# Solar cycle and geomagnetic activity : A review for geophysicists. Part I. The contributions to geomagnetic activity of shock waves and of the solar wind

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SUMMARY. In this paper, written for geophysicists, we review a new classification of the geomagnetic phenomena established according to their interplanetary sources, namely the series of travelling shock waves occurring at random and the large scale structures of the solar wind which « corotate » with the Sun and are sources of recurrent phenomena of the geomagnetic activity.

The analysis according to the above classification of the centennial series of geomagnetic data beginning on 1868 supplies us with quite interesting results.

They concern the respective contributions to the geomagnetic activity of shock waves and of the solar wind, the separate properties of the quiet and disturbed day patterns, the identification of a genuine cycle of the geomagnetic activity, of the relationships of its separate components to the activity level of the sunspot cycle and the separate roles of the Earth's field in the magnetospheric coupling of shock waves and of wind streams respectively.

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## 1. INTRODUCTION

In this paper we review a new classification of the geomagnetic phenomena established according to their interplanetary sources, namely, on one hand, the series of travelling shock waves occurring at random and, on the other, the large scale structures of the solar wind which « corotate » with the Sun and are sources of recurrent phenomena of the geomagnetic activity (Simon, 1979 ; Legrand and Simon, 1981, 1983, 1985*a*, *b*, 1987, 1988*a*, *b* ; Simon and Legrand, 1984, 1985*a*, *b*, 1986, 1987).

In section 2, we discuss the specific properties of the geomagnetic index *aa*, its close correlation with the solar wind velocity and the shock « signature » of the sudden storm commencement (SSC).

We describe, in section 3, our method of analysis of the distribution in a Bartels diagram of the centennial series of both the daily *Aa* indices and the SSCs. We identified, on one hand, a series of shock events distributed at random, on the other, three categories of recurrence patterns generated by a slow wind flow, by high speed wind streams and by fast fluctuating wind streams respectively.

According to our data analysis, in section 4, we point out the scarce contribution of the shock events, the new roles in the geomagnetic activity of the slow wind flow and of the fast fluctuating wind streams respectively. We establish the definite differences taking place between the topologies and the latitudinal distribution of the large scale interplanetary structures both of the slow wind and of the moderate and high velocity wind respectively.

Finally each of the categories of the wind stream activity has a separate distribution during the solar cycle, a proper cyclical behaviour and a close link, in phase and in intensity, with the activity level itself of the sunspot cycle.

Therefore, according to this analysis, there are two separate solar cycles, the sunspot cycle and the solar wind cycle, which are roughly in phase opposition but which are closely linked in intensity.

In section 5, we discuss two separate categories of phenomena, the latitudinal distribution of auroras and the semi-annual variation of the geomagnetic activity, which both suggest that the magnetospheric coupling of shock events and of wind streams does not depend on the same way upon the Earth's magnetic field.

All these results will be used in the study of the solar sources of the wind stream activity (Part II).

## 2. THE GEOMAGNETIC DATA

The geomagnetic data we used form a homogeneous series, established by Mayaud (1973), both of *aa* indices, resulting from a monitoring of the geomagnetic activity at two antipodal stations and of storm sudden commencements (SSCs) listed according to 3 collections of original records. The series begins on 1868 (fig. 1).

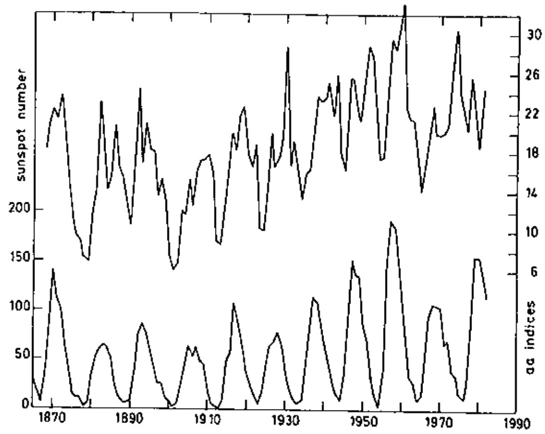


Figure 1

*The centennial series of geomagnetic indices aa (annual averages) (top, right scale) and the relevant series of annual relative sunspot numbers (bottom, left scale). On annual averages, the aa index is proportional to the velocity at the power 2.25 of the solar wind sweeping the Earth (see fig. 2) and the sunspot number to the area of the sunspots on the disk (Waldmeier, 1966).*

The *aa* index is derived from the trihourly *K* indices obtained at two stations of middle latitude located at the antipodes, in England and in Australia respectively. Let us remember that the *K* index is scaled from the recorded variations of the geomagnetic field from which has been removed the regular daily variation *Sr* generated by the X and UV solar emissions. Therefore the *aa* index is a pure magnetospheric index.

At mid-latitude, the geomagnetic activity is sensitive both to the auroral phenomena associated to the particle precipitations (substorms and auroras) which are at the origin of the *AE* polar activity and to the equatorial ring current, source of the *Dst*. Consequently the *aa* index is an integral index of that magnetospheric activity.

At two antipodal stations, the diurnal effects are out of phase. Therefore the daily *Aa* index, i.e., the average of the daily set of the 8 trihourly indices, is free from any diurnal effect. In addition, according to Mayaud (1973), the *aa* index is closely correlated to the planetary *am* index : the correlation coefficients reach 0.994 and 0.998 for the monthly and the yearly averages respectively. Therefore the *aa* index is a planetary magnetospheric index.

According to Svalgaard (1977), as result of the study of more than 9000 trihourly intervals, there is a close correlation between the trihourly indices *am* and the solar wind velocity measured *in situ* on Earth orbiting satellites (fig. 2). He found that

$$am = (0.7 \pm 0.05)\, V_0^{(2.25 \pm 0.05)}$$

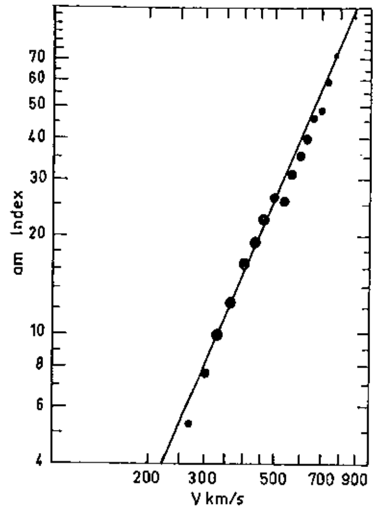


Figure 2

*Average dependence of the trihourly am index on the solar wind velocity V according to a set of 9000 three-hourly intervals from 1965 to 1973. For an average over 100 three-hourly intervals the error is of the order of 10 % of the average values (Svalgaard, 1977).*

with $V_0 = V/100$. This result applies also to the *aa* indices. Consequently most of the time the *aa* indices can be used in order to study the temporal distribution at the Earth's orbit of the solar wind velocity.

The SSCs are transitory equatorial disturbances sensitive to the crossing of an interplanetary shock wave by the magnetosphere (see for instance a review by Smith, 1983).

