destructive towards the goal of a successful theory of magnetism. The significance of the English approach lies in the body of magnetic experiments that was developed to refute the incorporeal interpretation of magnetic action.

During the decade from 1650 to 1660, the English took aim at the incorporeal theories of magnetism using the weakness which was previously noticed, the changes in magnetization due to heating and mechanical deformation. This approach can be traced to Pierre Gassendi's Philosophiae Epicuri Syntagma, published in 1649, where Gassendi briefly notes that evidence for the corpuscular theory of magnetism is provided by the decay of magnetic virtue with time, its destruction by heat, and by the differences or variations exhibited in magnetic strength. The idea was picked up by Walter Charleton who presented it as his first experimental proof that the magnetic virtue was caused by a "corporeal efflux." According to Charleton in the Physiologia Epicuro-Gassendo-Charletonia published in 1654:

"The materiality of the magnetic virtue is inferrible likewise from hence, that it decays in progress of time (as all Odours do) and is destroyed by fire, in a few minutes, and is capable of Rarity and Density (whence it is more potent near at hand, than at the extremes of it[s] sphere) all which are the proper and incommunicable Attributes of Corporeity."[28]

Henry Power, a physician from Halifax and a supporter of Descartes magnetic theory, took up the challenge of extending Walter Charleton's argument supporting materialistic magnetism by producing new experiments. Following the new inductive method, during the years 1656 to 1659 he subjected magnets to a wide variety of harsh mechanical treatments. They were heated, cooled, struck, stroked, bored, and drilled. Anything that would justify a mechanical explanation was tried. The result was nine new demonstrations of the mechanical production of magnetism which were contained in a book on magnetism entitled Experimental Philosophy, The Third Book, Containing Experiments Magnetical: With a Confutation of Grandamicus, published under the auspices of the Royal Society in 1663. The most persuasive of these was described in Argument 8 as follows:

"Take a rod of Iron (or a Puncheon) as before; heat it red-hot, and according to the laws in its refrigeration, you may endue this or that extreme with whether polarity you please; now afterwards by striking it with a Hammer in the same posture that it was cooled in, you may much advance and invigorate its Magnetical virtue, as we have formerly declared: But now the main Observable of all, is That after both the reception of the virtue by convenient refrigeration, as also the augmentation of it by percussion, you may by inverting and repercussing the Extremes, alter the polarity at your pleasure; and then, which is stranger, that if you strike the Iron in the middle 'twixt the two extremes, it will destroy its formerly acquired magnetism."[28]

When Power's initial results were first communicated to the magnetic committee of the Royal Society in 1661, there was little interest. John Wilkins is credited with bringing Power's work to the attention of Robert Boyle and Robert Hooke, after they became interested in performing magnetic experiments themselves.

English Mechanical Magnetism from 1659 to 1680

Robert Boyle and Robert Hooke are the two most important personages in the story of English mechanical magnetism. Both are illustrious names. Boyle is called the father of chemistry, and Hooke is justly known as the greatest experimenter of the period. Boyle was a wealthy aristocrat, son of the Earl of Waterford, who attended Eaton and Oxford. He lived from 1627 to 1691. Hooke was a commoner who got his start working as an experimental assistant to Boyle. He lived from 1635 to 1703. They began their association at Oxford where Boyle's air pump experiments were first performed in the year 1659. The Oxford connection is important is because almost all of the important proponents of the English mechanical approach to magnetism are Oxonians, who attended Oxford colleges: Walter Charleton, Robert Boyle, Robert Hooke, John Mayow, William Petty, John Wilkins, Christopher Wren, and Robert Plot. [29]

In 1659 Robert Boyle, with Hooke as his assistant, constructed a vacuum pump at Oxford that enabled the Cartesian theories of magnetism to be tested. In 1659 he performed experiments, which were published in his famous book, New Experiments Physico-Mechanical, Touching the Spring of the Air, and its Effects... in 1660. One of the many experiments was performed by placing a compass needle inside the evacuated receiver of the vacuum pump, the compass behaved

"according to the laws magnetical, without any remarkable difference from what the same loadstone would have done had none of the air been drawn away from about the needle."[28]

The failure to cause an effect upon the compass needle was not an occasion of concern for Boyle or Hooke. Although Boyle preferred Gassendi's theories to Descartes, he professed to be objective regarding his theoretical prejudices. The experimental result did not suggest to him that anything was wrong. A careful examination shows that Descartes theory of the compass did not require action of the air to align the compass needle. So the result was not decisive in this case. It also remained possible to argue that the vacuum pump was not effective in removing the magnetic corpuscles from within the receiver. The particles could also be conceived as capable of passing through the walls of the receiver.

