History of Solar-Terrestrial Relations as Deduced from Spacecraft and Geomagnetic Data: Solar M Regions

by

John M. Wilcox

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This brief history is organized around the long problem of the solar M region, i.e. the structure on the sun that is responsible for recurrent geomagnetic disturbances.

Our history begins on 1 September 1859 when R.C. Carrington was engaged in his daily task of mapping sunspots. In his own words (Carrington, 1860) "two patches of intensely bright and white light broke out .... my first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by which the general image is thrown into shade, for the brilliancy was fully equal to that of direct sun-light; but, by at once interrupting the current observation, and causing the image to move by turning the R.A. handle, I saw I was an unprepared witness of a very different affair. I thereupon noted down the time by the chronometer, and seeing the outburst to be very rapidly on the increase, and being somewhat flurried by the surprise, I hastily ran to call someone to witness the exhibition with me, and on returning within 60 seconds was mortified to find that it was already much changed and enfeebled. Very shortly afterwards the last trace was gone, and although I maintained a strict watch for nearly an hour no recurrence took place."

At the November meeting of the Royal Astronomical Society Mr. Carrington described this observation, and pointed out that a moderate but very marked disturbance in the geomagnetic field observed at Kew took place within two minutes of the time of the white light flare. About four hours after midnight there commenced a great magnetic storm, which subsequent accounts established to have been as considerable in the southern as in the northern hemisphere. While the contemporary occurrence may deserve noting, he would not have it supposed that he even leans toward hastily connecting them. "One swallow does not make a summer." (forgoing description from Meadows, 1970)

We may note that even at this time the course of events was influenced by the available technology. It had been suggested earlier to Carrington that a daily sequence of <u>photographic</u> observations of the sun would be desirable, but Carrington considered that the technique of photography was not reliable enough for his purposes. He therefore made hand-drawn records of the sun each day, and was therefore viewing the solar image at the time when the great white light flare erupted.

In the following years considerable work was devoted to comparing the variation of geomagnetic activity with the variation of the number of sunspots through the eleven year cycle. The relationship between the solar cycle and magnetic disturbances on the earth was almost universally accepted in the latter half of the century: the last important astronomer to oppose it was Faye, and he acceeded to the majority opinion in 1885 (Meadows, 1970).

In 1892 Lord Kelvin, in his Presidential Address to the Royal Society, gave a rather severe lecture to the astronomers. He examined the energy in a typical magnetic storm and concluded "in this eight hours of not very severe magnetic storm as much work must have been done by the sun in sending magnetic waves out in all directions in space as he actually does in four months of his regular heat and light. This result, it seems to me, is absolutely conclusive against the supposition that terrestrial magnetic storms are due to magnetic action of the sun, or to any kind of action taking place within the sun, or in connection with hurricanes in his atmosphere, or anywhere near the sun outside. It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been a mere coincidence". (Thomson, 1892)

This is one of the first, but by no means the last, examples of the fact that solar-terrestrial relations is a somewhat contentious subject.

Lord Kelvin also noted that for the source of the sun's energy he favored Helmholtz's theory of the work done by gravitation on a shrinking solar mass, as compared with the competing theory of energy generated by cosmical matter plunging into the sun.

We now examine the discussion of recurrence phenomena in terrestrial magnetism by Chree and Stagg (1927). They say "of late, owing partly to a supposed connection between wireless and magnetic phenomena, the existence of a 27-day interval in magnetic disturbance has received increased attention". "In accordance with ideas prevalent since the time of the late Professor K.R. Birkeland, it is supposed that magnetic disturbance is due to the discharge from the sun of some form of electricity carrier, and it is often assumed, following Birkeland, that sunspots are the areas where the discharge originates". We have here an early opinion in the long dispute as to the solar regions that cause magnetic disturbance. We note that Chree and Stagg are a little cautious by saying "it is often assumed that sunspots are the areas".

Chree and Stagg used the method of superposed epochs to investigate the recurrence properties of geomagnetic activity. They chose as zero days the five most disturbed days of each month and plotted the average value of the geomagnetic character figure near the zero days. They also plotted the average value of the character figure near an interval 27 days before and after the zero day, 54 days before and after, etc. Exactly the same analysis was performed using as zero days the five quietest geomagnetic days of each month.

