A BRIEF HISTORY OF MAGNETOSPHERIC PHYSICS BEFORE THE SPACEFLIGHT ERA

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Abstract. This review traces early research on the Earth's magnetic environment, covering the period when only ground-based observations were possible. Observations of magnetic storms (1724) and of perturbations associated with the aurora (1741) suggested that those phenomena originated outside the Earth; correlation of the solar cycle (1851) with magnetic activity (1852) pointed to the Sun's involvement. The discovery of solar flares (1859) and growing evidence for their association with large storms led Birkeland (1900) to propose solar electron streams as the cause. Though laboratory experiments provided some support, the idea ran into theoretical difficulties and was replaced by Chapman and Ferraro's notion of solar plasma clouds (1930). Magnetic storms were first attributed (1911) to a "ring current" of high-energy particles circling the Earth, but later work (1957) recognized that low-energy particles undergoing guiding center drifts could have the same effect. To produce the ring current and aurora, plasma cloud particles required some way of penetrating the "Chapman-Ferraro cavity": Alfvén (1939) invoked an electric field, but his ideas met resistance. The picture grew more complicated with observations of comets (1943, 1951) which suggested a fast "solar wind" emanating from the Sun's corona at all times. This flow was explained by Parker's theory (1958), and the permanent cavity which it produced around the Earth was later named the "magnetosphere" (1959). As early as 1905, Birkeland had proposed that the large magnetic perturbations of the polar aurora reflected a "polar" type of magnetic storm whose electric currents descended into the upper atmosphere; that idea, however, was resisted for more than 50 years. By the time of the International Geophysical Year (1957–1958), when the first artificial satellites were launched, most of the important features of the magnetosphere had been glimpsed, but detailed understanding had to wait for in situ observations.

INTRODUCTION

This is an account of early research on the Earth's distant magnetic environment, work that led to magnetospheric physics and to space plasma physics. It tells of a science in its earliest, most primitive stage, when explanations were qualitative and full of speculation. The early stage lasted here a long time, because remote sensing of the space environment from the ground did not tell enough for a full understanding. Researchers relied mainly on global magnetic data with some help from solar and auroral observations. Their prime tools were insight and imagination, and their mathematical skills could only occasionally be brought to bear. With all those limitations it is remarkable how many of our fundamental ideas on space physics were glimpsed during those early years.

Note that for early work, recent and relatively accessible publications are sometimes given and readers seeking the original papers will find them cited there. The *Journal of Geophysical Research* was known prior to 1957 as *Terrestrial Magnetism and Atmospheric Electricity.*

EARLY WORK ON GEOMAGNETISM

The history of geomagnetism begins with the magnetic compass, invented in China around the year 1000 and quickly adopted by Arabs and Europeans [*Mitchell*, 1932]. Gradually, it was realized that the magnetic needle did not point to true north; Columbus observed during his crossing of the Atlantic that it shifted from one side of true north to the other [*Mitchell*, 1937].

Magnetism was the avocation of William Gilbert, Queen Elizabeth I's personal physician. Gilbert gave a convincing explanation of the action of the compass: the Earth was a great magnet. He reached his conclusion with the help of a spherical magnet, a model of the Earth which he named the "terrella," or "little Earth." Moving a compass over the surface of the terrella, he observed that its needle pointed toward the magnetic poles, and he also demonstrated this before the queen. Gilbert's book *De Magnete* appeared in 1600 and described all that was then known about magnetism and electricity [*Gilbert*, 1958]. It was one of the important scientific books of the age of

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Galileo and among other things contained the first use of the term "electric force" which led to the later term "electricity."

Important advances in geomagnetism followed in the next two centuries [*Chapman and Bartels*, 1940, volume 2, chapter 26; *Nelson et al.*, 1962]:

1. The discovery by Gellibrand in 1635 of the slow variation of the Earth's field [*Malin and Bullard*, 1981; *Brush and Banerjee*, 1988].
2. The discovery by *Graham* [1724] (see *Chapman and Bartels* [1940, section 26.9]) of "magnetic storms" (later term), large irregular disturbances of the compass needle.
3. The first magnetic survey of the Atlantic Ocean by Halley, in 1699 [*Bullard*, 1956; *Ronan*, 1969; *Evans*, 1988].
4. The discovery by Oersted in 1820 that electric currents produced magnetic forces [*Shamos*, 1959; *Dibner*, 1962].
5. The laws of electromagnetism, by Ampère in 1821 [*Williams*, 1965, 1989].
6. Electromagnetic induction, by Faraday in 1831 [*Faraday*, 1952; *Williams*, 1963, 1965].

In 1839 Carl Friedrich Gauss [*Gauss*, 1839, 1877; *Dunnington*, 1955] published a method for mathematically describing the Earth's field **B** by means of a scalar potential γ,

$$\mathbf{B} = -\nabla\gamma \qquad (1)$$

expanded at any point (r, θ, ϕ) in spherical harmonics:

$$\gamma = a\,\Sigma\,(a/r)^{n+1}\;P_n^m\,(\theta)\,[g_n^m\,\sin m\phi + h_n^m\,\cos m\phi]$$

$$+\,a\,\Sigma\,(r/a)^n P_n^m(\theta)\,[G_n^m\,\sin m\phi + H_n^m\,\cos m\phi] \qquad (2)$$

The first sum represents sources inside the Earth, and the second one external sources. Gauss and his associate Wilhelm Weber then went on to found a network of observatories, greatly expanded by British and Russian help [*Cawood*, 1979; *Malin*, 1969]. From data thus obtained, the coefficients due to sources inside the Earth were derived [see *Barraclough*, 1978]; as for the external coefficients, the calculation gradually confirmed what had been suspected, that better than 99% of the field originated inside the Earth.