During the winter of 1662-63, Boyle performed experiments to determine if cold temperatures affected the attractive force of a loadstone. His results published in History of Cold (1665) seemed to indicate that “the sphere of their activity was found to be sometimes greater and sometimes less, to a considerable difference, in ten good stones employed to this purpose.”[28]

In 1669, Boyle published the results of additional experiments, performed with the vacuum pump, designed to test the Cartesian theory of magnetic attraction for iron. The results did not verify that the air played a role in the attraction. When a load of iron was suspended from a magnet placed inside the receiver of the pump, evacuation of the air showed no effect. The force of attraction remained unchanged. This was clearly contrary to the Cartesian theory which held that the attractive action resulted form the pressure of the air forcing the iron and magnet towards each other. Boyle also tested whether air played a role in the attraction of two different magnets by placing them under water, with the result that no measurable difference was noticed.

These results were clearly damaging to the Cartesian magnetic theory, but this was not the interpretation of the English mechanical philosophers. Although the results of Boyle’s experiment failed to conform with the expectations derived from the Cartesian theories, the conclusion which Boyle and the mechanists reached did not reject that theory. The result was an interesting controversy over the effectiveness of the experiment, showing the tenuous nature of experimental method. Thomas Hobbes explained the result by claiming that Boyle's apparatus was a fraud, the experimental failure was a “manifest sign” that Boyle’s air pump did not pump air, as he claimed. The ensuing controversy obscured the fact that the Cartesian theory had been disproved.

The failure of the English experimentalists to detect the existence of the magnetic effluvia, did not prevent them from pursuing the effort. In 1673, Boyle returned to this goal by a new experimental test. He conceived of the idea that the harshest condition that he could impose upon the passage of magnetic effluvia was to “cause some needles to be Hermetically sealed up in glass-pipes” because “Glass is as close as any body is”. Boyle’s expectation was that the glass would block the passage of the magnetic particles. But, this was not the result, because the magnetic needles performed the same as if they were not enclosed in glass. But, this did not disprove the Cartesian explanation of magnetism. Boyle interpreted the result as confirming “the Strange Subtility, Determinate Nature, and Great Efficacy of Effluviums.” By this time the English commitment to the paradigm of a mechanistic natural science was so strong that no experimental evidence was sufficiently strong to deflect them from a belief in it.

In 1674, Sir William Petty presented a paper before the Royal Society on the 26 of November with the title: “Concerning the use of duplicate proportion in sundry important particulars; together with a new hypothesis of springing or elastic motions.”This paper is of interest because it appears to anticipate the modern idea of magnetic moment of atoms or elementary particles.[30]

Martin Lister’s Gilbertian Origin of Fossils

Martin Lister was a York physician who made important contributions to the science of biology. He was originally interested in natural history but later turned to the study of fossils. A Fellow of the Royal Society, Lister became interested in the formation of minerals, and during the decade of the 1670's developed a theory of fossil formation based on Gilbertian mineralogical theories. In a letter written in 1683, he says

" that there were but two only Succi lapidescentes (juices of petrification) in nature, that I know of, viz, the vitriolic (glassy), proceeding from the pyrites, and the succus calcarius (juice of calcium oxide) proceeding from that genus of fossils."[28]

To understand this we need to learn about the terms and practice of metallurgy.

When an ore is heated it produces two liquids, the smelted metal and the slag which is usually a glassy substance, or vitriolic fluid. Here vitriolic means glassy, which is the appearance of the slag after it has cooled. But, it does not appear that this is what Lister means by juices. It is more likely that he is referring to the exhalations of the earth to which William Gilbert attributes the formation of metals, particularly iron. Lister's theory attributes the formation of iron to the juices of iron pyrites. An exhalation from the earth, or the heavens, which solidifies into iron and iron pyrites. Lister attributes the vitriolic property of to this juice of pyrites, because it results in a solid concretation which when burned or calcined, yields an iron powder residue.

