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Solar Terrestrial Relationships

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ABSTRACT. The identification of moderate geomagnetic activity with various solar regions has been discussed in the light of the long sequences of annual variation (30 to 50 solar rotations) obtained from the analysis of geomagnetic activity of the low sunspot activity periods 1920—24, 1930—34, 1940—44 (no long sequences) and 1950—54 and solar axial hypothesis. On the basis of these identifications it is shown that the geomagnetic activity can broadly be grouped in three heads—(1) Intense geomagnetic storms, (2) disturbed M-storms and (3) quiet M-storms.

Various features of these geomagnetic storms are qualitatively explained from the focussing of solar-ion streams taking account of the local and general solar magnetic field. It is found that the streams emerging from the solar regions of large magnetic field may get dispersed, while they may come out in the form of concentrated streams from quiet solar regions which do not possess large magnetic fields. Further qualitative explanation for the formation of coronal plumes near the sunspots and of coronal streamers around the sunspot minima have also been given.

1. Introduction

It is generally believed that the Earth and specially its upper atmosphere is affected by the particles coming from the Sun which give rise to geomagnetic storms and aurorae. Direct evidence of these radiations has been put forward by Meinel (1951, 1952), Gartlein (1950, 1951), and Vegard (1952). From the study of $H\alpha$–line in auroral spectrograms, Meinel indicated a maximum limit for the velocity of impact about 3200 km/sec with a mean velocity of 450 km/sec for the protons.

Recently Bennett (1955, 1958) has developed a theory for magnetic storms and aurorae through the magnetic self focussing of such solar corpuscular streams. However, he has not taken into account the general and local solar magnetic fields. On the other hand Alfvén (1955, 1958) has propounded an electric field theory of magnetic storms and aurorae. In his theory he takes into account the external magnetic field which remains 'glued' to the highly conducting matter of the beams. Alfvén's electric field theory is in good accord with the observed effects of geomagnetic storms on cosmic rays (Forbush decreases) which are difficult to explain on Chapman and Ferraro Theory. Recognizing the importance of magneto-hydrodynamics in cosmical problems, we, in Section 5, consider the effect of an external magnetic field on the focussing of solar ion streams *specially in the neighbourhood of Sun's atmosphere.* It is found that corpuscle streams emanating from the active centres of the Sun disperse and do not get focussed while the streams from quiet solar regions may do so. In Section 6, it is shown that the effect of general and local magnetic fields of the Sun on corpuscular stream is qualitatively in good agreement with the observed solar terrestrial relationships as discussed in Section 4. A physical picture has also been proposed to explain the formation of coronal streamers near the sunspot minimum and that of coronal plumes in the neighbourhood of sunspots. Earlier in Sections 2 and 3 annual variation of geomagnetic activity and the association of M-region with various solar features has been discussed.

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2. Annual variation of Geomagnetic Activity and *M*-Regions

Bartels (1932) first investigated the relation between geomagnetic storms and the visible features of the solar disc. Using monthly mean of geomagnetic activity he found that these storms show for the high, the medium and the low sunspot activity a six-monthly periodicity with maximal disturbances in the months of March and October. He, however, failed to obtain significant correlation of sunspots, bright or dark flocculi or faculae with geomagnetic activity for the period 1928—30, and attributed this geomagnetic activity to some hypothetical regions of the Sun. These regions are known as *M-regions* and are supposed to emit continuously corpuscular radiation for long periods.

It was generally believed that after about seven or eight recurrences the recurrent storm sequences terminate and the *M*-regions responsible for these storms become inactive. However, Naqvi and Bhargava (1954) reported that the *M*-regions are very much longer lived than hitherto supposed. The recurrent type of geomagnetic activity, after remaining well marked for a few rotations, diminishes to such proportions that it can no longer be classified as storm. Furthermore, after a few 27-days recurrence of rather low activity, the storm-like character appears again and the continuity of the sequence is maintained. After making several improvement on the work of Naqvi and Bhargava (Naqvi and Tandon 1955, Tandon 1956 a, b), the recurrent geomagnetic activity has been extensively analysed for the four periods of low sunspot activity 1920—24, 1930—34, 1940—44 and 1950—54 (Tandon 1957). It was found that recurrent geomagnetic storms last much longer, about 30—50 solar rotations, show annual variations and that the predominant effect of the *M*-regions is obserable on particular dates separated from one another by an interval of 27days. These conclusions are, however, valid only for the period of low sunspot activity. A suggested probable cause for the annual variation of geomagnetic activity is the axial hypothesis

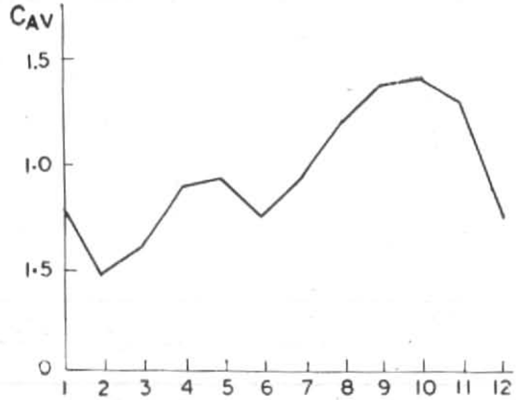

Fig 1. Plot of monthly mean C–fig. value for A–sequence of 1950-54 (based on period Jun 1950-May 1954)

The numerical numbers 1 to 12 correspond to the months Jan to Dec respectively

which also gives some clue to the position of the *M*-region on the solar disc.