However, as Graham's work suggested, some magnetic effects did originate on the outside. Observations of such effects were advanced by the work of Charles Coulomb, who in 1777 greatly increased the sensitivity of magnetic measurements by suspending a magnetic needle from a fine string [*Gillmor*, 1971; *Shamos*, 1959]. Such instruments could be made even more sensitive by attaching a small mirror which moved a spot of light, and this type dominated geomagnetism for close to 200 years [*Nelson et al.*, 1962; *Multhauf and Good*, 1987].

With such tools it was observed that the Earth's field was occasionally disturbed for a day or so: these events were termed "magnetic storms," but no one knew their cause. Celsius found that the large magnetic disturbance of April 5, 1741, was detected simultaneously by him in Uppsala and by Graham in London [*Chapman and Bartels*, 1940, section 26.10], demonstrating the nonlocal nature of magnetic storms. The magnetic network started by Gauss and Weber later showed the storms to be a worldwide phenomenon.

THE SUNSPOT CYCLE

Enter the Sun. In the first half of the nineteenth century there lived in the German town of Dessau a pharmacist named Samuel Heinrich Schwabe whose hobby was astronomy [*Newton*, 1958]. Every day when the Sun was not obscured, Schwabe observed it, paying attention to sunspots, noting their numbers, and keeping a tally of days when they were absent [*Meadows*, 1970]. He started observing in 1826 and 10 years later published a report of his results: no one seemed to pay attention. In 1843 he published a more complete account, suggesting a 10-year cycle: at first, again, no response. Eventually, however, Schwabe's work caught the eye of Alexander von Humboldt, naturalist and promoter of the sciences, who in 1851 included Schwabe's results in his third volume of *Kosmos*, an encyclopaedic compilation of information about the physical world [*Schwabe*, 1851]. Suddenly, sunspots and their cycle became a hot topic: astronomers began counting sunspots and studying them, earlier cycles were reconstructed from old observations, and searches began for terrestrial effects which correlated with the sunspot cycle.

Very soon such a correlation was found. Edward Sabine, a British scientist and the main architect of a worldwide network of magnetic observatories (an expansion of an earlier effort by Gauss and Weber), announced in 1852 that the frequency of magnetic storms rose and fell with the number of sunspots [*Sabine*, 1852; *Meadows and Kennedy*, 1982] (see also *Lamont* [1852]).

Evidence was soon also found that the polar aurora was more frequently seen (at relatively low latitudes) near the peak of the sunspot cycle. Here too a magnetic connection existed: as early as 1741 the Swedish scientist Celsius reported that during auroral displays the magnetic needle was disturbed [*Stoermer*, 1955, section 6; *Eather*, 1980]. The actual discovery may have been due to Hiorter, a student of Celsius who later wrote that when he reported the magnetic effect of the aurora to his mentor, Celsius said that he too had observed the phenomenon but had not mentioned it in order to see whether his student would find it independently.

SOLAR FLARES

How did sunspots exert their influence? The first clue came on September 1, 1859, in an unexpected observation by the distinguished British astronomer Richard Carrington [*Meadows*, 1970, p. 181]. Carrington was in the middle of an 8-year study of sunspots and was observing a large sunspot group when "two patches of intensely bright and white light broke out . . . the brilliancy was fully equal to that of direct sunlight." Noting that the spot was rapidly brightening, Carrington rushed off to find a witness, but coming back only 60 seconds later he found the spot of light "much changed and enfeebled" and soon afterward it faded altogether [*Carrington*, 1860].

As luck had it, the astronomer *Hodgson* [1860] (see *Meadows* [1970, p. 187]) observed the same event from another part of England. An unusually intense magnetic storm followed 17 hours afterward, accompanied by polar aurora that could be seen far from the polar regions (another such storm had occurred a few days earlier, probably from the same sunspot group). Carrington noted the coincidence but added "one swallow does not make a summer."

We now know that Carrington had seen a solar flare, a rapid release of energy probably drawn from the sunspot's magnetic field, capable of accelerating electrons and ions to high energies. Flares rank among the most rapid of the Sun's observed phenomena: they can extend over tens of thousands of kilometers, and their fastest features have time scales of seconds, though the whole sequence usually lasts tens of minutes to an hour.

Only rarely do flares emit intense white light, as Carrington's did, but they are readily observable through filters which isolate the red Hα brightenings near sunspots, and in 1892 George Ellery Hale [*Wright*, 1966] devised the spectroheliograph, which produced images of entire areas on the Sun using only a single spectral wavelength. On July 15 of that year, Hale produced a series of photographs documenting the evolution of a large flare, which was followed 19 hours later by a large magnetic storm [*Hale*, 1892].

More such correlations soon followed, leaving no doubt that something was propagating from the Sun to the Earth at about 1000 km/s (or faster, as in the two events cited here), causing a magnetic disturbance upon its arrival [*Fitzgerald*, 1892].

ELECTRON BEAMS FROM THE SUN?

What was it? One clue seemed to come from discharges in low-pressure gases and from beams of "cathode rays" propagating between electrodes in evacuated vessels. Laboratory studies showed that these "rays" consisted of electrically charged particles whose properties were measured by J. J. Thomson and which were eventually named electrons [*Thomson*, 1967; *Shamos*, 1959]. Electron beams propagated at great speed, which led to the plausible suggestion that the source of observed disturbances was streams of electrons emitted from sunspot regions.

The first serious study of this phenomenon was performed by the Norwegian Kristian Birkeland [*Birkeland*, 1901, 1908; *Egeland*, 1984, 1986; *Devik*, 1968; *Boström*, 1968]. In 1896 Birkeland aimed cathode rays at a magnet and found that the magnet apparently "sucked in" cathode rays: he suggested that the Earth's field did the same to beams from the Sun. He communicated his findings to his former teacher, the French mathematical physicist Henri Poincaré, who showed that rather than being attracted, charged particles were guided by magnetic field lines [*Pointcaré*, 1896]. Poincaré calculated the motion of an electron in the field of a magnetic monopole, a completely soluble problem, and found that the electron spiraled around a cone bounded by field lines, gradually losing headway until at a certain distance it was reflected backward [*Rossi and Olbert*, 1970, section 2.5; *Mitchell and Burns*, 1968].