William Gilbert's idea was that metals grew, developed, or blossomed within the earth; a process he calls efflorescence. In On the Magnet, Book I, Chapter 7, Gilbert explains the origin of metals as follows:

"...Our opinion is that metals have their origin and do effloresce in the uppermost parts of the globe, each district by its form, as do many other minerals and all the bodies around us...The earth gives forth sundry humors, not produced from water nor from dry earth, nor from the mixtures of these, but from the matter of the earth itself...The humors come from sublimed vapors that have their origin in the bowels of the earth...Aristotle is partly in the right when he says that the exhalation which condenses in the earth's veins is the prime matter of metals: for the exhalations are condensed in situations less warm than the place of origin, and owing to the structure of lands and mountains, they are in due time condensed, as it were in wombs, and changed into metals. But they do not of themselves alone constitute the veins of ore; only they flow into and coalesce with solider matter and form metals."

The following seems to be the source of Martin Lister's idea regarding iron pyrites as an exhalation which produces fossils:

"Thus exhalations are the remote cause of the generation of metals; the proximate cause is the fluid from the exhalations: like the blood and the semen in the generation of animals. But these exhalations and the fluids produced from them enter bodies often and change them into marchasites (The crystalized form of iron pyrites) and they pass into veins (we find many instances of timber so transformed), into appropriate matrices within bodies and these metals are formed; oftenest they enter the more interior and more homogenous matter of the globe, and in time there results a vien of iron, or loadstone is produced which is nothing but a noble iron ore; and for this reason and also on account of its matter being quite peculiar and distinct from that of all other metals, nature very seldom or never mingles with iron any other metal, though the other metals are very often comingled in some small proportion and are produced together."[31]

Martin Lister's theory which asserted that the principle of magnetism was embodied in the exhalation which formed iron pyrites (iron sulfide) seems peculiar from the modern viewpoint. But in terms of seventeenth century thought it is an interesting innovation. Lister, a disciple of Gilbert, was developing the Gilbertian magnetic philosophy. He was a mineralogist intent upon interpreting the mineral world in magnetic terms. By the 1680's Lister had developed a theory for the origin of minerals based on his extension of Gilbert's ideas. These ideas first appeared in print in the years 1682-1683, in his book De Fontibus Medicatis Angliae, which was privately printed. In this book, Lister asserted that all vitriolic minerals "arise out iron Pyrites", by making it a fundamental explanatory substance within his system. Lister claimed pyrites was a concreted spirit of inflammable sulfur whose ignition was responsible for thunder and lightning, volcanoes and earthquakes. In the solid form its ignition produces pure iron and is the cause of magnetism.
"Now, in order to know which metal possesses Pyrites, and how much, apply a Loadstone to it, when the metal has, of course, first been powdered and burnt, and the experiment will never deceive you."[28]

Lister saw within iron pyrites the sulphurous principle of fire, and the result that its burned ash was magnetic (because it is iron) suggested to him the idea of the origin of magnetism.

Lister's theory resulted in an increased interest in magnetism that centered around the calcining of numerous substances in the search for magnetic properties. The reason for this is ambiguous. If magnetism was detected within the calcined powders, did this prove that the original body was magnetic or that the fire made the body magnetic? This seems to be the basis for a controversy between Lister and Robert Hooke. At Oxford, Lister's theory aroused interest just as the Oxford Society was meeting for the first time in October 1683. The theory "gave occasion to a farther discourse concerning magnetism." It was decided that John Ballard should undertake to answer the questions raised at the meeting. This initiated a renewed interest in the magnetic demonstrations of Henry Power performed many years earlier

"Dr. Powers experiment was ordered to be tryed, viz: whether a bar of Iron heated, & when cold, struck violently will lose its polarity?"[28]

The experiments upon heating, cooling, and quenching as well as other mechanical manipulations were all retested and extended. The reason seems clear; to refute the origin of magnetism asserted in Lister's theory. The mechanical philosophers were intent upon proving that the magnetism was due to some form of mechanical process, either by heat, or cold, or percussion, or any other mechanical means. When Robert Hooke learned of these experiments he resolved to provide an irrefutable demonstration of the mechanical origin of magnetism.