## 3. SELECTION OF GEOMAGNETIC DATA ACCORDING TO THEIR INTERPLANETARY SOURCES

We analysed as a function of the solar rotation (27.3 days) our two sets of about 40000 daily *Aa* indices and of about 2740 SSCs respectively according to their distribution in a Bartels diagram of a total length of about 1500 « 27-day rotations » (for details, see Legrand and Simon, 1981 and 1985*b*).

We considered two classes of geomagnetic phenomena : a transitory component, generated by the transit at the Earth of a series of travelling shock waves, and a « wind stream activity », resulting from the crossing by the Earth orbit of the large scale « wind velocity structures » of the interplanetary medium.

Effectively the temporal distribution of the geomagnetic activity can be used in order to distribute our series of geomagnetic data among the two above categories. On one hand, the geomagnetic disturbances following a SSC and distributed at random should be the result of the transitory events generated by the sunspot activity ; on the other hand, the recurrence patterns should be generated by those of the steady wind streams which both corotate with the solar rotation and have a life duration longer than several solar rotations.

We took also into account the differences occurring between the time profiles of two categories of geomagnetic storms. On figure 3, we see a typical

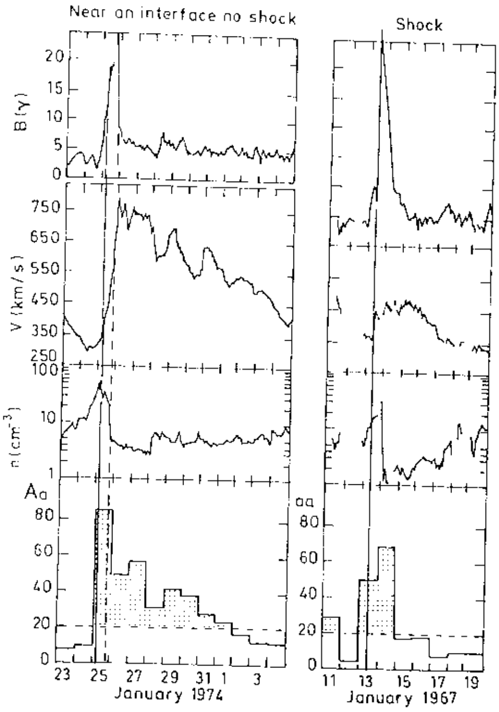


Figure 3

*During the transit at the Earth of a high speed wind stream (left) and a shock wave (right), the distribution, from top to bottom, of the interplanetary magnetic field intensity* **B**, *of the solar wind velocity V, of the plasma density n and of the daily geomagnetic index Aa (interplanetary data according to Burlaga and King, 1979). The storminess occurring above the quiet-day level of* 20 nT *is shaded. The duration of the storm generated by the shock transit is rather short (2 days) in comparison with the one of the storm occurring during the Earth orbit crossing of the high speed wind stream (8 days). In this last case, the storminess associated to the magnetic field compression (solid and broken vertical lines) is followed by some storminess associated to the high velocity of the solar wind. After the shock transit, by lack of high wind velocity the level of activity remains below* 20 nT.

sample of the interplanetary and geomagnetic data related to the crossing of a wind stream by the Earth orbit and to the terrestrial transit of a shock wave respectively. One can notice that in this last case (on right) the geomagnetic disturbance is an event of a quite short duration (~ 2 days). The relevant storm selected from the 20 nT quiet day level (see section 3.2 below) is limited to the duration of the shock transit shown by the field intensity increase, and its time profile reaches a level far above the one expected from the Svalgaard correlation with the wind velocity (fig. 2). In the case of a wind stream crossing (on left), during 1 or 2 days the disturbance is not related to the wind velocity but to the definite field intensity increase of the stream-stream interface. This first step is followed by a several days interval during which the level of activity is closely correlated to the wind velocity. Finally the duration of the storm depends entirely upon the size of the wind stream.

### 3.1. Shock activity

We selected as shock activity the series of storms which follow a SSC, are of short duration (2-3 days), generate a definite increase of the activity level above the surrounding level occurring in the Bartels diagram. Finally, in this set of SSC-storms, we selected as shock events only those which have not any recurrence property. According to the above criteria, two separate series of SSCs are not associated to a shock activity. On one hand, a few SSC storms of longer duration are included in recurrence patterns which shows definitely that they are generated by corotating wind streams. On the other, a quite large number of SSCs are not followed, during the next 3 days, by any definite « jump » of the activity level. They occur in recurrence patterns either of quiet days or of fluctuating activity (see below) but, as a matter of fact, not any noticeable change in the time profile of the activity in progress can be associated to the shock transit. Among the 2740 SSCs of the centennial series, only 45.5 % are followed by a definite storm fulfilling all the above criteria. They form the series of transitory events most likely generated by the sunspot activity.

### 3.2. « Wind stream » activity

In this case the time profile of the geomagnetic activity depends upon the spatial distribution, at the Earth orbit, of the large scale structures of the solar wind velocity.

Let us recall the geometrical parameters involved in this problem. In that case the distribution of the relevant geomagnetic indices in a Bartels diagram is dependent upon several items :

1. Upon the solar rotation of 27.3 days since the wind structures are generated by corotating solar wind sources having a longitudinal distribution. During each rotation the Earth passes through the series of separate wind structures which take place on its orbit. As a consequence of the difference in the time transit, the longitudinal distribution of the wind velocity might slightly change from the Sun to the Earth.

2. Upon the heliolatitude of the Earth just because, at the distance of the Earth's orbit, the wind structures have also a latitudinal distribution. As a result of the tilt by 7.2° of the solar axis on the ecliptic plane, the Earth (fig. 4) reaches an heliolatitude of 7.2° North at the beginning of September and 7.2° South at the beginning of March. Therefore any wind activity occurring close to the equinox has, in the interplanetary medium, a source situated at a latitude of about 6-7°, and the one occurring close to the solstice, an equatorial source.

According to the figure 4 among these wind structures only those in an equatorial belt of 14.4° width are « scanned » twice a year by the Earth orbit. Therefore the shape of the recurrence patterns shows the shape, at the Earth's orbit, of the stable large scale wind structures of long duration (six months or longer). Finally, in each selected recurrence pattern, the number of indices depends upon the size of the wind structures and, according to figure 2, their distribution inside the pattern is a reliable indicator of the velocity distribution in the wind structures.