Birkeland then built a large vacuum tank, placed in it a spherical magnet—like Gilbert he called it a terrella—and aimed at it beams of cathode rays (Figure 1). Bright spots appeared where the beams hit the terrella, generally in the polar regions. In some experiments there were even bright rings around the magnetic poles.

By that time, appreciable information had accumulated about the aurora. Elias Loomis of Yale published a map of contours of equal auroral frequency in the northern hemisphere [*Loomis*, 1860], showing that they centered on the magnetic pole (rather than the geographic one) and that their frequency was highest in an oval band about 20° from the pole [*Eather*, 1980]. Hermann Fritz conducted a similar study with far greater precision [*Fritz*, 1881]. Following Birkeland's work the pieces suddenly seemed to fall into place: flares (or sunspots) apparently emitted electron streams, which were steered by the Earth's field toward the auroral zones—and since a stream of electrons carried an electric current, a magnetic disturbance would also be produced [*Stoermer*, 1917].

This view was supported by *Maunder* [1904], who had deduced a tendency of storms to recur at 27-day intervals, the rotation period (relative to Earth) of low solar latitudes where sunspots tend to occur. He noted that recurrent storms were hard to correlate with solar phenomena (see further discussion below), but he still believed that "solar streams" were responsible and wrote as follows:

> That, therefore, which Lord Kelvin spoke of twelve years ago as "the fifty years' outstanding difficulty" is now rendered clear. Our magnetic disturbances have their origin in the Sun.

> The solar action which gives rise to them does not act equally in all directions, but along narrow, well-defined streams, not necessarily truly radial. These streams rise from active areas of limited extent. These active areas are not only the source of our magnetic disturbances but are also the seats of the formation of sun-spots. . . .

Birkeland certainly did his best to promote the notion of solar electron streams. He also asked a colleague, the young mathematician Carl Stoermer, to calculate the motion of electrons in a dipole field, and Stoermer spent a large part of his career attacking that problem [*Stoermer*, 1955; *Nutting*, 1908]. Unfortunately, motion in a dipole field (unlike the monopole problem) has no analytical solution but is beset by pathologies resembling those of the notorious three-body problem of celestial mechanics [*Dragt and Finn*, 1976], so that Stoermer never achieved what he had sought, though he did integrate many orbits numerically.

He did, however, manage to prove that a wide class of orbits existed in the dipole field that were trapped and did not extend to infinity. He furthermore showed that for sufficiently low particle energies all orbits hitting the terrella at low and middle latitudes were trapped, so that particles arriving from a distant source, like the electrons in Birkeland's experiment, never reached those latitudes but were always steered to the polar regions or turned away, in full accord with Birkeland's observations.

In the Earth's field, Stoermer's theory worked well for cosmic ray particles in the Gev range, but not for auroral electrons. It was realized quite early that the atmospheric density at 100 km, where auroral electrons generally stopped, was so low that the energy of such electrons had to be low too. For instance, *Harang* [1951, table 31] estimated their speed at 0.3*c*, corresponding to about 23 keV. At such low energies, Stoermer's theory predicted impacts very close to the magnetic poles, contrary to observations that showed the midnight aurora peaked around magnetic latitude 68°. Neither could it explain the observation that auroras were scarce near the magnetic pole itself.

The theory of solar electron streams soon hit another snag: Arthur Schuster [*Schuster*, 1911; *Chapman*, 1934; *Bartels*, 1934*b*] showed that electrostatic repulsion would quickly disperse any stream of solar electrons.