The main results obtained in the above analysis are summarised in Table 1 wherein we have given for the particular sequence (eight in number) the dates of beginning, the dates of ending, number of recurrences, months of maximum and minimum activity and the periodicity of the sequence. From this table it is clear that the *M*-regions show some tendency to a 22-year cycle. It is also apparent that the *M*-regions belonging to the period 1920—24 and 1930—34 were favoured by the southern solar hemisphere while those of 1950—54 were favoured by the northern solar hemisphere.

Figs. 1 to 3 represent the typical curves for A, B and C sequence respectively and represent broadly the features associated with them. Here we have plotted the monthly mean C-fig. value for the particular sequence. If in a particular month for the year two storms of the particular sequence fall, the mean of the two C-fig. values has been taken to represent the activity of the month. The numerical numbers 1 to 12 correspond to the months January to December respectively.

3. Identification of *M*-Regions

Several attempts have been made to identify these *M*-regions on the basis of the visible

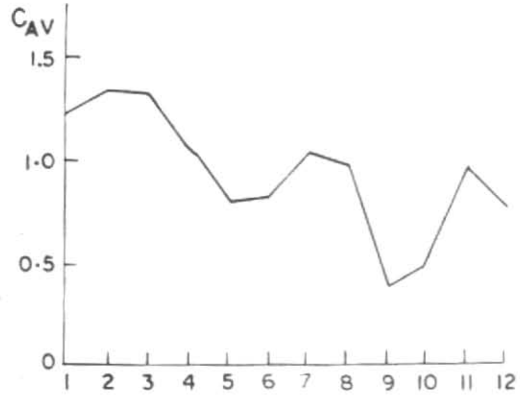

Fig. 2. Plot of monthly mean C-fig. value for B-sequence of 1950–54 (based on period Jan 1951-Dec 1953)

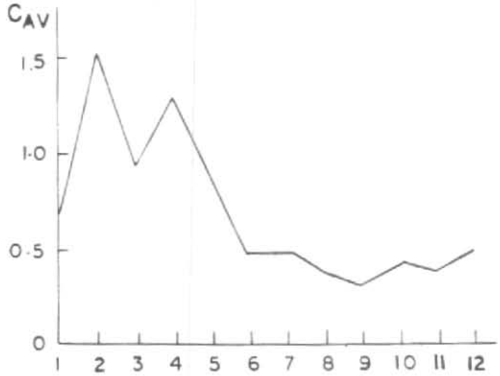

Fig. 3. Plot of monthly mean C-fig. value for C-sequence of 1930–34 (based on period Jan 1930-Dec 1934)

The numerical numbers 1 to 12 correspond to the months Jan to Dec respectively

features occurring in the solar corona and on the solar disc but no one-to-one correspondence has yet been found.

Wulf and Nicholson (1948, 1950) and Richardson (1951) have associated the *M*-regions responsible for the moderate geomagnetic activity with the appearance of the bright hydrogen and calcium flocculi on the east limb of the solar disc. Such identifications are not tenable since the ultra-violet theory for the development of geomagnetic storms does not explain most of the storm features.

In some communications Newton (1943, 1944) and Denisse (1952, 1953) suggested that some magnetic storms may be associated with active centres having large and frequent flares. In our opinion these regions may not be identified with *M*-regions since flares are very short lived phenomenon but can account for other type of activity.

Tandon (1956 a) has discussed the identification of *M*-regions proposed by Maxwell (1952) with a decaying sunspot group having an intense radio emission in the metre wave band. He found that the *M*-region responsible for the A_1-sequence cannot be identified with a coronal region overlying a sunspot group.

We shall now discuss in the light of annual variation of geomagnetic activity, the identification of *M*-regions with various solar features as proposed from time to time.

According to Allen (1944), the *M*-regions seem to avoid regions within 40° (which is equivalent to 3 days of the Sun's synodic rotation) of sunspot groups, which may even suppress the activity of the existence of *M*-regions. Recently, Pecker and Roberts (1955) have also come to the same conclusion from an independent analysis. They postulated that the disturbed solar regions form a cone of avoidance of the order of 30°—40°.