We selected as « quiet days », generated by the slow wind structures, the days during which $Aa$ is inferior to 20 nT ($V < 450\ \mathrm{km\,s^{-1}}$). This supposed « noise background » (Legrand and Simon, 1981), useful as a

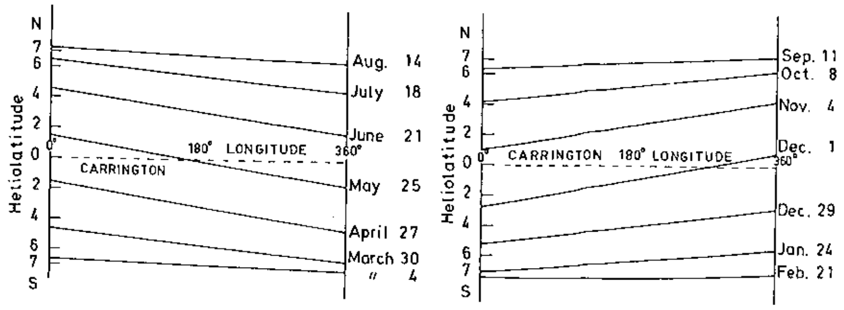


Figure 4

*Annual variation (solid line), in two separate sketchs, of the heliocoordinates of the Earth. Latitude in ordinate (left scale), Carrington longitude in abscissa (broken line). During a solar rotation, the Earth longitude decreases from 360° to 0° : consequently in these sketchs the time is increasing from right to left. The Earth orbit being in the ecliptic plane which makes a 7.2° angle with the solar equator plane, the Earth latitude is moving Northward, up to 7.2° North, during about six months (left sketch, date scale on right), and Southward, down to 7.2° South, during the following six months (right sketch). One can notice that the Earth spends more time at the highest latitudes than close to the equator.*

reference level in any study of both the shock events and the recurrence patterns of activity, as a matter of fact by itself forms recurrence patterns. However according to Mayaud (1973), only the days with *Aa* inferior to 10 nT are, with 98 % of probability, « true quiet days » : therefore among our quiet days we selected apart those last days as a series of « very quiet days ».

Therefore all the days which are not selected as « quiet days » are « disturbed days ». Those of the disturbed days which are not related to a shock event form two separate categories of recurrence patterns : the smooth and the « fluctuating » patterns.

The smooth high level patterns of the recurrent storms are formed by stable high speed wind streams in which a smooth and stable distribution of the wind velocity takes place. Their patterns have quite sharp boundaries.

The not-smooth patterns of the fluctuating activity are formed by wind streams of long duration in which there is a lack of stability in the spatial distribution of the wind velocity. Most of the time the storms have no sharp boundaries and their levels are fluctuating at the time scales both of the day and of the Bartels rotation. Up to now this storminess was supposed to depend upon the frequent occurrence of solar events : the recurrence patterns show without any ambiguity that they are a special category of the « wind stream activity ».

Therefore according to the actual shapes of the recurrence patterns we had to consider 3 separate categories of wind structures : the slow wind structures sources of the « quiet days », the high speed wind streams sources of the « recurrent storms » and the « fast » streams in which, at small scale, takes place some lack of stability of the wind velocity, sources of the « fluctuating activity ». All these streams have a life duration longer than 3 solar rotations.

### 3.3. Shock waves and solar wind during more than one century

Finally, according to these criteria concerning the temporal distribution of the *Aa* indices and of the SSCs, we carried out the selection of 4 separate series of daily indices. Therefore we could compute, for each category of geomagnetic activity, the annual sums of the relevant daily indices (fig. 5), the annual

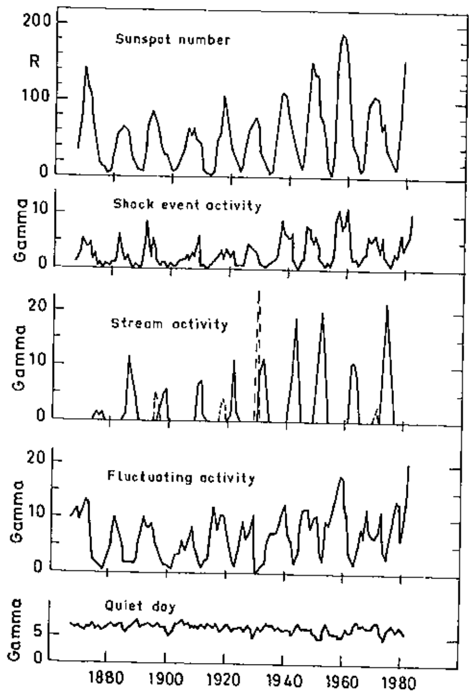


Figure 5

*From top to bottom : the annual distribution, from 1868 to 1982, of the sunspot number, of the shock activity level, of the stable high speed wind stream activity level (solid line, with a seasonal effect ; broken line, without any seasonal effect), of the fluctuating activity level and of the quiet-day level.*

distributions of the quiet days (fig. 6) and the percentages in our centennial series of the number of daily indices and, with respect to the average activity level, the percentage of the activity level of each category. They show respectively their frequency of occurrence and their average contribution to the activity level (fig. 7). On tables 1 and 2 we summarized the main properties of these separate categories as they are discussed in this paper. We completed the table 1 by

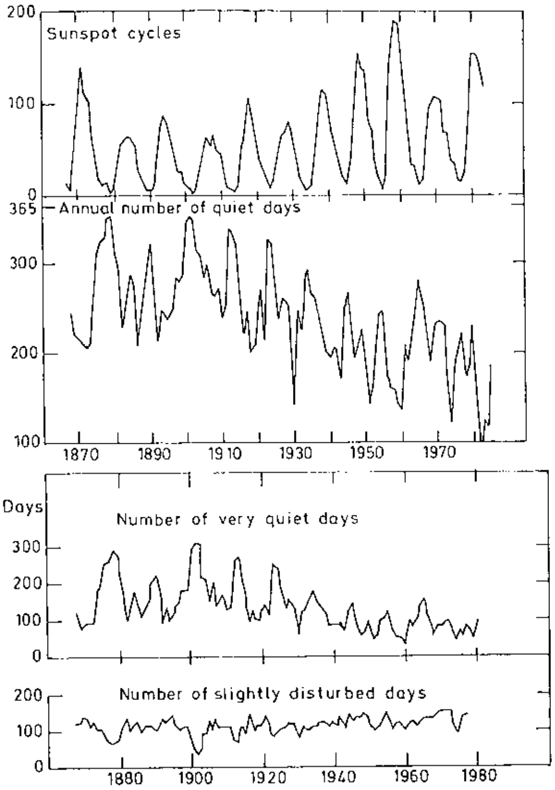


Figure 6

*From top to bottom : the annual distribution, from* 1868 *to* 1980, *of the sunspot number and of the number of quiet days (Aa inferior to* 20 nT*), of very quiet days (Aa inferior to* 10 nT*) and of « slightly disturbed days » (Aa from* 10 *to* 19 nT*). Please note the difference in the day number scales between the quiet day diagram and the following diagrams.*

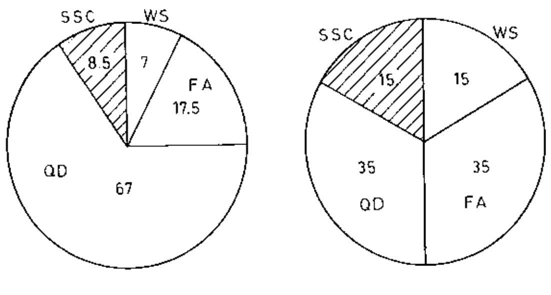


Figure 7

*Piegram of the distribution (in percentage) of the number of days (left) and of the average activity level (right) relevant respectively to the shock events* (SSC, *hatched), the high speed wind stream activity* (WS), *the fluctuating activity* (FA) *and of the quiet-day activity* (QD) *according to our analysis of the centennial series. The hatched area shows the activity generated by the sunspot activity. The fluctuating activity is the main source of storminess. Only the shock events and the high speed wind streams generate « definite » storms.*

the identification of the solar sources which will only be discussed in Part II.