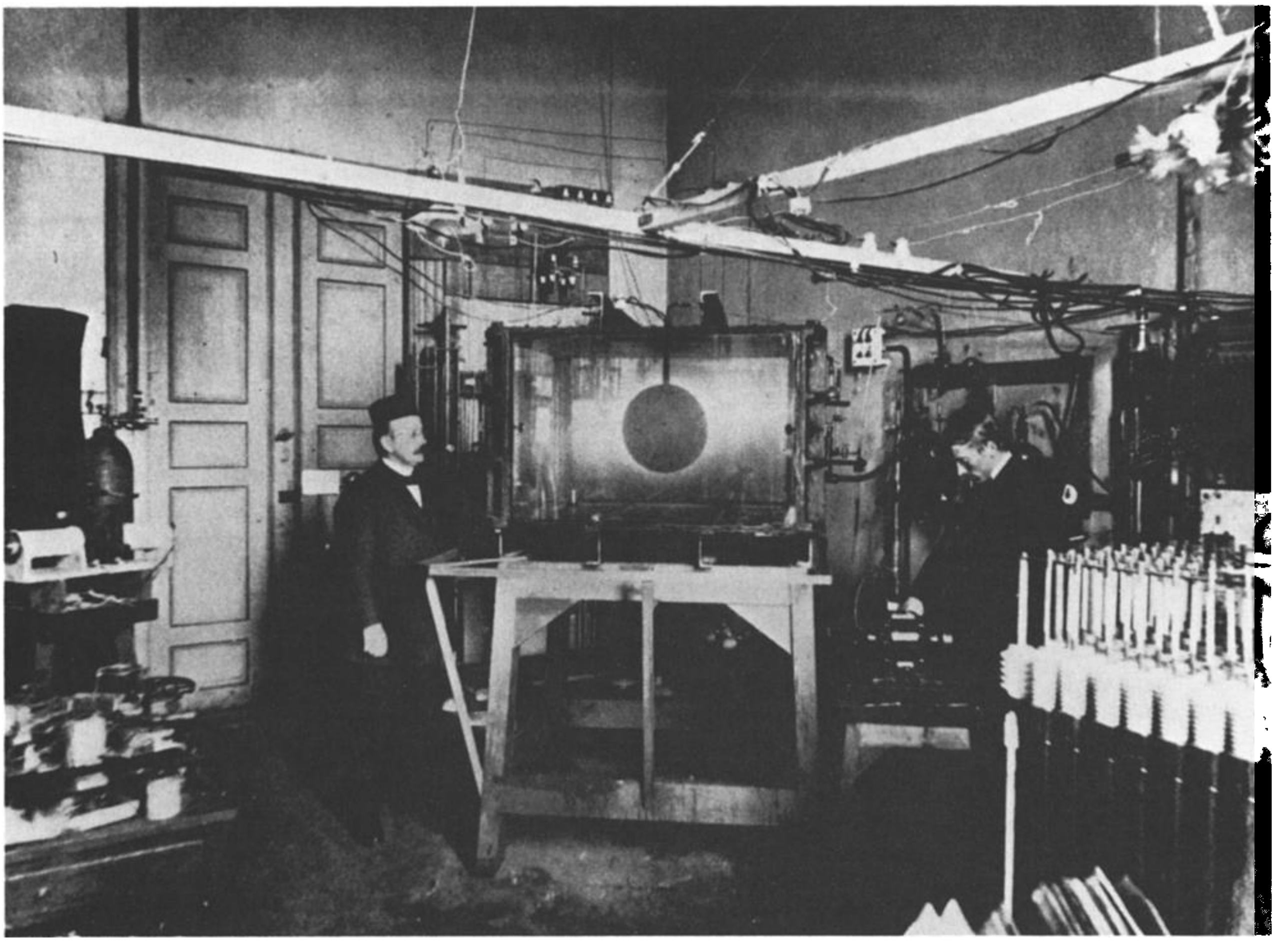

Figure 1. Birkeland (left) in his laboratory with large terrella experiment.

THE CHAPMAN-FERRARO CAVITY

Sidney Chapman, a relative newcomer to the field of geomagnetism who was apparently unaware of Schuster's work, again raised the idea of solar electron streams in a 1918 paper on magnetic storms [*Chapman*, 1918; *Akasofu et al.*, 1969]. He was pounced upon by Frederick Lindemann, Oxford professor of physics (Lord Cherwell, Winston Churchill's controversial World War II science adviser), who pointed out that the negative charge accumulated on the Earth would disrupt the process [*Lindemann*, 1919]. Lindemann then suggested that any cloud or stream expelled from the Sun would have to be electrically neutral, containing equal charge from ions and electrons.

It took more than 10 years before Chapman figured out how a neutral beam could cause magnetic disturbances. In 1927 he was joined in his quest by Vincent C. A. Ferraro, newly graduated [*Cowling*, 1975].

The two had realized that an electrically neutral mixture of ions and electrons—what would nowadays be called a plasma—would be a very good conductor of electricity. Therefore, when a cloud of such matter approached the Earth, electric currents would be induced in it, creating a magnetic disturbance. But how could such currents be calculated? Chapman felt that as an approximation to a three-dimensional cloud one might start with a two-dimensional conducting sheet, approaching the Earth in its equatorial plane [*Ferraro*, 1969]. He knew that Maxwell had calculated currents induced in conducting sheets and advised Ferraro to look up that work. However, when Ferraro saw Maxwell's calculation, he realized that a different sheet approximation would be even better.

If a large plasma cloud nears the Earth, its front boundary appears like an approaching wall—as the elephant did to one of the blind men in the parable [*Saxe*, 1936]. Furthermore, if the cloud is a perfect electrical conductor, all induced currents flow on the surface of that "wall." Maxwell had shown that when a perfectly conducting flat plane approached a dipole, its externally induced field was the same as the field of an equal "image dipole" located symmetrically on the other side of the plane. Thus the initial magnetic disturbance caused by the cloud should resemble the field of an image dipole at twice the distance of the cloud, rushing toward Earth at twice the cloud's speed (Figure 2).

That was how Chapman explained the "sudden commencement," a rapid steplike increase in the magnetic field heralding the onset of many (though not all) magnetic storms [*Chapman and Ferraro*, 1930, 1931, 1932]. There was a postscript [*Dungey*, 1979]: much later, *Gold* [1955] pointed out that the fact that the cloud maintained a sharply defined front boundary long after it had left the Sun suggested that this boundary was a collision-free shock and that therefore a sufficient density of interplanetary plasma existed for such a shock to form.

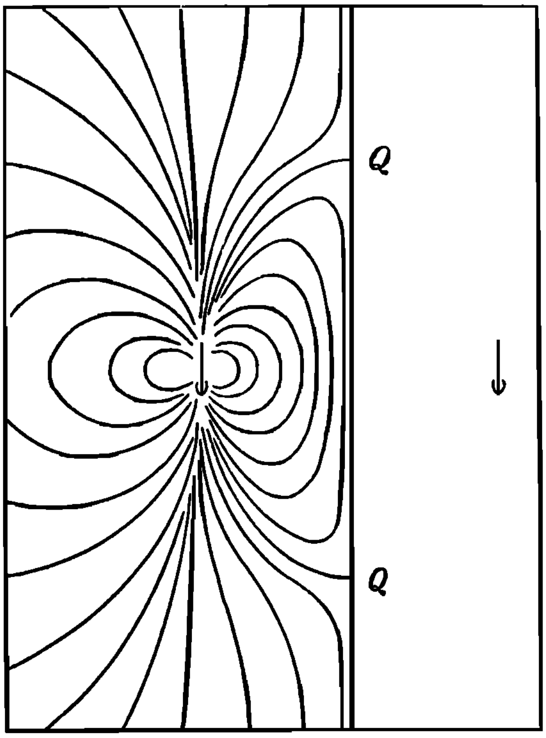

Figure 2. The Earth's dipole field (left), flattened by the addition of the field of an image dipole (right), as proposed by Chapman and Ferraro.