Allen further pointed out that the coronal streamers seem to have a number of features in common with the *M*-regions. For instance the maximum development of the coronal streamers occurs in the equatorial regions of the Sun about one or two years before the sunspot minimum and hence they may be identified with *M*-regions.

During the total eclipse of 25 February 1952, von Klüeber (1952) photographed a long coronal streamer from the equatorial region (P.A. 70°) at the east limb. This streamer lies in the northern solar hemisphere. Assuming that the streamer was situated exactly at the east limb on 25 February 1952, it was due to pass the central meridian of the Sun by about 3 March 1952. By 5 March *M*-storm sequence commenced over the Earth and recurred over several rotations of the Sun. If the corpuscular stream responsible for the *M*-storm activity leaves the Sun along the coronal streamer radially (while passing through the central meridian) the above observation indicates a transit time of about two days or so from the sun to the earth. The analysis of 1950—54 period (Tandon 1956, 1957) indicates that the storms related to coronal streamer observed at the eclipse of 25 February 1952 do not belong to any of the four sequences. Further, since this streamer lies in the northern solar hemisphere and keeping in view the fact that the streams get more and more focussed as they proceed from the Sun towards the Earth, this streamer should not give rise to a sequence which begins from the month of March. However, if one may assume that the streamer was not at the east limb but was nearer to the central meridian of the Sun on 25 February 1952, one can possibly associate it with the *A*-sequence of 1950—54 period which have been favoured by the *M*-region belonging to the northern solar hemisphere.

Kiepenheuer (1947, 1952) ascribed the activity of the *M*-region to the increase in filament area near the CMP. However, in view of the relationship with coronal streamers suggested by Allen, he considered that the activity of the *M*-region may be attributed to the coronal streamers lying above the filament. But Das and Bhargava (1953) could not find any connection between the *M*-region activity and any long-lived filament. More recently, Bell and Glazer (1954 a) have pointed out that they too do not find any physical connection between the coronal streamers and the *M*-regions. These findings based on only a few observational data are, however, not conclusive.

There seem to be strong grounds to believe that *M*-regions have a coronal origin. The *C*-regions—those small areas of the coronal associated with the brightening of the green

TABLE 1

S. No.	Period	No. of sequences	Designation of sequence	Approximate date of		No. of recurrences	Month of activity		Periodicity	Latitudes of *M*-regions
				Beginning	Ending		Max.	Min.		
1	1920–24	One	B	22-12-21	15-6-23	20	Mar	Sep	Annual	Below 7·2° S
2	1930–34	Three	A	1-8-32	15-11-34	31	Sep	Mar	Annual	Above 7·2° N
			B	26-1-31	28-4-34	44	Mar	Sep	Annual	Below 7·2° S
			C	16-1-30	1-5-34	58	Feb (Pri.) Apr (Sec.)	Sep (Pri.) Mar (Sec.)	Annual	About 4·8° S
3	1940–44	Zero	—	—	—	—	—	—	—	—
4	1950–54	Four	A	19-6-50	16-6-54	54	Sep	Mar	Annual	Above 7·2° N
			B	1-1-51	14-5-53	32	Mar	Sep	Annual	Below 7·2° S
			A_1	15-6-50	15-1-53	35	Sep	Mar	Annual*	Above 7·2° N
			B_2	2-1-50	1-5-53	45	Mar	Sep	Annual*	Below 7·2° S

*These sequences apparently show six-monthly periodicity with maximum activity in the month of March as well as September and minimum in the months of December and June. Amongst the two maxima one is more pronounced. In fact these sequences should show the maxima and minima as indicated in the table if the two streams responsible for these sequences would not have superposed with each other.

coronal line at λ 5303 Å–were considered by Waldmeier (1939) as identical with M-regions. He found that M-regions set in one day after the CMP of the C-region. Similar results were obtained by Shapley and Roberts (1946), Trotter and Roberts (1952) and Müller (1953). In the later communications Waldmeier (1946, 1956) suggested that the regions of high coronal intensity, the regions of more prominence activity and the regions associated with coronal streamers which occur in spot free area, should all represent Bartels M-regions.

On the other hand, Bell and Glazer (1954 a, b; 1956) have associated the recurrent magnetic storm with the regions of weak coronal line (λ 5303 Å) intensities located on the same side of the solar equator as the Earth. Further, they found that CMP of regions of weak λ 5303 Å corona tend to be followed 1 to 3 days later by above average index or by disturbed geomagnetic condition. On the contrary CMP of regions of strong corona tends to be followed 1—4 days later by diminished K_p. Tandon (1956 a) has also shown that the A-sequence is mostly associated with regions of weak coronal line intensities. In a recent communication Bell and Glazer (1956) have associated respectively the A- and the B-sequences with regions of weak corona in northern and southern solar hemisphere. Both these regions of weak green line emission persists, substantially unchanged through the life time of the geomagnetic sequences and show no annual variation. The relative stability of these two areas of weak λ 5303 Å corona and the clear waxing and waning of the two apparently associated sequences of geomagnetic storms, present strong support for an identification of M-regions with regions of unusually weak emission in the corona in the favourable solar hemisphere. If these conclusions are correct then it can possibly explain the exact 27-days recurrence tendency, as observed by us from the differential rotation of the Sun.