In the below discussion of the solar wind activity data, we should have in mind that, as a result of our method of selection, the quiet days and the recurrent storms form 2 separate but homogeneous sets of data. In the fluctuating activity, the data sets have a wide range of levels but they concern only disturbed days. Therefore in this last case the distributions of wind velocities do not include any significant amount of « slow wind ».

In addition such are the actual distributions of the 3 concerned categories of activity, as we will have to consider only large samples of trihourly indices *aa*. For instance, 10 % of days in a year involves about 300 trihourly indices *aa*. Therefore the close correlation established by Svalgaard (1977) between the *am* indices and the wind velocity applies to all our data sets. Of course, any comparison between the « average levels » of separate series of *Aa* indices does not mean a comparison between some related « average wind velocities » but between the mean distributions, spatial or temporal, of the concerned wind velocities. We will use the figure 2 in order to identify these distributions by a « standard wind velocity » established from their « average activity level ».

## 4. SHOCK WAVE, WIND STREAM, SUNSPOT CYCLE AND CYCLE OF THE GEOMAGNETIC ACTIVITY

The main results of this analysis concern respectively the frequency of occurrence and the separate properties of the sources of the geomagnetic activity, the identification of the main components of a cycle of the geomagnetic activity and the link, in phase and in intensity, taking place between the geomagnetic and the sunspot cycles.

### 4.1. The interplanetary sources of the geomagnetic activity as from 1868

First of all, according to figure 7, the sunspot activity is not the main source of the geomagnetic activity (see also Sheeley and Harvey, 1976). The shock activity concerns only 8.5 % of the days and 15 % of the activity level. In addition, as shown on figure 5, its cyclical behaviour does not follow closely the sunspot cycle. The peaks of the shock activity do not occur at the sunspot maximum and the shape of its time profile is not the one of a sunspot curve. Consequently during 91.5 % of the time, the geomagnetic activity is under the control of the solar wind velocity : it concerns 85 % of the activity level.

A second result concerns the origin of the quiet days. As shown on figure 7, during 67 % of the time, the Earth crosses a slow wind flow which is at the origin of 35 % of the activity level. As pointed out above, the number of quiet days shows the size of the concerned slow wind structures. The comparison between the high variability of the quiet day number, on figure 6, and the quasi constant level of the sum of the quiet day indices, on figure 5, shows that the slow wind velocity is not distributed at random but that its distribution depends on the size of the slow wind structures. It means that the slow wind flows from a series of separate solar sources. One can notice that every year some slow wind structure takes place in the equatorial belt of 14.4° width scanned annually by the Earth orbit. On figure 6, by the time profile of the quiet day number, one sees that the size of the slow wind structures follows a cyclic behaviour which currently generates, around the sunspot minimum, a peak in the quiet day number. One can also note on figure 6 that, in our data set, their size currently evolves between a maximum and a minimum which both seem to have some relationship, in an inverse way, with the sunspot maximum numbers of the sunspot cycles. Finally the separate display of the very quiet days and of the « slightly disturbed days » shows that the size of the slow wind structures depends upon the one of the slower wind structures. It suggests, as we will establish in Part II, that the topology of the interplanetary slow wind structure taking place in the equatorial belt scanned by the Earth orbit has cyclic properties and that some relationship links together both the slow wind sources and the sunspot cycles.

The third result concerns the distribution, according to their solar origin, of the disturbed days. We pointed out above the rather small contribution to the geomagnetic activity of the sunspot activity. But according to figure 7 we can add two new conclusions. The main source of the geomagnetic storminess is the fluctuating activity which, in our data set, occurs during 17.5 % of the days (53 % of the disturbed days) and generates 35 % of the activity level (53 % of the disturbed level). As pointed out above (section 3.3) that activity does not generate « classical » storms : the disturbed interval does not have neither a sharp beginning nor some typical time profile. The mechanism of its solar origin will be discussed in Part II. The « recurrent storms » form a well established category of « definite storms » which is attached to the decline of the sunspot activity (fig. 5). During a few years they might generate a very high activity level but their overall contribution to the geomagnetic activity remains modest (15 %) because they concern only 7 % of the days.

### 4.2. Quiet and disturbed day patterns and wind velocity distribution

Most of the $Aa$ indices (91.5 %) form recurrence patterns. Of course the basic difference between the quiet and the disturbed day patterns is the level separating the two classes of indices. But we found two more separate properties which concern on one hand the distribution of the $Aa$ indices as a function of the pattern size and on the other their latitudinal distribution (table 1).

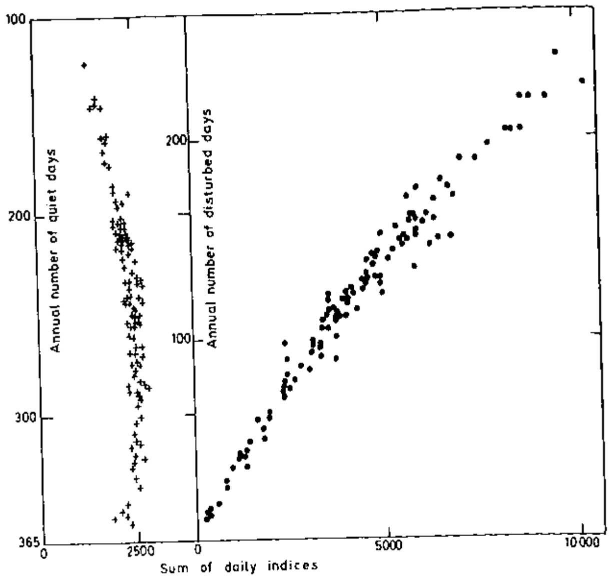


Figure 8

*Annual sums of the daily indices of the quiet days (left) and of the disturbed days (right) versus the number of related days. Please note that the two scales of the day numbers are numbered in opposite ways : therefore the two representative dots of the same year are on the same line.*

On figure 8, one can find separately the annual sums of the daily indices of the quietness (left) and of the storminess (right) as a function of the relevant number of days (please notice the opposite scales of the day numbers on the left and on the right sides).

As a consequence of the nearly constant level of the quietness sums, it is obvious that the greater the number of quiet days, i.e., the bigger the size of their recurrence patterns, the lower the average value of the quiet day indices and, of course, the lower the related standard wind velocity. For instance the average $Aa$ drops from 13 nT in the case of 120 quiet days to 5 nT in the one of 354 quiet days. According to figure 2, it means that the standard wind velocity drops from 360 to 250 km s$^{-1}$.