The Earth's magnetic field also exerts a force on the induced currents, and that force grows stronger as the cloud draws nearer. Ultimately, Chapman and Ferraro argued, it became strong enough to stop any further frontal advance of the cloud toward Earth; however, the flanks continued to advance, so that soon a cavity was formed, enveloping the Earth. That was known for many years as the "Chapman-Ferraro cavity," the region from which the plasma of the cloud was excluded by the action of the Earth's magnetic field (Figure 3).

Solar flares were one obvious source of plasma clouds. However, as Maunder had already noted, many storms could not be traced to any clear source, not even to definite sunspots. This held especially for moderate storms with a 27-day recurrence, extensively studied by *Bartels* [1932] and *Newton* [1932], who named their elusive sources "M-regions." The mystery deepened with the realization [*Bartels*, 1934*a*] that in one carefully studied solar cycle, recurrent storms tended to cluster around solar minimum, including periods when no sunspots were visible at all. The answer was delayed until Mariner 2 detected high-speed streams in the solar wind [*Snyder et al.*, 1963; *Neugebauer and Snyder*, 1966], which seem associated with recurrent storms. Still later it was shown by solar

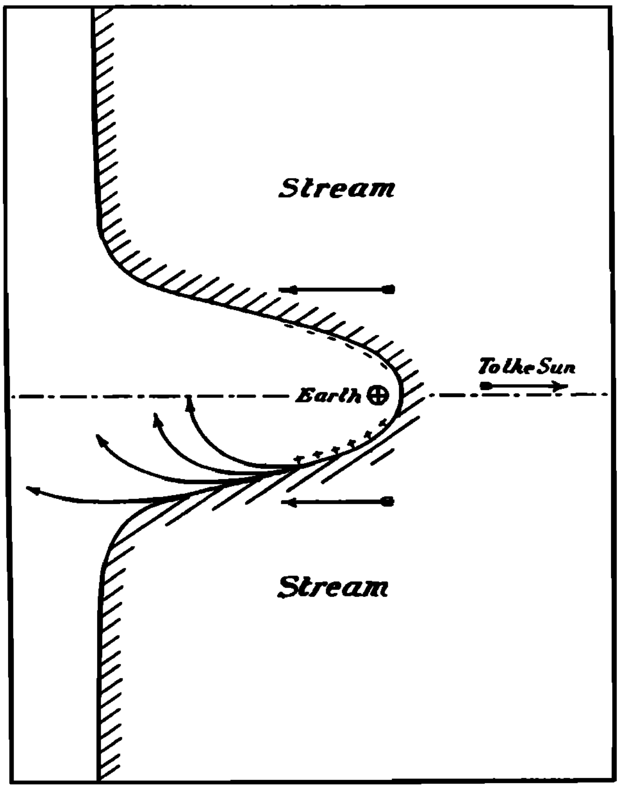

Figure 3. The formation of the Chapman-Ferraro cavity. Arrows trace the paths of ions and electrons which Chapman and Ferraro proposed to account for ring current effects.

observations from space and especially those of Skylab [*Bohlin*, 1977, section 1a] that such streams came from "coronal holes," most prevalent near solar minimum [*Zirker*, 1977; *Hundhausen*, 1979].

An additional problem was posed by the imperfect correlation between sudden commencements (sc) and magnetic storms: often an sc is followed by no storm, and storms often occur without any sc. This problem, too, required space data for its resolution: it was only explained in the 1960s with the realization of the major role played by the interplanetary magnetic field (IMF) in solar-terrestrial interactions, in particular by the north-south component of the IMF. When the direction of the IMF is not favorable, the arrival of a plasma cloud may well produce no storm. Nowadays a sudden steplike rise of the magnetic field is termed an ssc (storm sudden commencement) if it is followed by a storm and an si (sudden impulse) if not.

THE RING CURRENT

If the cloud advances at 1000 km/s, the cavity will be fully formed in a few minutes. A typical magnetic storm, however, lasts much longer. Its main features are a "main phase" in which the north-south component of the Earth's field (at low and middle latitudes) gradually weakens over 6–12 hours, followed by a slow recovery of the field lasting 1–3 days. This part of the storm disturbance can be far more intense than the "sudden commencement," yet the Chapman-Ferraro cavity provided no good explanation.

In the early 1900s the idea arose that a "ring current" of trapped particles might exist around the Earth's equatorial plane. Electrons and positive ions of sufficiently high energy could circle the Earth's equatorial plane in opposite directions, each contributing an electric current in the same sense, which always weakens the Earth's main field as observed.

Carl Stoermer proposed such a ring current [*Stoermer*, 1910, 1911, 1912] to overcome a discrepancy in his theory, which predicted the aurora far closer to the magnetic pole than where it was observed [*Smith*, 1963; *Chapman and Bartels*, 1940, section 24.13]. Soon afterward, however, Adolf Schmidt suggested that a ring current was also the cause of the main phase of magnetic storms [*Schmidt*, 1924].

The main problem was that the energy required for motions like those suggested by Stoermer was rather high: such orbits, when close to the Earth (distant orbits have other problems) are now recognized as appropriate for cosmic ray particles. As part of their theory, Chapman and Ferraro also proposed their own version of the ring current concept, set up (somehow) inside the Chapman-Ferraro cavity [*Chapman and Ferraro*, 1933; *Smith*, 1963]; the curved arrows in Figure 3 are related to their theory. This was later expanded by *Martyn* [1951] and *Stoermer* [1955, section 60]. But as Chapman remarked [cited by *Hulburt*, 1937],

> The whole theory is necessarily both speculative and difficult; probably the most doubtful feature is that relating to the ring current, the existence and formation of which are still very uncertain.