In a recent paper Babcock and Babcock (1955) have associated the most prominent "Unipolar" Magnetic (UM) region (heliographic latitude 15° N) with the most predominent 27-days recurrence sequence of the year 1953 and also with the region of weak coronal line (λ 5303 Å) intensity overlying this UM-region. Tandon (1956 a) has also considered the identification of this UM-region and found a close association with A-sequence of 1950—53 period. He concluded that there is a large probability of identifying M-regions with these newly observed UM-regions.

Recently Simpson, Babcock and Babcock (1955) have shown that there is a close connection of this UM-region of 1953 with (i) time of maximum primary cosmic ray intensity as measured by neutron detectors and an ionization chamber and (ii) with the recurring geomagnetic storms—the magnetic storms being most pronounced about 3 to 4 days after both the CMP of the UM-region and the time of maximum cosmic ray intensity. On the other hand, Wood (1956) who independently studied the magnetogram records of Babcock and found that except in one case considered by Babcock and Babcock and by others the UM-region in general do not give unique agreement with recurrent type of geomagnetic activity: Babcock (1957) is not in favour of Wood's analysis. Tandon (1961) analysed the cosmic ray and geomagnetic data for the period 1950—54 and found that the cosmic ray data for meson intensity at Huancayo and Cheltenham do not show any significant and consistent increase at the CMP of the UM-region reported by Babcock and Babcock. Further since these UM-regions do not last the duration of our long sequences, we are also not quite sure about the association of the UM-regions with M-sequences. Thus we conclude that further observation over a long time interval will be required before any association with UM-regions can be established conclusively.

Tandon (1961) has also shown that the sequences A, B and A_1 of the period 1950—54 (see Table 1) are accompanied by an increase of 0·3—0·4 per cent in cosmic ray intensity after about 2—3 days when the magnetic storm is over, *i.e.*, when C-figure values go below 1·0. However, sequence B_1, does not show such increases. Further, there is no substantial decrease in cosmic ray intensity around zero day indicating thereby that the streams responsible for such storms do not possess large magnetic fields as is expected from the identification of these sequences with low coronal line regions. The increase might be associated with a secondary source of cosmic radiation in the outer Van Allen Belt.

4. Classification of Geomagnetic Storm

From the study of geomagnetic activity one can distinguish two fundamentally different types of geomagnetic storms. Storms of the first type are intense, are associated with sunspots, follow flare by about one day, have world wide sudden commencement and show no recurrence after 27 days. They generally last for several days and show a moderate rise in frequency after CMP of the active regions with a maximum on the fifth day of CMP. These storms are generally associated with intense radio noise. Becker and Denisse (1954) have studied these storms in details and concluded that the regions associated with these storms show maximum corpuscular activity after about 3 days of the CMP. Thus we conclude that these storms do not possess 'cone of avoidance.' Further these storms appear to follow the sunspot cycle in frequency of occurrence.

The storms of second type known as *M*-storms are of a more moderate intensity, are independent of large sunspots and flares, begin gradually, show strong tendency to recur with a period of about 27 days and are generally unaccompanied by intense radio noise. They reach their maximum development one or two years before the sunspot maximum. These storms whenever associated with sunspots or other disturbed solar regions show the presence of a 'cone of avoidance' or in other words they show a marked decrease in frequency of occurrence after central meridian of sunspots with a minimum around fourth day of CMP. Some of the moderate storms or long sequences at the time of sunspot minimum which continue for the duration of about 30 to 50 solar rotations show their maximum development on day +3 after the CMP of a weak λ 5303 Å coronal line regions and hence do not possess a 'cone of avoidance'. These coronal line regions which show their maximum development around sunspot minimum were found to be fairly stable for about 2 to 4 years. Thus we can distinguish the two types of *M*-region activity and having marked 27-days recurrence tendency, *viz.*,

(*a*) *The disturbed M-storms*—These storms are generally associated with active solar region, *e.g.*, isolated spotgroups, intense λ5303 Å coronal line region etc and possess a 'cone of avoidance.' The period of recurrence fluctuates by about ±1 or ±2 days around the 27-days periodicity ; and

(*b*) *The quiet M-storm*—These storms are associated with quiet solar regions, *e.g.*, weak coronal line regions, prominences etc and do not possess 'cone of avoidance.' They generally occur near the sunspot minimum and form long sequences lasting as long as 50 solar rotations. The period of recurrence for these sequences is found to be exactly 27 days. Further they are unaccompanied by radio noise.