The Controversy Over Magnetism And Lightning

Returning to the year 1632, Pierre Gassendi discovered that a portion of the iron cross of the Church of Saint Jean at Aix had become magnetized after being struck by lightning.[23] The phenomenon was not unambiguous, because as had been described by Gilbert a magnetism had been imparted to an iron rod on the church of Saint Augustine at Arimini. The interpretation given was that the rods became magnetized by a long exposure to the earth's magnetic field. However, it seems more likely that exposure to lightning was the real cause.

This phenomenon remained a curiosity of magnetism until accounts of the strange behavior of ships compasses after being struck by lightning were received. The first that is recorded is reported by Mr Haward as follows:

"Being on board of the ship Albemarl, July 24, 1641...in latitude of Bermuda...after a terrible clap of thunder...it was found that the compass card was turned around, the N. and S. points having changed positions and, though Mr. Grofton brought with his finger the flower-de-lys to point directly N., it would immediately, as soon as at liberty, return to this new unusual posture, and upon examination he found every compass, (three) in the ship of the same humor; which...he could impute to nothing else but the operation of the lightning or thunder mentioned."[32]

This report is the first link that connects lightning with electromagnetism. In the seventeenth century, this was certainly an unexpected development. Magnetism was at the time a well defined conception firmly associated with manifest attractive forces, not lightning.

Interest in the explanation of lightning had languished during the middles ages, following the classical attempts to explain it in terms of the fall of aether or some other form of fire from the upper regions upon ruptures of thunder clouds. During the renaissance a chemical explanation was advanced that suggested it was some form of gunpowder. Descartes returned to a mechanical explanation, which regarded lightning as the result of a rupture or tearing of thunder clouds, and the consequent release of the pent up force of the winds running amok and colliding with each other. When the clouds passed over church steeples, they were punctured and ripped open, spewing forth lightning.[33]

The accumulated instances associating magnetism and lightning did not pose an immediate threat to the prevailing mechanical explanation by Descartes, until Martin Lister advanced his new theory of lightning. Lister's theory was a return to the theory advanced by Aristotle to explain thunder and lightning. Aristotle says that

"But if any of the dry exhalation is caught in the process as the air cools, it is squeezed out as the clouds contract, and collides in its rapid course with the neighboring clouds, and the sound of this collision is what we call thunder....It usually happens that the exhalation that is ejected is inflamed and burns with a thin and faint fire: this is what we call lightning, where we see as it were the exhalation coloured in the act of its ejection."[34]

The new element in Lister's theory of lightning was his invocation of the inflammation of an exhalation, which he identified with a mineral substance. This was consistent with the chemical approach to lightning common at the time. To understand this, lets return to the chemical theory of lightning which was advanced by Paracelsus more than a hundred years earlier.

The idea of a chemical explanation of thunder and lightning clearly arises from the explosive technology of gunpowder; a violent chemical reaction resulting from the combustion of charcoal, sulfur, and potassium nitrate (niter or saltpeter). In the Grossen Wundarznei, Paracelsus gives a specific and detailed chemical explanation of thunder and lightning as follows:

“The matter of thunder and lightning is a Saltpeter-Sulphur of the Firmament. In the same way that Sulphur and Salniter grow out of the earth and therefore become ordered together in one mass and substance, the heavenly materials behave. As an example: as Water grows in the heavens and then falls on the earth, so may also Fire grow in it. And as snow grows in the Heavens, so may also Salniter and other things grow out of the fire. Therefore from such things we should understand that the heavenly lightning is of a heavenly composition made out of the same materials as spring out of the earth and which through the stars are ordered in such a behavior and way.”[35]

Paracelsus concept of thunder and lightning reminds us of the classical Greek conception of thunder and lightning as the fall of the burning hot aether from the heavens. The Paracelsian innovation was to provide a natural definition of the nature of the heavenly fire in terms of the chemical nature of gunpowder. This provided a connection between the earthly realm and the heavenly, which appealed to Paracelsus’ spiritual sensibilities and tinged the theory with the ideas of natural magic and Hermeticism.