Other evidence for plasma in the distant geomagnetic field came from low-frequency radio emissions and especially from whistlers [*Helliwell*, 1965, chapter 2; *Alpert*, 1980]. Starting with the work of *Preece* [1884] note was taken of clicks and whistles on long telephone lines: the cause was later identified as electromagnetic waves in the audio frequency range, picked up by the lines, which acted as antennas. Such sounds were also noted on field telephone lines during World War I and included a sound like "piou," descending in frequency. The phenomenon was studied by *Barkhausen* [1919, 1930] and later by *Eckersley* [1925], and the descending tones were named "whistlers." Owen Storey [*Storey*, 1953, 1956] definitely identified their source as lightning, sometimes occurring in the opposite hemisphere: the waves were guided along magnetic field lines and often oscillated several times between hemispheres before decaying. Their dispersion suggested an appreciable plasma density even in the most distant portions of the field lines, and that subject was widely studied by 1957, the year the first artificial satellites were orbited. However, it should be realized that the plasma involved here was mostly thermal, more related to the ionospheric plasma than to the more energetic particles of the ring current.

Shortly before the discovery of the radiation belt, *Singer* [1957] pointed out that trapped particles of low energy could also carry a ring current, even though their motion was more complex. An ion confined to the equatorial plane, for instance, tends to circle locally around field lines, but its circle will be slightly tighter where it comes closest to Earth, because the field there is slightly stronger. This causes the mean position of the ion to drift slowly in longitude, gradually carrying it around the Earth (Figure 4); ions and electrons drift in opposite directions, and therefore a neutral plasma yields a net circulating current.

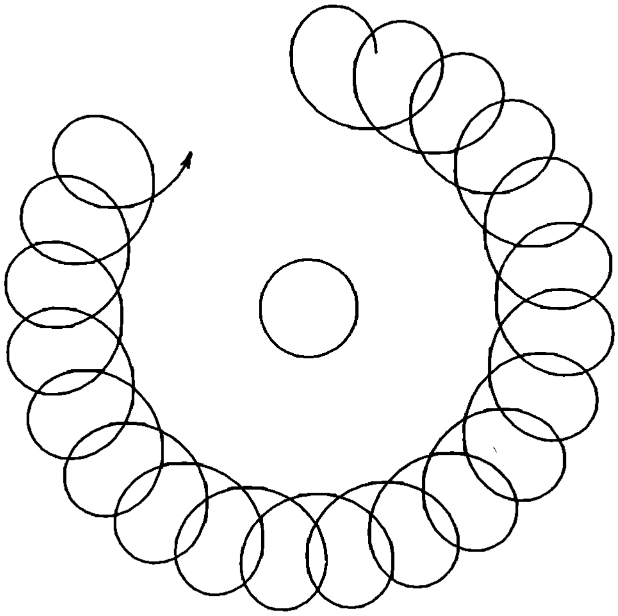

Figure 4. Schematic drift path of an equatorial ring current proton around the Earth, viewed from north of the equator.

The concept of such drift motion was first noted by *Gunn* [1929] and was described by *Alfvén* [1950] in *Cosmical Electrodynamics*, where he presented the equations of guiding center motion. Slow motion around the Earth was also found in Stoermer's numerically integrated orbits [*Stoermer*, 1955]. *Singer* [1957] noted that owing to this motion, a ring current could also be carried by a belt of trapped particles of relatively low energy; he suggested that such belts were formed in magnetic storms and lasted up to a few days before decaying.

And yet, if those orbits were truly trapped, both entry and escape would be impossible. If they became populated during storms, how did particles reach them?

ALFVÉN'S THEORY AND ELECTRIC FIELDS

Hannes Alfvén in Sweden was an early investigator of plasmas in space. In the last years before World War II he proposed that ring current effects (and auroras as well) were due to the entry into the Earth's field of particles from the solar plasma cloud, convected there by an electric field due to the cloud's motion. If the cloud has a high electric conductivity, then the local electric field **E*** inside it vanishes,

$$\mathbf{E}^* = \mathbf{E} + \mathbf{v}\times\mathbf{B} = 0 \qquad (3)$$

yielding the so-called MHD condition. The electric field **E** enables particles to flow perpendicular to magnetic field lines, imparting to their average position ("guiding center") the velocity

$$\mathbf{v} = \mathbf{E}\times\mathbf{B}/B^2 \qquad (4)$$

Alfvén did not believe in the Chapman-Ferraro theory, which treated the cloud as a continuous fluid [*Alfvén*, 1951] but rather viewed the cloud as a collection of individually moving particles. Those particles would flow together with the above bulk velocity v until they came close to the Earth's dipole; there the guiding center motion (in a manner somewhat similar to what was later invoked by *Singer* [1957] for trapped particles) would move ions and electrons in opposite directions, creating a cavity around the Earth and also leading to the ring current field (Figure 5).

Alfvén's argument was somewhat more involved and also included an explanation of the aurora. Chapman, as might be expected, strongly disagreed [*Dessler*, 1970; *Akasofu*, 1970], and in the end, Alfvén's article on his theory was not accepted by any major journal but appeared in Sweden in a relatively obscure format at the end of 1939 [*Alfvén*, 1939; *Cowling*, 1942] (see also *Stoermer* [1955, section 61] and *Stern* [1977]). Though it made some important points, in 1957 it was still poorly known and appreciated outside Scandinavia.