To summarise, the geomagnetic storms can broadly be grouped as —

(*i*) The intense storms

(*ii*) The moderate storms or *M*-storms

(*a*) The disturbed *M*-storms

(*b*) The quiet *M*-storms

5. Focussing of Solar Ion Streams

In this section we investigate the effect of a general magnetic field H on the solar ion streams. Following Bennett (1955) let us assume that the corpuscular streams which first emerge from the Sun consist of an electrically almost neutral mixture of fast positive ions and fast electrons moving along together at about the same velocity. These streams possess a magnetic field, H, which remains 'glued' to the corpuscles on account of very high conductivity of the stream. We further assume that each kind of particle in the stream has distributions in velocity and in radial distance from the axis which are approximately uniform along the stream at any distance and which are symmetric about the same axis at all times. No restriction will be imposed on the radial variation of these distributions with time. The ions and electrons may initially each have any distribution in velocity component parallel to the axis, each such distribution may be divided into a large number of sub-distributions which consist of all the particles of one kind in the stream having the velocity component parallel to axis in a small interval of such velocity component. The various sub-distributions are mixed with each other in space but not necessarily in uniform proportions because each sub-distribution may have a radial distance from that of the other which initially is different from that of the other sub-distribution. Each sub-distribution is supposed to continue to be symmetric about the axis while its radial distribution may vary with time.

The expression for the virial of Clausius in cylindrical co-ordinates (see Appendix) becomes—

$$\frac{1}{4}\frac{d^2I}{dt^2} = N\psi + \tfrac{1}{2}(q^2 - i^2/c^2) + m \qquad (1)$$

In this equation

$$I = \sum_{\alpha} \int_0^{\infty} m_{\alpha} r^2 \rho_{\alpha}(r)\, 2\pi r dr$$

=the moment of inertia per unit length of the stream

N=the total number of particles per unit length of the stream

ψ=the mean kinetic energy of the particles due to the transverse component of velocity

$$q = \sum_{\alpha} e_{\alpha} \int_0^{\infty} \rho_{\alpha}(r)\, 2\pi r dr$$

= he total charge per unit length of the stream

$$i = \sum_{\alpha} e_{\alpha} u_{\alpha} \int_0^{\infty} \rho_{\alpha}(r)\, 2\pi r dr$$

=the total current in the stream of unit length and

$$m = \sum_{\alpha} \frac{e_{\alpha}}{2c} \int_0^{R} \mathbf{r}(\mathbf{V}_{\alpha} \times \mathbf{H})\, \rho_{\alpha}(r)\, 2\pi r dr$$

= he polarised electric field energy per unit length of the stream

Here e_{α} is the charge on each particle of the α^{th} sub-distribution, m_{α} the mass of such a particle in that sub-distribution, ρ_{α} the numerical density of particles in that sub-distribution and u_{α} the axial component of velocity of particles $\mathbf{V}_{\alpha}$ in that sub-distribution.

It then follows that the condition for the beam to get focussed is—

$$d^2I/dt^2 < 0 \qquad (2)$$

that is,

$$i \geqslant i_c = c\,(2N\psi + q^2 + m)^{1/2} \qquad (3)$$

Thus the beam will get focussed if the total current i of the stream exceeds the critical value i_c. If $\mathbf{H}$=0, m=0 and we obtain Bennett's expression. The same condition is also obtained when the velocity and magnetic field are in the same direction. If m is small, the condition (3) may be satisfied and hence the beam may get focussed. Further, it is evident from condition (3) that in the neighbourhood of active center of the Sun, m will be relatively large and hence the magnetic field will disperse the corpuscles from the stream and the stream may not get focussed in the neighbourhood of coronal regions where the magnetic field of the active centers decreases considerably.

The above results are physically quite obvious. When $H=0$, the equation (1) expressed in an integrated form, represents the fact that a plasma stream tends to be expanded by pressure or by any unneutralized charge in it, but is contracted when an electric current flows down it because of the Maxwell tension in the lines of magnetic force produced by the current (*cf.* the theory of pinched discharge). The introduction of a magnetic field inside the stream will add an additional pressure—the magnetic pressure, and will thus oppose contraction. When magnetic pressure becomes very much larger, which will happen around the sunspots on account of their very large magnetic field, the cylinder will try to expand to keep itself in equilibrium—the result expected from condition (3) for very large values of m.

6. Discussion of results

Let us now assume that the corpuscular streams are being ejected by various solar regions in the form of neutral ionized streams of very high electrical conductivity from some unknown magneto-hydrodynamic phenomena. These streams are thus accompanied by general and local solar magnetic fields which remain 'glued' to the stream particles on account of very high electrical conductivity and they (the corpuscles) are responsible for magnetic storms and aurorae.