The results are shown in Figure 1. The limitations of technology are shown by the fact that it was only feasible to compute values in Figure 1 during a few days near multiples of 27 days, since all the work was being done by hand and 20 years of data were involved. A complete plot similar to Figure 1 would be a trivial operation on any modern computer.

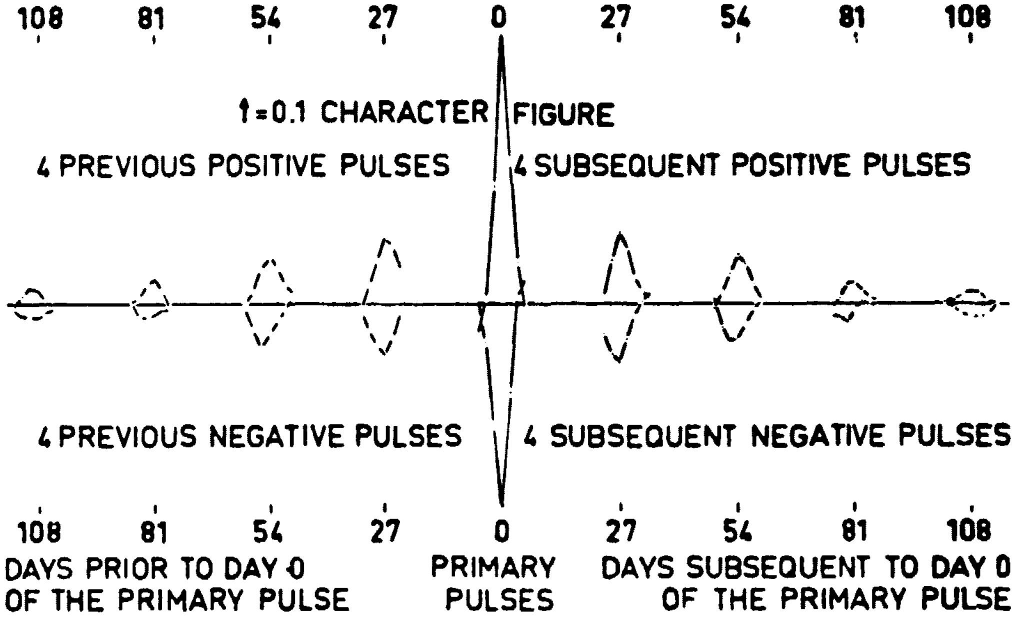

Figure 1

Superposed epoch analysis of recurrent geomagnetic activity. (Chree & Stagg, 1927).

A strong recurrence tendency with a period very close to 27.0 days is evident in Figure 1. Chree and Stagg point out that the period is rather precisely determined by the fact the fourth recurrence before and after the zero time is at 108 days rather than at 107 or 109 days.

It is evident from Figure 1 that the recurrence tendency is equally marked in quiet days as in active days. This fact was largely lost sight of during the investigations of the following years, in which a picture of solar active regions sending a tongue of plasma out into the vacuum of interplanetary space predominated. This picture could well account for a recurrence tendency in active days, but <u>not</u> for a recurrence tendency in quiet days.

Chree and Stagg say "if a magnetic disturbance on the earth is associated with limited disturbed areas on the sun, and if the rotation period of these areas is 27 days, as the numerous data of this paper suggests, then a solar area may continue highly disturbed for a number of months, or it may go through a succession of alternate states of high disturbance and unusual quietness. In some years a forecast based on a single disturbed day is just about as likely to supply an especially quiet day as a really disturbed day. In other years, with reasonable luck, one might forecast a succession of several disturbed days". Chree and Stagg had not yet made the distinction that large geomagnetic activity tends to be sporadic while moderate activity tends to be recurrent.

Chree and Stagg rather thoroughly disposed of a suggestion by Deslandres that magnetic disturbances have recurrence periods which are 27n/6 days, where n is a small integer. This is an early example of the side issues that have, from time to time, clouded investigations of solar-terrestrial relations. In this connection we note that many years of data are usually necessary to firmly establish the situation. Quite anomalous results can appear in only a few years of data.