The mystical nature of lightning as a spiritual fire and its association with the material elements has a long tradition going back at least as far as Heracleitus of Ephesus, circa 500 B.C., who says:
“The transformations of fire: first, sea; and of sea, half becomes earth and half the lightning-flash.”[36]
The idea of fire in Heracleitus is fundamental, but it is not the fire of the earth, it is the heavenly fire:

”This universe, which is the same for all has not been made by god or man but it always has been, is, and will be-an ever-living fire, kindling itself by regular measures and going out by regular measures.”[36]

The most mystical element is within the principle of lightning because Heraclitus tells us that: ”The thunderbolt pilots all things.”[36]

Another classical Greek conception, espoused by Anaximendes, was that the air consisted of both a material principle and a spiritual one. The spiritual principle was the source of life, conceived as pneuma, present within the air. Anaximendes says:

“As the soul (psychê), which is air (aêr), holds a man together and gives him life, so breath-wind (pneuma) and air hold together the universe (kosmos) and give it life.”[37]

The idea that the soul (anima) was a kind of air, was one to the fundamental ideas of the classical period.

The innovation which gives significance to Paracelsus ideas is the identification of the spiritual with the material aspect of the vital fire of life. This is not specifically clear from the quotation on lightning, but it is strongly hinted at. The main problem is to understand how the spiritual or immaterial principle is combined with the material world to give it life and vitality. Paracelsus' principles of fire have two conceptions, an immaterial form of fire, which is fire of material combustion, and the vital fire of life. The fundamental problem is to understand how these two kinds of fire appear within our material world. Paracelsus identifies the fire principle with both Sulphur and Salt, but it is not immediately apparent which is the spiritual and which is the material fire. The ambiguity arises from the conception which associates the heavenly fire of lightning with the material combustion of gunpowder. What is clear, is that both come from the heavens, and both are present in the air.

The association of early chemical ideas with the alchemical and magical is unfamiliar to us today. We do not appreciate that the chemical ideas of the sixteenth and seventeenth centuries were closer to the forbidden practices of magic and Aristotelian occult qualities than to the modern atomic theories. This was particularly true regarding the concept of the vital spirit of the air. This idea was clearly abhorrent to the proponents of a mechanical natural philosophy. The approach of the mechanical philosophers of the seventeenth century was to attribute the "vital spirit" to a material cause present within the air.

During the restoration, John Mayow was the primary exponent of the mechanical explanation of the vital spirit. He modified the older ideas into the conception of the vital spirit as a material principle present within the air. This principle was termed the aerial niter; an idea which is considered to be a anticipation of the theory of oxygen. Mayow also embraced the gunpowder theory of lightning based on the idea of the explosion of the aerial niter and sulfur. Mayow was a graduate of the Oxford schools which provides a connection to Boyle and Hooke, who were also "Oxonians".[38]

The suggestion by Martin Lister that lightning was a combination of the material principal of fire with a spiritual principle of fire in the form of magnetism was a dangerous threat to the materialist program of Boyle and Hooke, who were performing experiments with the air pump in order to support the idea of Mayow's aerial nitre. Boyle's experiments with the air pump had firmly associated the necessity of the corporeal air with fire and life. This would appear to destroy the immaterial principle of life as carried in the air spiritually. In one sense the experiments supported the Boylean experiments. Since the principle of magnetism was not excluded by the air pump, the experiments showed that this principle was not responsible for life and combustion. Because the air pump did not exclude magnetism.

Returning to the story line of the previous section. When the Oxford scientists selected John Ballard to investigate the mechanical production of magnetism, using the methods pioneered by Henry Power, news of the effort via correspondence with the Royal Society roused them into action. Robert Plot, another Oxonian, was selected to perform the experiments required by the society:

"it was required, that the three following [Oxford experiments] should be tried at the next meeting.
1. To strike a loadstone with a hammer, and to see the ramenta hang upon the stone.
2.To file a touched iron, to try whether the polarity be lost.

3.To see whether a needle begins to turn just at the center of gravity."[28]

Following the demonstration of these experiments, Robert Hooke conceived of a way whereby the mechanical origin of magnetism could be established. Hooke was firmly convinced of the mechanical nature of magnetism and saw a mechanical means to demonstrate it by the extreme mechanical forces induced in iron by drilling.