INTERPLANETARY PLASMA

Chapman and Ferraro had assumed that except for their plasma clouds, interplanetary space was relatively empty, but evidence to the contrary came from observations of comet tails. For many years it was held that the long tails of comets were adequately explained by the pressure of sunlight, but *Hoffmeister* [1943, 1944] found that many comet tails deviated by several degrees from the radial direction, in a way suggesting that they were shaped not by sunlight but by solar particles propagating at a lower velocity. After World War II this was picked up by

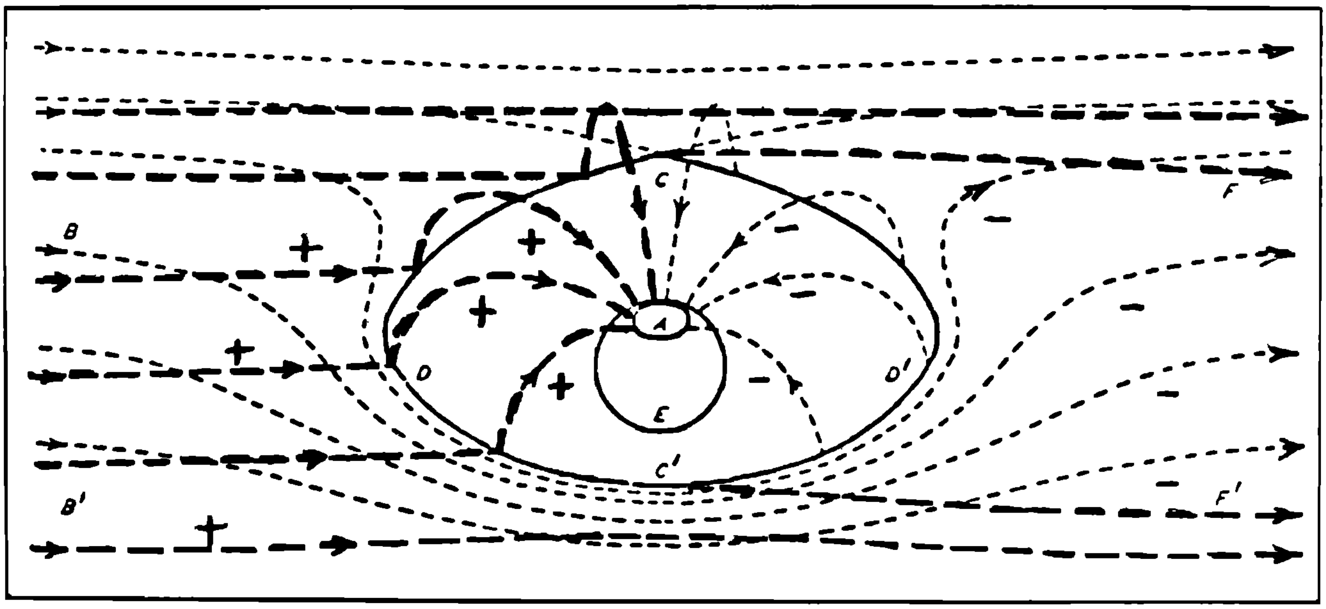

FIG. 1—PERSPECTIVE DRAWING OF PATHS OF IONS AND ELECTRONS NEAR THE EARTH (AFTER ALFVEN); FOR SIMPLICITY, ONLY THE PATHS OF CHARGES REACHING THE NORTH AURORAL ZONE ARE SHOWN

LEGEND: PATHS OF IONS = ——→; PATHS OF ELECTRONS = - - - - -; E = EARTH; CURVE A = NORTH AURORAL ZONE; BB' = IONS AND ELECTRONS APPROACHING EARTH IN EQUATORIAL PLANE; CDC'D' = BOUNDARY OF FORBIDDEN REGION; CF AND C'F' ARE BOUNDARIES OF SHADOW OF EARTH WHERE NO IONS ARE PRESENT

Figure 5. The motion of ions (dark lines) and electrons (light lines) according to Alfvén's theory [after *Cowling*, 1942]. The Sun is to the left.

Biermann [1951], who noted that dust tails, whose spectra resembled scattered sunlight, could be explained by light pressure, but that the distinct ion tails often showed huge accelerations which could only be accounted for by a "solar corpuscular radiation." For a long time, however, more direct evidence was lacking.

When it was discovered, from spectra of highly ionized species [*Grotrian*, 1939; *Edlén*, 1941, 1942, 1945; *Shapely*, 1960; *Billings*, 1966, chapter 1; *Lang and Gingerich*, 1979] that the Sun's corona had a temperature around 10^6 °K, the question arose of how the Sun's gravity could keep such a hot atmosphere attached [see *Lüst*, 1962; *Parker*, 1964]. Coronal temperature near the Sun was observed not to decrease with height, and this was explained by the high heat conductivity of the plasma, which seemed to preclude a stratified atmosphere like the Earth's, with temperature decreasing with height. Chapman proposed a theory in which a static equilibrium was still possible, yielding moderately lower temperatures at the Earth's orbit. Eugene Parker, however, derived an alternative solution in which the corona was not in equilibrium but instead continually streamed away from the Sun to form a high-speed "solar wind" [*Parker*, 1958; *Dessler*, 1967; *Brandt*, 1970]. The process converted heat to kinetic energy rather efficiently.

The debate between proponents of a static corona, Parker's solar wind theory, and an alternative "solar breeze" theory of *Chamberlain* [1960, 1961; *Dessler* 1967] was only settled by observations from space. *Gringauz et al.* [1960] (see also *Gringauz* [1961]) mounted charged-particle traps on Lunik 2 (September 1959) and later on Lunik 3 (October 1959), and they detected far from Earth a flow of energetic positive charges, consistent with solar wind ions and also displaying appropriate modulation due to spin of the spacecraft. In 1961 the Massachusetts Institute of Technology particle trap aboard Explorer 10 obtained more detailed evidence for the solar wind [*Rossi*, 1984; *Bonetti et al.*, 1963], and information concerning the continuous nature of the solar wind came in 1962 from the flight of Mariner 2 to Venus [*Snyder et al.*, 1963; *Neugebauer and Snyder*, 1966]. It then became clear that the Chapman-Ferraro cavity was not a temporary feature but existed at all times, and it received the name "magnetosphere," coined by *Gold* [1959]. Rapidly spreading plasma clouds produced by solar flares, like those envisioned by Chapman and Ferraro, are sometimes superposed on the solar wind flow. We now know that when the expansion velocity of such clouds greatly exceeds that of the solar wind, they are indeed preceded by collision-free shocks.