The distribution of the storminess sums follows an opposite law : the higher the number of disturbed days, the higher the average value of the disturbed day indices and, in case of wind stream activity, the higher the standard wind velocity. For instance the

Table 1

*Properties of the wind streams sources of quiet and disturbed days respectively.*

| Activity level | $Aa < 20$ nT | $Aa \geqslant 20$ nT |
|---|---|---|
| Solar wind velocity | $V < 450$ km s$^{-1}$ | $V \geqslant 450$ km s$^{-1}$ |
| Stream topology and wind velocity distribution | The greater the stream size, the lower the wind velocities | The greater the stream size, the higher the wind velocities |
| Peak in heliolatitude of the distribution at the Earth's orbit | Equatorial $\lambda \approx 0°$ | « High » latitude $\lambda \approx 7.2°$ |
| Solar origin (Part II) | The « slow wind sheet » a slower wind source associated to the neutral sheet | — Polar coronal holes (high speed wind streams)<br>— Unstable regions apart from the slow wind sheet (fast fluctuating wind stream) |

average $Aa$ grows from 31 nT in the case of 65 disturbed days to 39 nT in the one of 250 disturbed days. It means that the standard wind velocity increases from 520 to 650 km $s^{-1}$.

Incidentally it means that in any study of an annual set of $aa$ indices, one should have in mind that, on one side, the level of activity depends roughly upon the number of disturbed days (Legrand and Simon, 1985*a*) but, on another side, the annual level of the quiet days does not depend upon their number but it remains nearly constant.

The quiet and disturbed days patterns have also separate latitudinal distributions. According to Green (1984) (fig. 9), the peak of distribution of the quiet

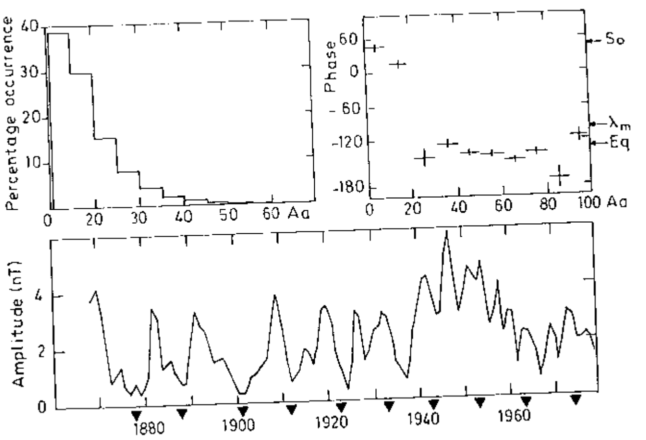


Figure 9

*Top : (left) differential frequency distribution of Aa daily indices (1868-1980) for class widths of 10 nT and (right) related seasonal effects for the same class widths from the computed phase (scale at left) of the yearly distribution and according to the annual date (scale at right). So, Eq and λm are for the dates of solstice, equinox and maximum heliolatitude of the Earth.* Bottom : *annual amplitude of the semi-annual variation of the geomagnetic activity (Green, 1984). The seasonal effect shows that the peaks of the latitudinal distribution of the slow and fast wind sources are respectively at the equator and at 6-7° of latitude but the annual amplitude shows the high degree of variability of the annual distributions.*

days occurs « at the solstice » and the one of the disturbed days « at the equinox ». Really Green does not use our selection of the quiet days, but the shift between both distributions of the $Aa$ indices takes place exactly at 20 nT, i.e., at the level separating both categories of days. Having in mind the size of the data set, about 321200 trihourly indices, the correlation established by Svalgaard (1977) with the wind velocity applies. Therefore, as pointed out in section 3.2 above, this « seasonal effect » shows a distribution in heliolatitude of the wind structures, the slow and the fast wind sources taking place respectively, in the equatorial plane and at the highest latitudes, i.e., at about 6-7° of latitude.

Finally, as summarized in table 1, the interplanetary wind sources of the quiet and disturbed days are different not only by the ranges of the wind velocity, but also by the laws of wind velocity distribution and by the average latitudinal distribution.

### 4.3. The cycle of the geomagnetic activity and its relationships with the sunspot cycle

As shown on figure 10, the shock events and these 3 categories of wind stream activity are not distributed at random during the solar cycle : they are the 4 components of a cycle of geomagnetic activity of which the 3 more important components are closely correlated, in phase and in intensity, to the activity level of the sunspot cycle. If the quiet days level (4) remains constant during the whole cycle, the recurrent storms (1) occur in opposite phase with the fluctuating activity (2), and the shock activity (3) occurs mostly during a 6-yr interval beginning on the first year before the sunspot maximum (M). Some of these

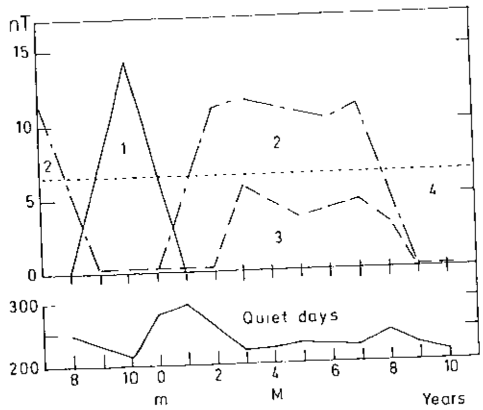


Figure 10

*Sketch of the average cyclical distribution of (top) the annual activity level in* nT *of the* 4 *selected categories of geomagnetic phenomena and of (bottom) the annual number of quiet days.* 1 : *High speed wind stream activity (solid line),* 2 : *fluctuating activity (broken and dotted line),* 3 : *shock activity (broken line),* 4 : *quiet days (dotted line). Abscissa are years, with* m *and* M *for sunspot minimum and maximum years respectively.*

activities show a definite cyclical behaviour. The recurrent storms (1) reach their peak of activity few years before the sunspot minimum (m – 3, m – 2) and the peak of the quiet day number (bottom) occurs close to the sunspot minimum (m, m + 1). Therefore the time profile of the geomagnetic cycle has 3 separate sources (fig. 10 and table 2) : the high speed wind streams which supply a peak of activity a few years before the sunspot minimum (m), and both the fluctuating activity and the shock activity which are distributed quite irregularly during a 5-6 yr interval.

In addition, as shown on figure 11, a series of close correlations has been established between, on one side the sunspot maximum number (M on fig. 10) and, on another side, the levels of the recurrent storms averaged during a 4-yr interval at the end of the sunspot cycle (1 on fig. 10), the peak of the quiet day number occurring near the sunspot minimum (bottom on fig. 10) and the sum of the fluctuating activity occurring during a sunspot cycle (2 on fig. 10) (Legrand and Simon, 1981 ; Simon and Legrand, 1986, 1987). Therefore the geomagnetic and the sunspot cycles are closely linked together since the activity level of the sunspot cycle, occurring on the year M, is closely correlated to the key parameters of

Table 2

*The components of the cycle of the geomagnetic activity.*

| Categories | Identification in Bartels diagrams | Distribution among the phases of the sunspot cycle | Relationship with sunspot cycle activity |
|---|---|---|---|
| Quiet days | Recurrence patterns of $aa < 20$ nT | A nearly constant annual level $aa \approx 6$ nT<br>A peak in the annual quiet day number at m or m + 1 | Both the sum (from m − 4 to M + 3) and the peak of the quiet day numbers are inversely proportional to $R$ max (M) |
| Fluctuating activity | Recurrence patterns of disturbed days with a fluctuating level at the time scales of day and of rotation | From m or m + 1 to M + 3 or later | Sum (during the full cycle) closely correlated to $R$ max (M) |
| Recurrent storms (High speed wind stream activity) | Smooth high intensity recurrence patterns of more than 3 rotations | With equinoctial properties from M + 3 to m or m + 1 | Sum (during a 4 yr interval) closely correlated to $R$ max (M) |
| | | Without any seasonal property from M + 1 to m − 2 | Not any link at all with any sunspot activity |
| SSC-Storms (Shock event activity) | A series of definite SSC-storms of short duration (2-3 days) without any recurrence property | Events occurring in any phase<br>Severe storms ($Aa > 100$ nT) grouped from M − 1 to M + 4 for 88 % of them | « Loose » correlation, if any, of the sum (during a cycle) with $R$ max (M) |

N.B. $R$ max stands for Sunspot Maximum Number occurring on the year M.
m and M stand for the years of Sunspot minimum and maximum respectively as described in figure 10.