The magnetic field, H, which remains 'glued' to the particles decreases rapidly from the active solar centers towards the Earth. Cowling (1953) has pointed out that the magnetic field above the active center will vary as the fourth root of the particle density and hence its value decreases considerably near the coronal regions. It is also known that the corpuscular streams emitted from active centers disperse radially while crossing the chromosphere and corona due to their thermal energy. This radial dispersion will increase in the presence of magnetic field (general solar magnetic field and the magnetic field of the particular solar region, *i.e*, the so-called local magnetic field) provided the current i of the stream is less than its critical value i_c given by equation (3). This increase in dispersion will be referred to as 'magnetic dispersion'. Now we shall consider the bearing of condition (3) on solar terrestrial relationships as discussed in Section 4.

First we consider disturbed M-storms. These storms are generally associated with disturbed solar region which possess large magnetic fields, often of very complicated structure. These magnetic fields will give rise to large magnetic dispersion which may continue to a distance of about one solar radius or so. Afterwards the focussing is likely to set in since the magnitude of the magnetic field at such large distances decreases considerably, on account of low density. Such a process of magnetic dispersion and subsequent focussing will lead the particles to remain away from the active centres or in other words the streams form a 'cone of avoidance', as postulated by Pecker and Roberts (1955) from storm observations, with the concentration of corpuscles at the edges of such cone. This process is roughly represented in Fig. 4. The edges of this cone will appear in the form of equatorial plumes in the sunspot zones at the time of solar eclipses with their centers not coinciding exactly with spot centers but will appear to come from the adjacent areas of the spots. This fact was observed by Allen (1944) in the coronal photographs. Further the width of cone will change because it depends on the magnitude of the magnetic dispersion or in other words on the magnitude of magnetic field of the region. Therefore, it will be smaller in the beginning and the end period of the active centers when the magnetic fields are not so large. Hence the period of recurrence may not coincide exactly with the sun's synodic period of rotation and can possibly depart by ± 1 or even ± 2 days from it.

On the other hand quiet M-storms are identified with low coronal line region (Bell and Glazer; Tandon) which do not possess high magnetic fields and hence will not be accompanied by large magnetic dispersion. The corpuscular streams from these regions will come out in the form of focussed beams with centers as the centers of these regions and the period of recurrence will remain stationary as they are not accompanied by a 'cone of avoidance'. Further since the particles are coming more or less axially, they have remote chance of collisions and hence of radio emission. As far as the author is aware these *M*-storms are not accompanied by enhanced radio noise.

The intense magnetic storms (as has already been pointed out) are generally associated with large sunspot groups, bright chromospheric eruptions etc. These solar features possess large magnetic fields having very complex structures, and also give rise to enhance radio emission. The features associated with the intense magnetic storms can, however, be understood physically as follows.

Consider two active centers situated quite close to each other in the same solar hemisphere. Each of these centers will magnetically disperse the streams emanating from them. These radially dispersed streams will interact with each other and their particles are likely to undergo collisions. These collisions in the presence of a magnetic field will give rise to enhanced radio noise. Further each stream is expected to form a 'cone of avoidance' of its own in the absence of interaction but on account of the interaction the particles will enter in the regions where a 'cone of avoidance' is expected to form and thus the particles will not possess a 'cone of avoidance'. The large sunspot groups or chromospheric eruption etc can be regarded as consisting of a large number of small active centres separated from each other by small distance. Such regions, according to above discussion, will give rise to enhanced radio noise and will not be accompanied by a 'cone of avoidance'. These results were obtained by Becker and Denisse (1954) from the analysis of geomagnetic activity associated with spot groups emitting radio noise. Since these spot groups or eruptions are not stable for a long time, the geomagnetic effects will not show 27-days recurrences.

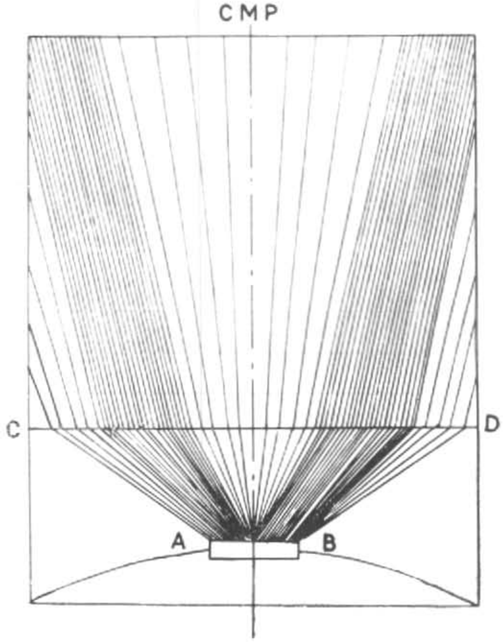

Fig. 4. Figure illustrating qualitatively the effect of magnetic field on the focussing of solar ion stream and the formation of 'cone of avoidance'