POLAR MAGNETIC STORMS

One additional piece of the picture deserves mention: magnetic disturbances associated with the aurora, like those observed by Hiorter and Celsius. Such disturbances are far more intense, rapid, and frequent than magnetic storms observed at low and middle latitudes. Birkeland studied them in 1902–1903 using a network of four stations—in Norway and on Iceland, Spitzbergen (Svalbard), and Novaya Zemlya [*Birkeland*, 1908, 1913; *Boström*, 1968]—and concluded that there existed a distinct type of magnetic storm, the "elementary polar magnetic storm" with a typical time scale of less than an hour, associated with the aurora and with electric currents which descended along auroral field lines and flowed horizontally along auroral arcs.

Birkeland died in 1918; his work was not followed up for many years, and in the decades that followed, relatively few magnetic studies were performed at high latitudes. Chapman did not believe that Birkeland's "polar storms" existed. He realized that they were much shorter than the nonpolar storms with which he was familiar, and in his encyclopedic two-volume treatise on geomagnetism, jointly written with Julius Bartels [*Chapman and Bartels*, 1940] (see also *Chapman* [1968]), he suggested that Birkeland's events were probably just isolated phases of magnetic storms. He noted there that "a great magnetic storm is a unitary phenomenon, going through regular phases" and maintained that Birkeland's polar storms ". . . seem to be clearly part of a single phenomenon, waxing and waning in unison with the non-polar disturbance field."

The name "substorm," coined by Chapman for this phenomenon about 20 years later, reflected that attitude, though by then Chapman must have begun to realize the importance of Birkeland's early observations [*Akasofu*, 1970, p. 603] (see also *Siscoe* [1980]). We now view substorms as impulsive acceleration events, quite possibly terrestrial analogs of solar flares.

By the 1950s this realization was slowly forming, and there was considerable interest in "magnetic bays," large magnetic disturbances in the auroral zone which would nowadays be classified as substorms [*Silsbee and Vestine*, 1942]. Currents flowing into the auroral zone and out of it, however, were observed only in the late 1960s, and their global pattern was first mapped in 1974 [*Zmuda and Armstrong*, 1974; *Iijima and Potemra*, 1976]: they are now known as Birkeland currents [*Schield et al.*, 1969, p. 247]. Contrary to Birkeland's interpretation, much of the horizontal part of their circuit, in the ionosphere, flows not along auroral arcs but perpendicular to them, for by a quirk of electrodynamics [*Fukushima*, 1969, 1976] the main circuit produces only a weak magnetic signature on the ground. What Birkeland observed was mostly the signature of an associated Hall current, the "auroral electrojet" which parallels auroral arcs.

ASSESSMENT

The reader should be cautioned here that the preceding discussion is in no way a complete account of pre-space age magnetospheric physics. It merely describes in austere detail the main lines of investigation, and many details and names are by necessity absent. Written with hindsight, it also paints a far tidier picture of magnetospheric physics than what actually existed: only through the original articles can the reader recapture some of the uncertainty, confusion, and high "noise level" which often obscured the modest achievements described here. Birkeland did not claim to have observed one type of polar magnetic storm but four or five: only later was it recognized that they all reflected the same phenomenon. Theories we now recognize as false, for example, some theories of the ring current and of the interplanetary plasma, often drew great attention, and where investigators did find a reasonable explanation for one facet, for example, the Chapman-Ferraro cavity or Alfvén's electric field, they often felt compelled to fill the rest of the pattern with guesswork which generally did not stand up to the test of time. This sense of confusion often marks work near the limits of data and understanding, and it may explain the long delays which often occur before the truth of a discovery is generally acknowledged.

The picture changed considerably after 1957, the start of the International Geophysical Year (IGY). The IGY was an international effort which included the launch of the first artificial satellites, and it formed a natural transition in the history of magnetospheric physics.

The implications of that transition are best appreciated in the context of other research on our physical environment. The surface of the Earth, the oceans, and atmosphere are completely accessible and can be directly studied, even experimented upon: in the jargon of Earth observation from space, we have "ground truth." The realm of the astrophysicist, on the contrary, can only be sensed remotely and imperfectly, and the amount of information we can ever hope to receive from it is severely limited [*Harwit*, 1981]. By necessity our explanations of astrophysical phenomena are laced with guesswork, and in many cases (e.g., the origin of cosmic rays) it is quite likely that such guesses will never find convincing confirmation.

Magnetospheric physics stands halfway between those extremes. Until the IGY it was very much like astrophysics: the magnetosphere could only be sensed remotely, and much of what was believed about it was merely intelligent guesswork. Then came artificial satellites and provided some "ground truth," and it is interesting to compare what they revealed with what was believed beforehand.

Many important magnetospheric features had indeed been inferred before spacecraft were available, but in almost every case some important detail was missing or wrong. The Chapman-Ferraro cavity was predicted as a temporary rather than permanent feature, and the same was true for the radiation belt. Alfvén's convection contained a nucleus of truth, but electric field effects supplemented rather than supplanted the Chapman-Ferraro picture, and the convection which they produced was found to flow from the tail sunward, opposite to its direction in Alfvén's theory. Birkeland's auroral currents did exist, but their configuration was not the one predicted. The existence and importance of the magnetospheric tail generally went unsuspected, and so did the existence of parallel electric fields along auroral arcs, although Alfvén later developed the theory of quasi-neutral equilibria, relevant to such fields. All this underscores the essential role of in situ observations: one can only speculate how much of this might be paralleled in astrophysics.

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