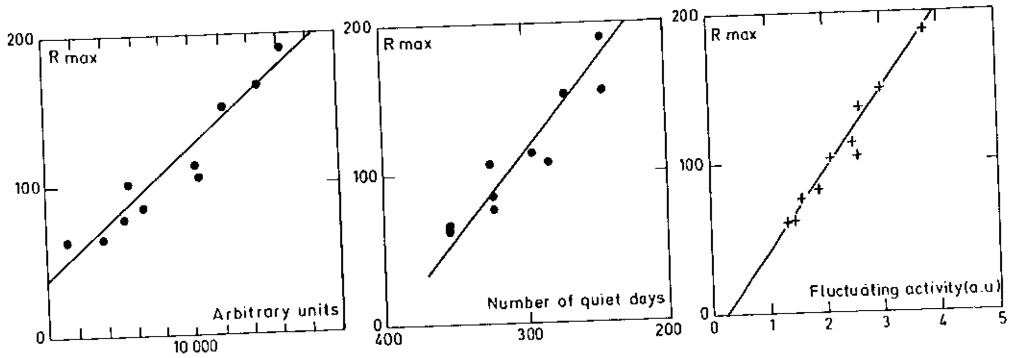


Figure 11

*During the* 10 *solar cycles under study (left) the average level of recurrent storms during a* 4 *year interval, (center) peak number of quiet days and (right) cyclical sum of fluctuating activity* versus *the relevant sunspot maximum number* (M *on fig.* 10).

every component, including the slow wind activity, of the wind activity cycle but with separate delays : 5-6 yr for the high speed wind streams, 3-4 yr for the maximum quiet day number and no delay at all for the fluctuating activity. The distribution of the shock activity does not show such a close link.

We should point out that all the above close correlations take place between parameters controlling the cyclic behaviour of the phenomena, on one side, the level of the sunspot activity cycle and, on the other, the levels of the separate components of the wind activity cycle. Therefore they cannot expect the occurrence of any close link between the annual levels of any category of geomagnetic activity and some relevant annual sunspot number of the sunspot activity in progress (Simon, 1979 ; Legrand and Simon, 1985*b* ; Simon and Legrand, 1986, 1987).

Finally this quite complicated scheme of relationships occurring between the various components of the geomagnetic activity and the sunspot cycle that we will discuss in more detail in the Part II is an explanation for the current lack of understanding in this domain. On one hand, it shows (fig. 10) that both the geomagnetic and the sunspot cycles have the same duration, about 11 years, but that they are in phase opposition with a delay of about 6 years of the sunspot activity cycle on the relevant geomagnetic activity cycle. On the other, it suggests that the largest part of the geomagnetic activity, namely the solar wind activity, is closely related to another component of the solar cycle that the sunspot activity itself, a topic that we will discuss in the Part II.

## 5. SHOCK WAVE, WIND STREAM AND MAGNETOSPHERIC COUPLING

Following our analysis, two categories of phenomena are at the origin of the geomagnetic activity : a series of separate events, the shock waves, sources of separate storms, and a permanent flux of solar wind generating either more or less fast wind streams which are sources of recurrent storminess or a steady flow of slow wind which is source of the recurrence patterns of the quiet days.

It is believed that the interconnection between the southward interplanetary magnetic fields and the magnetosphere is the mechanism by which the solar wind energy is transferred to the magnetosphere and released in the form of substorms. As an additional piece of information about this problem, we would like now to discuss two separate topics which show that during a shock transit and during a wind flow the magnetospheric disturbances have separate relationships with the terrestrial field. Let us summarize some of the properties of both sources of the geomagnetic disturbances.

According to the interplanetary data, a shock is formed by a compression of the magnetic field, a simultaneous increase of the density and of the velocity of the wind which travels at a high velocity (fig. 3). According to a series of analyses (Watanabe and Kakinuma, 1984), most of them form a kind of hemispheric shell (fig. 12) and several of them have

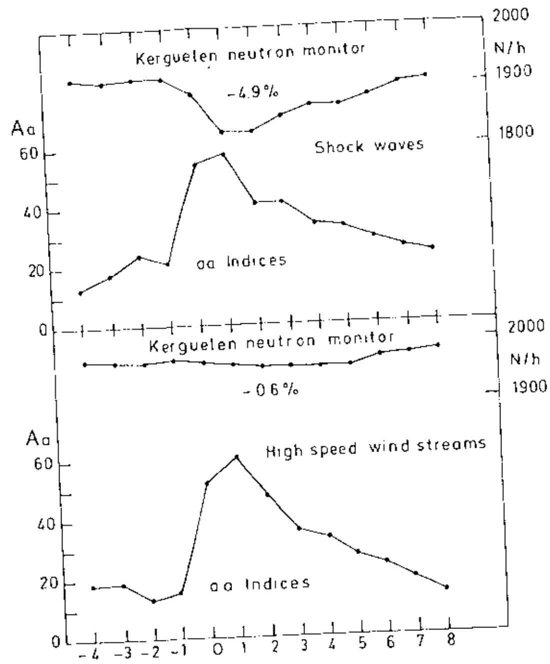


Figure 13
*Daily variation of the cosmic ray flux at Kerguelen Island (scale of neutron monitor count at right) and of the geomagnetic activity Aa (scale at left) during the Earth transit of 10 shock events of high intensity (top) and of 10 high speed wind streams (bottom).*

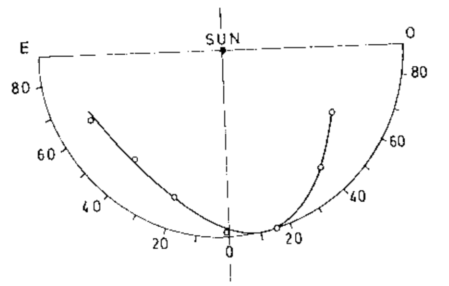


Figure 12
*Sketch of the hemispheric shell of the shock wave in the ecliptic plane (Caroubalos, 1964). The shock event is supposed to originate from the sun center.*

an oblate configuration, the latitudinal extent being smaller that the longitudinal extent. In the front of a high speed wind stream, the differences of wind velocities also generate a compression of the magnetic field (the stream-stream interface) (fig. 3) and a simultaneous increase of the density which is followed by the wind velocity increase. The stream-stream interface is a large scale structure (according to the recurrence patterns we pointed out a longitudinal extent which might reach 130-140°). Therefore both sources of geomagnetic disturbances are large scale structures of a compressed magnetic field.