We go on to the year 1931 and a new theory of magnetic storms by Chapman and Ferraro (1931). The first two paragraphs of their paper are worthy of quotation.

"Many attempts have been made, but hitherto without success, to explain how magnetic storms are produced. The present further attempt is described with a due sense of the pitfalls that abound in this difficult field of speculation. Possibly the fate in store for our theory is only to warn future theorists against some fallacy into which we have unwittingly fallen; yet if so, our work, and that of our critics, may be of value to later writers, just as we have benefited from the labors of past speculators and their critics. But our theory would of course not have been put forward without some confidence on our part in its substantial truth.

On good grounds, almost every theory of storms has ascribed them to the action of something propagated to the earth from the sun. Lord Kelvin in 1892 showed that the storms could not be directly due to variations in the sun's magnetic field, and Hale's subsequent measurements of the sun's field confirm this. The postulated solar agent has therefore been either some corpuscular emission or ultra violet radiation."

Chapman and Ferraro come down on the side of particle emission as the causal agent. The early attempts to have particles of only one sign of charge responsible were criticized by Lindemann on the ground that electrostatic repulsion would blow up such beams. The elegant treatment developed by Chapman and Ferraro will not be further discussed here, since from now on in response to limited time and space, we will focus our discussion on the concept of the solar M region.

We next examine a monumental paper on terrestrial magnetic activity and its relations to solar phenomena (Bartels, 1932). Bartels used monthly data of geomagnetic activity from 1872 to 1930, and constructed annual means back to 1835, since he thoroughly appreciated the importance of using a long series of data. The last sentence of Bartels' abstract contains a thought that is still true today. "Observations of terrestrial magnetic activity yield therefore not only information about geophysical influences of such solar phenomena that may be traced in astrophysical observations, but supplement these direct observations themselves."

Bartels points out that "the methods described in this paper may be used to test other relationships, such as those supposed in meteorology or in wireless transmission phenomena." Now that effects of solar activity on the weather are being seriously examined such tests are very pertinent.

Bartels complains about losing photographic traces of geomagnetic activity during unusually large activity in which the spot of light recording the activity either moves off scale or moves so fast that the trace can not be developed. A modern analogy to this difficulty can be found in some spacecraft telemetry records in which at times of unusually large geomagnetic activity the telemetry is sufficiently disturbed that the resulting spacecraft observations are represented by missing data. I have personally observed several examples of this.

Bartels notes that the direct solar radiation received by the earth on the whole daylight hemisphere is about 10^7 times the rate of supply of purely magnetic energy, even in higly disturbed months, and quotes Chapman "while the expenditure of energy during a magnetic storm is very great, it is quite insignificant compared with the supply continually being received by the earth through the ordinary solar radiation." This number has been recomputed many times since then.

An example of a side issue cleared away by Bartels is the suggestion that an "earth-effect" can be traced in the sunspots, in the form of a small but significant, annual variation of the sunspot numbers. Bartels shows that this is an artifact caused by a curvature effect in the data. His article contains several other examples of the pitfalls awaiting the unwary investigator.

Clear maxima in geomagnetic activity are shown by Bartels to occur near the time of the equinoxes. He felt that the explanation for this lay in the tilt of the earth's rotation axis to the ecliptic since the maxima were centered near March 21 and September 23, the time of the equinoxes.

Other investigators suggested that the tilt of the sun's axis of rotation by 7° to the ecliptic was the causal factor, since sunspots are observed to be rather rare at the solar equator and more common 10° - 20° away from the equator. If a plasma beam came radially away from a sunspot it would, on average, come closest to the earth at the times of greatest apparent inclination of the solar rotation axis, i.e. we see most of the northern hemisphere of the sun on September 7 and most of the southern hemisphere on March 5. We will follow this axial (sun) - equinoxial (earth) controversy down through the years.

Bartels notes that several of the physical effects he has discovered were seen only through the use of improved and accurate indices. This need continues to the present day, as we shall discuss near the end of this paper.