The controversy became heated when Lister responded to the assertions by his opponents "that most bodies would turn magnetical by the fire." This was a peculiar twist of interpretation. The mechanists were asserting that heat was a mechanical phenomenon, and that magnetism was produced by heat. So that Lister's demonstration using pyrites proved nothing. Lister's position in response to the mechanists was that only pyrite turned magnetical in the flame. The argument produced a curious episode. The Oxford group claimed to have produced a nonmagnetic iron. Lister's response was that he "desired to be satisfied , that the ingot, which they had made, was iron." The controversy was now clearly beginning to become very confusing. To assert that iron was not magnetic was contrary to everything which had been firmly established by Gilbert and his predecessors. But, the mechanists seemed intent upon achieving their objective of winning the day.

Lister's response was a paper presented at a meeting of the Royal Society in early 1684. The paper was titled "Concerning Thunder and Lightning being from the Pyrites." His argument was an elaboration upon his previous insistence that thunder and lightning were caused by the ignition in the air of the exhalation of pyrites. His proof consisted of the reports of compass reversal, which demonstrated that lightning was magnetic. This idea may have been stimulated by continued reports of instances of compass reversal. In 1681, a ship bound for Boston was struck by lightning. "The compasses were changed" so that "the north point was turn'd clear south". The reversal being exact, the ship was steered to Boston with the compass completely reversed.[39] This was certainly odd. Why was the compass exactly reversed instead of being changed to some other direction? The answer would not be determined until more than one hundred years later, when the oscillatory nature of the electric discharge of lightning would be understood.

After Lister's paper was read before the society, Robert Hooke performed a decisive experiment before a Royal Society meeting. He demonstrated that magnetism was induced in an iron drill bit by the mechanical action of drilling. But this did not immediately satisfy all concerns, because it did not address the "magneticalness of lightning". This was answered by an impact explanation of compass reversal. Henry Power had shown that the polarity of an iron rod could be reversed by percussion. This was advanced as the explanation for compass reversal to counter the "decidedly non-mechanical suggestion that there was a chemical, spiritual essence to magnetism." Hooke's explanation was given as follows:

"Mr. Hooke remarked, that by striking a needle with a brass hammer, the pole might be changed from north to south. To which it was answered by Dr. Wallis that there was nothing of hammering mentioned in this relation [of the lightning flash]. but with more probability a new touch of a magnet. However, Mr. Hooke was ordered to show at the next meeting, how the pole of a needle is altered by striking, that the applicableness to this case might the better appear."[28]

The illogic of the explanation did not seem to deter the exponents of the percussive theory. If the compass actually had been hit by lightning, it should have been completely destroyed or very badly damaged, but this was not the case. However, the experiments were performed as required and the results confirmed the expectations.

A controversy ensued with both sides performing experiments and counter experiments. It centered upon the fundamental issue of the nature of magnetism. Lister attempted to defend the conception that magnetism was a phenomenon associated with iron. Hooke attempted to demonstrate that substances other than iron would be assigned magnetic properties so that

"either all bodies, that are hard must be said to be magnetical, or else it will not necessarily follow, that every body that excites this virtue, is therefore to be esteem'd magnetical."[28]

The controversy was resolved at Oxford by John Ballard who was deputed to investigate. The result was "Discourse concerning ye Magnetism of Drills by way of an Answer to a letter of Mr. Aston's". Ballard supported Hooke's theory of corpuscular mechanical magnetism and put an end to the controversy as well as magnetic science in England. Magnetism was firmly secured within mechanical philosophy as an effect of purely mechanical processes. This had the result of removing from it the status of a philosophy or area of scientific inquiry. It became a purely mechanical effect that now commanded little scientific interest as a field of inquiry.[28]

Collapse of Terrestrial Magnetism

The destruction of magnetic science in England was completed by the collapse of interest in terrestrial magnetism. This occurred as a result of failure to produce decisive results regarding the magnetic variation. The actual cause was also a missed opportunity to make a significant scientific advance.

Interest in terrestrial magnetism was centered upon the idea of determining the longitude by measurement of the magnetic variation. The idea was rather simple. A ship could determine its longitude by knowing its latitude and the magnetic variation at its location. It was an idea that had been originally advanced by William Gilbert and developed in some detail in that book. Unfortunately, Gilbert's approach assumed that the variation was fixed in time, and that the magnetic pole was the geographic north pole. Both incorrect assumptions.