However, according to figure 13, the transit at the Earth of a shock event might be the source both of a geomagnetic storm and of a Forbush effect on the cosmic ray intensity associated with an increasing particle rigidity (spectral exponent − 1) (Venkatesan *et al.*, 1982). But the Earth transit of a high speed wind stream is just the source, during the occurrence of the recurrent storm, of a smooth and weak decrease of the cosmic ray intensity associated with almost a flat rigidity spectral variation (exponent 0).

In addition as noted above the duration of the storm does not depend upon the interface transit but upon the transit of the entire wind stream itself. Both above differences are the consequences of the separate « magnetic structures » of the shock and of the stream-stream interface respectively.

Additional differences occur in the magnetospheric coupling processes. For instance during a shock event, as shown on figure 3, the magnetic field keeps a high intensity during the all geomagnetic disturbance. In the wind activity, the high intensity field occurs only during the short interval of the stream-stream interface of high speed wind streams (fig. 3), a series of events limited to the decline of the sunspot activity. Most of the time, the wind activity is in progress without any increase of the interplanetary field intensity.

Most of the studies concerning this coupling process concern « definite storms » which are very often shock events (Akasofu, 1981 ; Baumjohann and Paschmann, 1987). However as shown by the distribution of the *Bz* polarities (fig. 14), during any solar wind flow, fast and slow, this reconnection process is currently in operation. Very few works have been devoted to the study of the causes of occurrence of these southward components of the interplanetary magnetic field and of their links, if any, with the wind velocity. Tsurutani and Gonzales (1987) suggest that most auroral activity may be caused by reconnection associated with Alfvèn waves in the interplanetary medium. Eselevich and Fillipov (1988) found that, in the case of the slow wind flowing in the neutral sheet, the solar differential rotation is very likely at the origin of the rotation of the vector **B**.

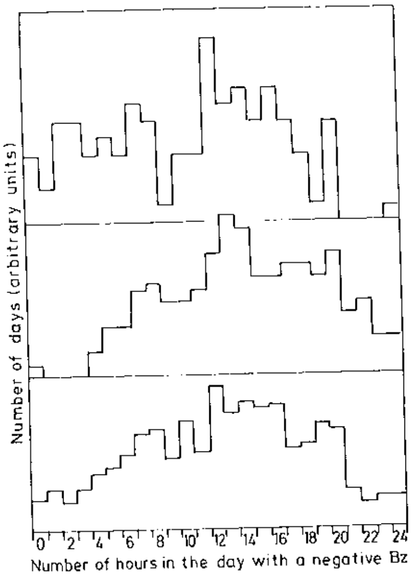


Figure 14
*Daily distribution of the number of hours with a negative Bz in a set of* 111 *quiet days (top),* 151 *disturbed days (medium), and* 616 *days including* 334 *quiet days and* 282 *disturbed days (bottom).*

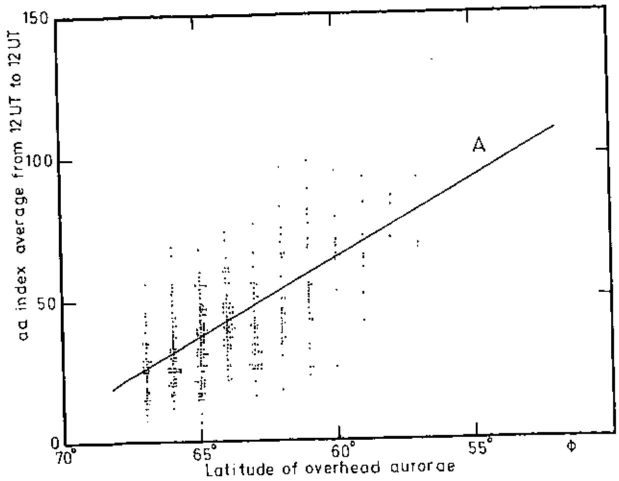


Figure 15
*Distribution,* versus *the latitude of the associated « overhead » aurorae, of the level reached by the geomagnetic activity during 374 corotating wind stream transists* (1956-1965).

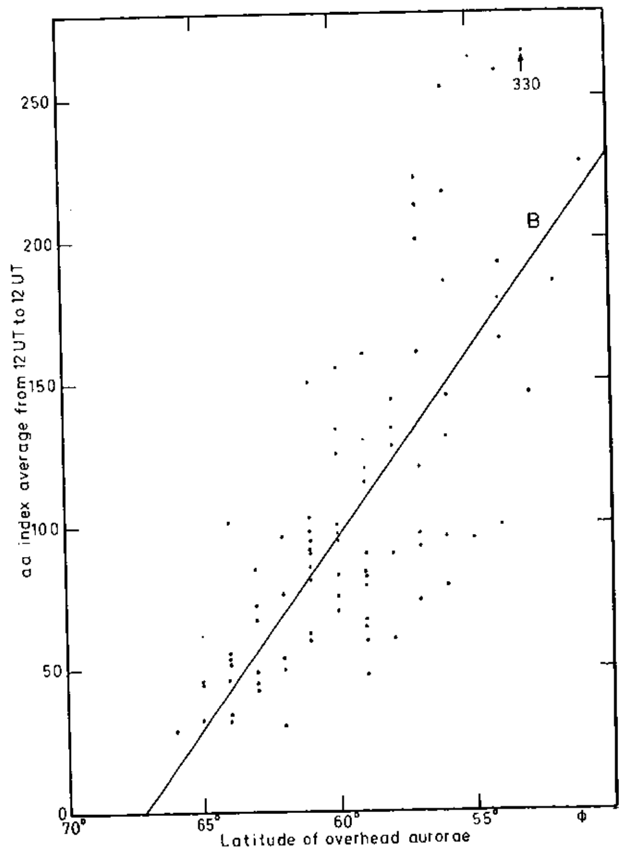


Figure 16
*Distribution,* versus *the latitude of the associated « overhead » aurorae, of the level reached by the geomagnetic activity during* 79 *shock wave transits* (1956-1965).

## 5.1. Geomagnetic activity and latitude of associated aurorae

From 1956 to 1965, throughout the entire duration of solar cycle 19, the Balfour Stewart Auroral Laboratory, in relation to the International Geophysical Year, established for the longitude of the British Isle a network of auroral observers. It comprised the stations of the British Meteorological Office and amators of the British Astronomical Association in the United Kingdom, the Faeroe Isles, Ireland and France. These observations were published in full in the review « The Observatory year Book (UK) ». Indeed, for this programme, the observers were not content to report the existence of an aurora but applied themselves to determining its latitude of appearance overhead or observing its dimensions to enable this to be calculated. We have used this unique collection of observations in order to determine the invariant latitude at which aurorae associated with solar wind streams and shock waves respectively were formed. We have thus been able to establish the invariant latitude of 453 aurorae, 374 associated with solar wind streams and 79 due to interplanetary shocks (Legrand and Simon, 1988*b*).