[AB is the active solar region which is assumed to possess large magnetic field. The central line gives the central meridian passage (CMP) of the active center. CD represents the location in the solar atmosphere from where the focussing will set in]

Now, we shall present a physical picture for the formation of coronal streamers specially around the sunspot minimum. Since the critical current (i_c) depends sensibly on the magnetic field, the particles will disperse near sunspots at the time of sunspot maximum and will not come out in an isolated stream on account of the large number of sunspots and of large magnetic fields. On the other hand the corpuscles will come in isolated streams, being unaccompanied by large magnetic dispersions, near the sunspot minimum since the disturbed regions are small in number and the magnetic field in the spot zone is 10^3 times smaller at the time of sunspot minimum as compared to that of sunspot maximum. This clearly reflects on the formation of coronal streamers specially around sunspot minimum. The actual formation of coronal streamers can possibly be attributed to the presence of two sunspot groups which are separated from each other by about 60° in heliographic longitude. As it has already been shown that the edges of a 'cone of avoidance' form an angle of about 30°—40° with the center of the spot group, the edges of the two cones formed by these spot groups will meet at great distances and will give the appearance of white light coronal streamer at the time of total eclipses. This explains the extension of coronal streamers to a distance of several solar radii.

7. Conclusions

It is evident from the above analysis that there exist three different types of geomagnetic storms against two as hitherto been supposed. Most of the features of geomagnetic storms and the presence of three distinct classes can very well be accounted for qualitatively by the solar-ion streams possessing 'frozen' in magnetic fields (local and general solar magnetic fields). So far the effects of 'frozen' in fields are considered near the Sun's atmosphere; the implication of these results on the theory of geomagnetic storms will be considered in a subsequent publication. However, we must emphasize that more data are needed, before one can reach to any definite conclusion regarding the identification of M-regions with various solar features. The presence of annual variation and the proposed identification of M-regions need further careful thought during the coming sunspot decline when more data will be at our disposal.

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Appendix

The force exerted on any particle with charge e_1 and velocity $\mathbf{V}_1$ by any other charge e_2 with velocity $\mathbf{V}_2$ separated from e_1 by a displacement $\mathbf{r}$ in the presence of magnetic field $\mathbf{H}$ is given by

$$\mathbf{E} + \frac{e_1}{c}\left(\mathbf{V}_1 \times \mathbf{H}\right) + + \frac{1}{c^2}\mathbf{V}_1 \times (\mathbf{V}_2 \times \mathbf{E}) \qquad (1)$$

where $\mathbf{E}$ is the Coulomb electrostatic force between charge particles in the direction of $\mathbf{r}$. The second and third terms are not necessarily in the direction of $\mathbf{r}$. Let us assume that the transverse component of velocity are of a lower order of magnitude than the axial component of the velocity so that the main contribution is from the axial component.

If e_α is the charge on each particle in the α^{th} subdistribution, ρ_α the numerical density of the particles in that subdistribution which is a function of radial distance r from the axis and u_α is the axial component of velocity of particles in that subdistribution, then the force (radially away from the axis) which the particles in the α^{th} subdistribution exert on any particle say one in κ^{th} subdistribution having charge e_κ and velocity $\mathbf{V}_\kappa$ (with axial component u_κ) in the presence of a magnetic field $\mathbf{H}$, is given by

$$\frac{e_\kappa}{c}\left(\mathbf{V}_\kappa \times \mathbf{H}\right)_{\text{radial}} + + \left[\frac{2\, e_\kappa\, e_\alpha}{r}\left(1 - \frac{u_\kappa\, u_\alpha}{c^2}\right)\right] \times \times \int_0^r \rho_\alpha\; 2\pi\, r\, dr \qquad (2)$$

and the total force acting on any particle of κ^{th} kind is —

$$F_\kappa = \frac{e_\kappa}{c}\left(\mathbf{V}_\kappa \times \mathbf{H}\right)_{\text{radial}} + + \sum_\alpha \left[\frac{2\, e_\kappa\, e_\alpha}{r}\left(1 - \frac{u_\kappa\, u_\alpha}{c^2}\right)\right] \times \times \int_0^r \rho_\alpha\; 2\pi\, r\, dr \qquad (3)$$

which is obtained by summing over all the sub-distributions in the stream.