Another side issue cleared away by Bartels was the question of annual recurrences in geomagnetic activity caused by the influence of comets and meteors. A more recent example of such a side issue was the suggestion by some authors of a lunar influence on recurrent geomagnetic activity. They showed that there clearly was power in the geomagnetic spectrum at 29.5 days. This controversy was (probably) resolved when it was pointed out that the solar recurrence centered near 27 days has power in a band of width several days, and that a narrow-band filter centered at 29.5 days could detect some of this power.

An important distinction is made by Bartels as follows "according to W.M.H. Greaves and H.W. Newton the recurrence-characteristic is mainly a property of the storms of smaller range, while the intense storms are generally followed neither by another storm nor even by a subsidiary disturbance". This distinction is, of course, crucial to an understanding of the solar causes for geomagnetic disturbances. It is an example of the continuing process of 1) making such crucial distinctions, and 2) discarding side issues "red herrings".

Bartels continues "the main results of the extensive work of C. Chree and J.M. Stagg were that disturbed and quiet magnetic conditions tend to recur after intervals of 27 days....while the investigations just mentioned deal mainly with averages for many cases, it seemed to be of interest to investigate the 27-day phenomenon individually....the record reads like a book". Note that although Bartels mentioned the word "quiet", this significant half of Chree and Stagg's work tended to be forgotten. Bartels then shows the first of his famous 27-day recurrence diagrams covering the years 1906 through 1931.

(It is interesting to note that Bartels chart was printed in red and black. Anyone today who has tried to publish a color figure in a scientific journal knows that this is an expensive and rather rare process. They surely did some things better in the old days: for example at the turn of the century at Mt. Wilson Observatory a spectrograph pit 80 feet deep was dug by hand labor into hard rock with a diameter of 10 feet. When we wished to build a similar spectrograph pit into soft sandstone for the Stanford Solar Observatory we were only able to afford a diameter of 6 feet.)

Bartels notes several significant features of his long chart of geomagnetic activity. First, of course, is the simple fact that 27-day recurrences are very prominent. The recurrence tendency is most pronounced near the minimum of the sunspot cycle and is prominent even when no spots are visible. Geomagnetic recurrences last much longer than sunspot recurrences. These two facts should have been a clue that spots are not in themselves critical for geomagnetic activity.

We should quote the words with which Bartel introduces the concept of the solar M region "If the time T of passage from the sun to the earth would be constant for all corpuscular streams, then our diagram could be conceived as a chart of the sun, indicating the heliographic longitude of the active regions on the sun -- which we shall call here M regions. Several investigators have shown that T may be as high as three or four days for moderate disturbances, while it may be as low as one day for the great magnetic storms. This latter value is also suggested by the discussion of G.E. Hale. Since our sequences mostly consist of minor disturbances, our chart incidentally supports the view that the time T of passage for these, whatever it may be, is certainly fairly constant because otherwise such sharp "fronts" of sequences as in 1923 and 1930 could not occur". Since Bartels was not exactly sure of the passage time T, it was obviously difficult to know exactly which solar region should be identified with geomagnetic disturbances. The time T for recurrent disturbances was tentatively fixed from observations of the solar wind velocity with the assumption of a constant velocity from sun to earth, and more definitely confirmed by comparisons of photopheric magnetic fields with interplanetary fields observed near the earth. The latter measurement eliminated any possible problems with low velocity solar wind plasma in the first few solar radii above the photosphere.

Bartels goes on to make a pregnant comment "The faculae have often been suggested as likely to have greater significance for geophysical phenomena than the spots". He noted that facular patterns persist for longer times than do sunspots, and made the very interesting observation "faculae frequently appear in streaks roughly at right-angles to the direction of the sun's rotation". This perhaps anticipates the north-south direction of photospheric sector boundaries.

Bartels hoped that the use of additional solar indices might clarify the problem, but he found that the solar indices were so highly correlated among themselves that they did not yield independent evidence. A similar problem arose in analysis of spacecraft observations of the various solar wind parameters with regard to producing geomagnetic activity, where again the various solar wind parameters proved to be so highly correlated among themseloves that it was difficult to separate out which, if any, of them had physical significance.