Gilbert's initial work in the science of terrestrial magnetism was extended by Professors of Astronomy of Gresham College. Gresham College was founded in London in 1697. In grew out of need felt by the in England was of the work performed by William Gilbert and reported in book On The Magnet. This work was centered on the group of savants which

Following the founding of the Royal Society in 1660, it established a Magnetics Committee charged with the objective of determining the magnetic variation at Whitehall by annual measurements. In June 1666, a committee including Robert Hooke, was ordered to check the predictions of variation made by Henry Bond, who had developed a theory of variation. The result was an embarrassing disaster. The prediction was for a variation of 1°30' West. The measurement results were uncertain varying from 1°30' East to 1°30' West. The huge errors provoked an immediate assessment of what was wrong. Were there undiscovered complications in the directive property of magnetic needles? A range of possible hidden variables was investigated. This was complicated by the results of the new mechanical theory of magnetism. Questions arose regarding a host of mechanical factors that could effect the accuracy of the compass needle. These ranged from questions regarding how the needles were stroked by a loadstone, to changes due to temperature, to questions concerning the stability of the earths core. If the Cartesian theory were correct, then earthquakes, changes in the air, tidal forces from the moon, and other unimaginable forces could effect the compass needle direction. The effect of cold temperatures was investigated because reports were received that magnetic needles behaved erratically in Iceland. [28]

The atmospheric theories developed by Boyle and Hooke raised more questions. How did the aerial and subterranean effluvia effect the compass needle? Earthquakes, volcanoes, and atmospheric disturbances of various kinds were thought to be responsible. The confidence in magnetic compass measurements deteriorated and collapsed. This did not even consider the problems associated with compass reversal. Was the compass perfectly reversed, or was the direction altered in a subtle way? All these questions created uncertainty. The fact that the effluvial theory of magnetism enhanced the suspected vagaries of the compass direction did not ease the concerns. The result is an irony. The acceptance of the mechanical theory of magnetism destroyed confidence in the stability in the direction of the magnetic needle. This led to a lack of interest in terrestrial magnetism, since the results of this science could not be relied upon.

It seems highly probable that these discrepancies were the result of geomagnetic storms. A discovery that would have significantly clarified the problem. The reported compass variations in Iceland supports this thesis. A program of regular measurement of compass variation would have revealed the problem and shown that average measurements over a period of time were stable, while individual measurements were unstable. This was not the approach taken. The result was a collapse in interest in terrestrial magnetism at the end of the seventeenth century.

A sign that interest in magnetism as a field of scientific endeavor was dead is the prominent lack of public interest by Issac Newton.

William Petty's Microcosmic Magnetic Philosophy

Sir William Petty, a founding member of the Royal Society, is another Oxonian of the seventeenth century who made important contributions to the sciences of mechanics, anatomy and astronomy. His contribution to the science of magnetism is a curious theory which anticipates the ideas of modern atomic theory. In a paper presented before the Royal Society in 1674, he presented a theory to account for the elasticity or as it was then called, "the spring" of the air. Petty tried to explain a problem that had excersised the greatest experimenter of the age, Robert Boyle. The problem, as Petty proposed it was it explain the "Springing or Elastique Motions" of the air which had resisted explication as that "hard rock in Philosophy... Which has long lain thwart Us in the Way of our Enquires". Petty's idea was to apply Gilbert's magnetic philosophy to the microscopic motion of the atoms of the air.[40]

The paper was delivered before the society on the 26th of November 1674. It had the long and cumbersome title: “Concerning the use of duplicate proportion in sundry important particulars; together with a new hypothesis of springing or elastic motions.” Petty argued by analogy that the laws of motion for the solar system should also apply to the microscopic world. This is what he means by duplicate proportion, a term we would not use today. According to Petty,

“every Atom” is “like the Earths Globe or Magnet, wherein are three Points considerable, viz. two in the surface called Poles, & one within the substance, called center or Byass [the center of gravity]”.[40]

The atoms in Perry’s theory were all conceived to be inherently magnetic. Thus for Petty, magnetism was a property that applied to the microscopic atoms, just as it applied in duplicate proportion to the earth and planets. Following Gilbert, Petty argued that the magnetic motions of an atom consisted of a rotation upon its axis as well as revolutions so that the atom