The probability that a charged particle of the κ^{th} kind is within a velocity range δv_r at v_r, δv_φ at v_φ and δv_z at v_z at a point, r, ϕ and z will be written as

$$f_\kappa\,(r,\ \phi,\ z\,;\ v_r,\ v_\varphi,\ v_z)\, dv_r\; r\, dv_\varphi\, dv_z \qquad (4)$$

These velocities refer to the κ^{th} kind of particles. When the function (4) is non-Maxwellion (as has been assumed for our subdistribution) it may be a function of the position co-ordinates, only. The velocity of the mass motion of the κ^{th} kind of particles has components given by

$$\left.\begin{aligned} v_{ro} &= \iiint v_r\, f_\kappa\, dv_r\; r\, dv_\varphi\; dv_z \\ r v_{\varphi o} &= \iiint r\, v_\varphi\, f_\kappa\; dv_r\; r\, dv_\varphi\, dv_z \\ v_z &= \iiint v_z\, f_\kappa\, dv_r\; r\, dv_\varphi\; dv_z \end{aligned}\right| \qquad (5)$$

The velocity of any kind of particles may be considered to consist of the velocity of mass motion at the position of that particle plus the velocity of that particle relative to the velocity of mass motion. Let the latter have components ξ, $r\eta$ and ζ so that

$$v_r = v_{ro} + \xi\,;\quad r v_\varphi = r\, v_{\varphi o} + r\eta\,;$$
$$v_z = v_{zo} + \zeta \qquad (6)$$

In the stream considered here, radial symmetry has been assumed so $v_{\varphi o} = 0$ and the longitudinal uniformity has been assumed so $\frac{dv_{zo}}{dz} = 0$. The mean square velocity of a particle of κ^{th} kind relative to velocity of mass motion has parts in the r and ϕ directions

$$<\xi^2{}_\kappa>_{Av} = \iiint v_r^2 f_\kappa dv_r\ r\,dv_\varphi\ dv_z - (v_{ro})^2$$

$$<\eta^2{}_\kappa>_{Av} = \iiint v_\varphi^2 f_\kappa dv_r\ r\,dv_\varphi\ dv_z$$

$$<\zeta^2{}_\kappa>_{Av} = \iiint v_z^2 f_\kappa\ dv_r\ r\ dv_\varphi\ dv_z - (v_{zo})^2 \qquad (7)$$

If we write the mass of a particle of the κ^{th} kind as m_κ, the moment of inertia of that particle about the axis is $m_\kappa r^2$ and

$$\frac{1}{4}\frac{d^2}{dt^2}(m_\kappa r^2) = \frac{1}{2} m_\kappa v_r^2 + \frac{1}{2} r m_\kappa \frac{d}{dt} v_r \qquad (8)$$

where $m_\kappa \frac{d}{dt} v_r$ is related to the force F_κ exerted on that particle (in the radial direction in the streams assumed here) by

$$r m_\kappa \frac{d}{dt} v_r = \mathbf{r}\ F_\kappa + m_\kappa r^2 v_\varphi^2 \qquad (9)$$

Substituting for F_κ from equation (3), integrating and summing over all particles in unit length of stream and writing the moment of inertia of all particles in unit length of stream as I, we get

$$\frac{1}{4}\frac{d^2I}{dt^2} = \sum_\kappa \left\{ m_\kappa v^2_{ro} + \frac{1}{2} m_\kappa <\xi_\kappa>^2{}_{Av} + \frac{1}{2} m_\kappa r^2 <\eta_\kappa>^2{}_{Av} \right\} \int_0^R \rho_\kappa\, 2\pi r dr + \sum_\kappa \frac{e_\kappa}{2c} \int_0^R r\,(\mathbf{V}_\kappa \times \mathbf{H})\ \rho_\kappa\, 2\pi\, r\, dr +$$

$$+ \sum_\alpha \sum_\kappa e_\alpha e_\kappa \left(1 - \frac{u_\alpha u_\kappa}{c^2}\right) \int_0^\infty \int_0^R \rho_\kappa (s) \times 2\pi s\, ds\, \rho_\alpha (r)\, 2\pi r\, dr \qquad (10)$$

where R is the radius of the cylinder. It can easily be seen (*c.f.* Bennett) that

$$\sum_\alpha \sum_\kappa \int_0^\infty \int_0^R \rho_\kappa (s)\ 2\pi s\ ds\ \rho_\alpha (r)\ 2\pi r\ dr = \frac{1}{2} \sum_\alpha \sum_\kappa N_\alpha N_\kappa = \frac{1}{2} N^2 \qquad (11)$$

where N_α is the total number of particles of the α^{th} kind per unit length of stream, and N is the total number of particles per unit length of stream. Writing ψ for the mean kinetic energy of particles due to transverse component of velocity we get

$$\frac{1}{4} \frac{d^2I}{dt^2} = N\psi + \frac{1}{2}(q^2 - i^2/c^2) + m \qquad (12)$$

This is the required expression for the virial of Clausius. Here

$q = \sum_\alpha e_\alpha N_\alpha$

= the charge per unit length of stream

$i = \sum_\alpha e_\alpha u_\alpha N_\alpha$

= the electric current in the stream and

$m = \sum_\alpha \frac{e_\alpha}{2c} \int_0^R \mathbf{r}\,(\mathbf{V}_\alpha \times \mathbf{H})\ \rho_\alpha (r)\ 2\pi r\ dr$

= the polarized electric field energy per unit length of the stream.