Bartels in 1932 came close to the idea of a continuous solar wind when he said "these solar observations will also help to decide whether the solar streams are nearly continuous or whether they consist of more or less separate clouds of particles which the active solar regions emit intermittently." However, after an extensive investigation of the solar structures to be associated with M regions, he concludes "terrestrial-magnetic activity reveals therefore solar influences ... recognized as such by the 27-day recurrences ... which cannot be traced in the direct astrophysical observations".

We now move 31 years later to Bartels (1963) discussion of time-variations of geomagnetic activity, indices Kp and ap, 1932-1961. What was accomplished in the intervening three decades? The conclusions of the 1932 paper were generally confirmed. It is pointed out that no month ever passes without at least a few quiet days. The largest number of quiet days occurs not at the minimum epoch of the sunspot cycle, but during the ascending part.

Bartels returns to an old question "At the maximum of solar activity, equinoxes and solstices do not differ with respect to the percentage of quiet intervals -- a fact which might be quoted to speak against the solar origin (inclination of the solar axis of rotation) of the semi-annual wave in geomagnetic activity, and in favor of the equinoxial explanation (inclination of the earth's axis). Equinoxes and solstices would then not differ in the relative number of solar gas clouds sweeping across the earth, but mainly in the effect of these clouds on the geomagnetic disturbance, which would be stronger in the equinoxes, when the earth's magnetic axis, gyrating around the axis of rotation, with the system of radiation belts, stands more or less perpendicular to the direction of the oncoming clouds. This is a tentative explanation; however, whatever might be the physical reason, the new statistical fact ... should help to find it". I think this is a good example that if statistical analysis can establish definite, pertinent facts then the theory will be not far behind.

An example of the perversity of nature, or to put it in another way, the considerable variation that may occur in a short interval of years, is found in Bartels noting that "the last years, 1958-1961, in which satellites provided data on density variations of the high atmosphere, exhibited the semi-annual wave in magnetic activity particularly badly".

Bartels notes that "the Kp-index is a planetary measure of geomagnetic activity characterizing conditions in the auroral zones and outside. The fact that some activity may occur in high geomagnetic latitudes even in times with Kp = 0, had already been pointed out by J. Olsen in the individual disturbances recorded at Godhavn (Greenland), at only 10° distance from the geomagnetic axis pole". Only later was it recognized that the polar geomagnetic activity is a separate system, and that the polarity of the interplanetary magnetic field can be reliably inferred from examination of the daily variation of polar geomagnetic activity.

Next Biermann, Chapman and Parker moved us into the modern era. From analysis of a small aberration in comet tails Biermann concluded that the comets were flowing through a corpuscular medium having a radial velocity away from the sun of several hundred kilometers per second. He thus came close to the observed solar wind velocity, but over-estimated the solar wind density by about an order of magnitude because the interaction between the solar wind and the comet tails was stronger than first anticipated. Chapman calculated that the extended solar atmosphere would have a large thermal conductivity and would thus be very hot at great distances from the sun, but he was thinking in terms of a static atmosphere. Chapman's description of his results to Parker led to the well-known theoretical description of the solar wind. The initial discussion took place at a swimming pool in Chicago, a fact that does not surprise anyone who knew Sidney Chapman. An interesting controversy arose immediately when Chamberlain described a solar breeze theory in which the coronal expansion would be subsonic. Some fairly vigorous discussions were finally settled by direct spacecraft observations. Apparently the solar breeze theory described a perfectly respectable astronomical object, but not the sun.

In the discussion of the modern era I plan to not cite names and references, in the hope of keeping a few friends. In his latest book John Kenneth Galbraith (1975) has a pertinent comment "The importance to be attached by a historian to a paper written by himself is a troublesome matter and one on which anything but extreme modesty must invite skepticism".

Mariner-II made the first continuous observations of the solar wind during several rotations. It found a continuous solar wind with a quiet time velocity of 350-400 km per second, and established observationally the existence of high speed solar wind streams at times of recurrent M disturbances. The initial paper did not show or discuss interplanetary magnetic field observation because at this time each principal investigator tended to interpret only his own observations. The present trend toward coordinated attacks on physical problems by all investigators seems a very healthy one.

Mariner-II reported very large velocities in the high speed streams which were not observed during the several following years. It began to seem that the large velocities observed by Mariner II might be somewhat dubious, until in recent years in the decline of the sunspot cycle similar high speed streams were finally observed.