“may move about his own Axis, and about other Atoms also, as the Moon does about the earth; Venus and Mercury about the Sun; and the Satellites Jovis about Jupiter &c”[40]

This revolution of atoms about other atoms was effected by the magnetic attraction of the atoms for each other, just as Newton supposed the gravitational force attracted the planets of the solar system and caused them to revolve about the sun. Just as Petty says

“all Atoms have, like a Magnet, two motions, one of Gravity whereby it tendeth towards the Earth, and the other Verticity, by which it tendeth towards the Earths-Poles, and whereby Magnets joyn to each other by their Opposite Poles.”[40]

The motions of Petty’s magnetic atoms are the same as Gilbert’s magnetic motions of the solar system. The important point is that where for Gilbert the Earth was a giant version of his magnetic terrellas, Petty’s atoms are microscopic versions of a terrella. Hence Petty is not asking us to envision anything that is not already present and known in nature, because as he explains it

“all the motions I fancy in my Atoms, may be represented in gross Tangible-Bodies, and consequently may be made intelligible and examinable....My matter is so simple, as I take notice of nothing in each Atom, but of three such points as are in the Heavens, the Earth, in Magnets, and in many other bodies. Nor do I suppose any Motions but what we see in the greater parts of the Universe, and in the parts of the Earth and Sea.”[40]

Petty’s speculations have a significant impact upon the thinking of his fellow natural philosophers. As we have seen, Gilbert’s magnetical philosophy was soon to fail to have any relevance to the mechanical philosophers of the period. However, the idea of atoms as miniature solar systems was an idea to have great appeal in the early decades of the twentieth century.

A Retrospective Look At Magnetism Of The Seventeenth Century

Scientific historians refer to the seventeenth century as, the century of genius, because of the emergence during this period of a collection of the greatest scientific minds ever brought together in history. The list of first-rate minds includes the names Kepler, Galileo, Descartes, Pascal, Newton, Leibnitz, Fermat, and Huygens. Significantly, the list excludes William Gilbert. None of these great minds made significant contributions to the sciences of electricity or magnetism. We know that Kepler, Galileo, Descartes, Newton and Huygens studied magnetism but did not make great discoveries or contributions. Only Descartes developed a magnetic theory; unfortunately a flawed one that was influential for a hundred years. The hidden secrets of electricity and magnetism remained securely locked away after the intellectual assaults of these brilliant minds. The wave of progress which occurred during the scientific revolution of the seventeenth century washed over magnetic science and left it behind, almost the same as it was at the beginning the century.

One measure of scientific progress is the discoveries or new facts that have been added to science. Based upon this criteria, progress in magnetic science was not significant. The mechanical demonstrations developed by Henry Power and Robert Hooke showed that magnetism could be induced mechanically. But, these new facts are not deemed important today. The missed opportunities are more significant.

Galileo missed the opportunity to make the important discovery that a magnet can both attract and repel iron or steel. This is an important magnetic effect. Gilbert failed to detect it as well. He insisted that Albertus Magnus was wrong in his discovery that a magnet could both attract and repel iron. The effect results from the fact that a strong magnetic field is needed to reverse an induced magnetic field. Galileo shows how the result can be used in an entertaining why. But he failed to publish his results.

The discovery of compass reversal by lightning should have been followed up with the discovery that lightning was magnetic. However, this seems to have been beyond the thinking of the mechanical fashion. The incident shows how the experimental method often fails. The result was interpreted as proof of the mechanical nature of magnetism, not the magnetic nature of lightning.

Another missed opportunity was the failure to follow up on the failed attempts to measure the variation in 1666. There were efforts urged to perform systematic measurements over a long period of time. but these were not implemented. The pursuit of science at this time was not sufficiently organized and methodological to encourage such an enterprise. The Royal Society seemed to be organized to achieve short term goals, and long term scientific programs of discovery were not seen as valuable efforts.

A major area of decline was experienced in the practice of magnetic measurement. There is no evidence of magnetic work using Gilbert's techniques with the compass needle. The use of iron filings however, was widely adopted. But, there was no systematic mapping of the field using the compass or short wires. This is the basis for asserting the decline of magnetic science during the period. The only measurements that were performed were done using balance scales, as used by Hooke to perform measures of magnetic force.

Next Chapter **Exit**

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