The interplanetary magnetic field observed by Mariner-II had two sectors. These were discussed by pointing out that the magnetic flux from a single active region or sunspot could spread out and fill an entire sector under reasonable assumptions. With the advantage of observed solar wind velocities, the Mariner-II experimenters followed the solar wind back to its source on the sun, but the M region was still a mystery, no solar structure could be associted with the source region.

The IMP-1 spacecraft at the end of 1963 also observed continuous solar wind containing high speed streams. Each stream was contained within a single magnetic sector. The four sector structure observed by IMP-1 was also independently observed in the diurnal variation of cosmic rays by investigators in Japan. The observed interplanetary sector structure was shown to be similar to the structure of the photospheric magnetic field as observed at Mt. Wilson Observatory. The Unipolar Magnetic Regions previously discussed by the Babcocks fell within a solar sector. Again, as had earlier been pointed out by Bartels, by observing near the earth we may learn about solar structure.

Comparison of the observed interplanetary magnetic field with the photospheric field observed at several solar latitudes led to a photospheric sector structure having boundaries in the the north-south direction. We may compare with Bartel's earlier comment that faculae tend to stream out in the north-south direction. Faculae have also been used to deduce the solar polar field variations during several past sunspot cycles.

Another of the interesting controversies concerned whether or not solar active regions were the source of geomagnetic activity. Those who did not favor active regions developed the "cone of avoidance" picture in which the strong magnetic fields over active regions shielded them from having interplanetary effects. The discussion of this problem depends on establishing the correct transit time from sun to earth, and also on a careful distinction of sporadic from recurrent geomagnetic activity. When spacecraft established an approximately four-day transit time, recurrent activity was associated with weak corona and quiet intervals with bright corona. This anticipated the latest results, but was a matter of controversy at the time.

Mariner II investigators established an average linear relationship between the geomagnetic activity index Kp and the velocity of the solar wind. The IMP 1 investigators confirmed this and established a linear relation between Kp and the magnitude of the interplanetary magnetic field, and also showed that southward interplanetary field was more geomagnetically effective. These subjects were pursued by several subsequent authors, but the inter-relations between the various interplanetary quantities tended to confuse the issue, just as a few decades earlier the inter-relations between the various solar indices confused attmepts to establish the solar source of geomagnetic activity.

As the transfer of energy from the solar wind to the magnetosphere has been shown to depend upon the direction of the interplanetary magnetic field it was attempted to explain the semi-annual variation of geomagnetic activity as a result of the semi-annual variation of the probability of observing a southward directed interplanetary magnetic field. This explanation, however, predicts Universal Time variations other than those that are observed, and recent investigations suggest that both the observed semi-annual and Universal Time variations of geomagnetic activity result simply from the varying size of the magnetosphere. Because the size of the magnetosphere depends on the strength of the geomagnetic field at the subsolar point and because that quantity varies as a function of the angle between the dipole axis and the direction of flow of the solar wind, the size of the magnetosphere is smallest when the dipole is perpendicular to the solar wind flow direction, i.e. at the equinoxes.

Recurrent energetic particles were sometimes found within sectors and were interpreted as accompanying M region events. This continued over many months and even a few years, providing evidence of continuous acceleration. The terrestrial consequences of such energetic particles may not yet be fully understood, particularly as there may be some important regions of the energy spectrum that have not yet been adequately observed.

The early considerations of Chapman and Ferraro have deepened into our detailed understanding of the magnetosphere, magnetic tail, radiation belts, etc. These have been extensively reviewed elsewhere and will not be considered in the present work.

Our long search for solar M regions may be coming to a conclusion with the discovery of coronal holes -- first by Waldmeier and later by a few alert investigators using rocket photographs. A coronal hole appears to be a region with open (to the interplanetary medium) magnetic field lines and a low density and temperature coronal plasma. The sporadic rocket observations have been much enhanced by the continuous observations by Skylab and now probably by ground-based observations. The Skylab Workshop appears to be revealing a fascinating large-scale order and evolution in the coronal holes and, therefore, probably in the M regions, but since the Workshop has not yet finished we cannot include this in our history.

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