For each latitude of the appearance of aurorae, we have researched for the two types of events the average level of the associated magnetic disturbance during the corresponding 24 h interval (from 12 : 00 UT to 12 : 00 UT). Figures 15 and 16 give the distribution of values for each class of event so that the curve gives the average level of the associated disturbance. It shows in both cases the existence of a mean relation between the invariant latitude and the level of geomagnetic activity. Figure 17 permits a comparison between the two straight lines thus obtained. The difference in their slope indicates that the coupling of these two types of disturbance with the magnetosphere is not the same. It is admitted as shown by the data that if the wind speed in the streams never exceeds 1000 km/s, the aurorae associated with the streams never manifest themselves at the zenith at a lower invariant latitude than about 56°, whereas those associated with shock waves can reach much lower latitudes (fig. 18), as was the case on 25th September 1909 when an aurora was observed in Singapore ($\Phi = 10°$ South) during the most intense magnetic storm observed since 1868 ($aa = 546$ nT in the relevant half-day average). In addition we have

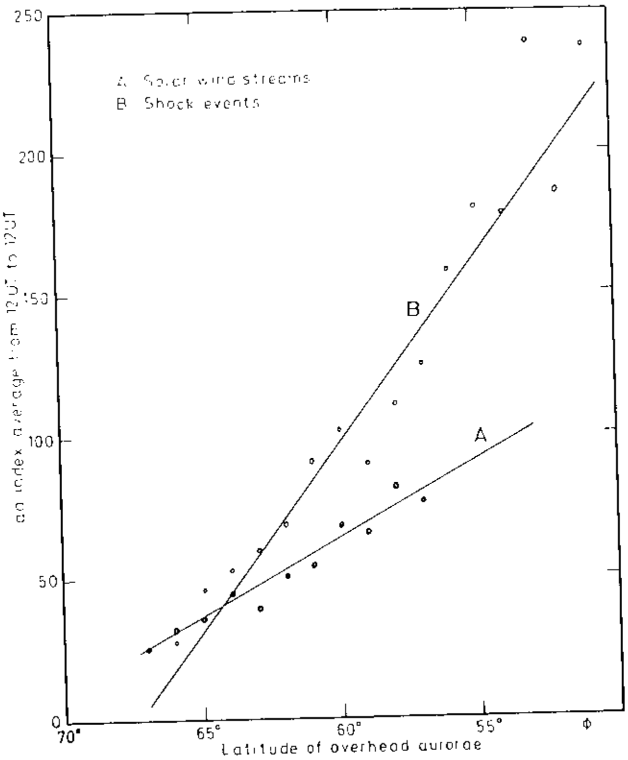


Figure 17
*Comparison between the distributions (straight lines) of the levels, averaged by latitude, reached by the geomagnetic activity during the Earth transit of corotating wind streams (black dots, A line) and of shock waves (open circles, B line).*

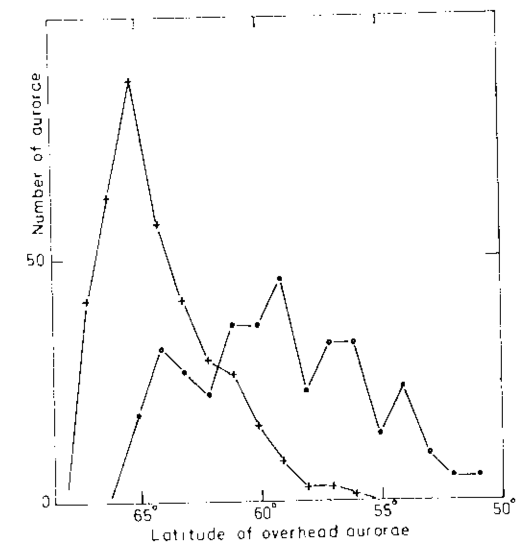


Figure 18
*Latitudinal distribution of « overhead » aurorae associated with wind stream activity (cross) and shock event occurrences (dot). Both distributions are normalized by the total number of events.*

two separate distributions of the auroral activity, the one of the stream activity centered on the latitude 65° with an extension toward the equator limited to 56° and the one of the shock activity centered on the latitude of 59-60° with an unlimited extension toward the equator.

Livesey (1985) noted this difference in expansion of aurorae towards the equator, as a result of the origin of the disturbance, while studying the evolution of auroral activity between 1962 and 1983.

From these two results we can conclude that at the same latitude, in case of a shock, the flux of particles precipitated into the ionosphere is larger (a higher level of geomagnetic activity) than in the case of a stream and this precipitation might take place at lower invariant latitude than in the case of a stream. In addition, according to our data set, in this last case the relevant storms reach higher levels than the one of any wind stream activity.

### 5.2. Seasonal effect of shock waves and wind stream activity

On figure 19, one can see the average « seasonal » effect of the indices *aa* as shown by the monthly data from 1868 to 1980. With an amplitude of about 4.5 nT, i.e., 13.5 % of the average activity level, that is, on the average, a phenomenon of small amplitude.

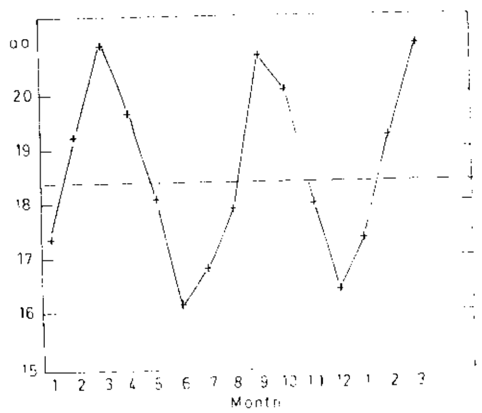


Figure 19
*According to the aa indices, monthly distribution of the geomagnetic activity between 1868 and 1980.*

According to the incidental result noted in our above analysis (section 4.2), this effect concerns the average distribution of the disturbed days. During an average month of 30.4 days we have, on the average, 10 disturbed days but, at the equinox, they are 11.8 and, at the solstice, 8.2 (see Legrand and Simon, 1985*a* for the relationship between the level of activity and the number of disturbed days). Therefore it concerns a « seasonal » distribution of a small number of disturbed days, on the average 21.5 days a year.

Two mechanisms are under discussion as the origin of this seasonal effect (see for instance Berthelier, 1976 ; Green, 1984 and Silverman, 1986).

The « equinoctial » mechanism postulates that it is the varying inclination of the Earth's dipole to the Earth-Sun line that is important. It supposes that there is a dependence of the coupling mechanism on the direction of the Earth dipole, the closest coupling occurring when the terrestrial dipole is perpendicular to the Earth-Sun line. The terrestrial dipole being tilted by 10° on the Earth axis which is itself tilted by 22° on the ecliptic plane, the equinoctial mechanism has a diurnal effect due to the daily rotation of the dipole and consequently its seasonal effect is not restricted to the dates themselves of the equinox, but the probability of a higher level of activity reaches a peak at the equinox and drops to a minimum at the solstice.

The « axial » mechanism takes into consideration the seasonal variation of the Earth heliolatitude which is a consequence of the tilt of the solar axis on the ecliptic plane. In that case, the direction of the Earth dipole does not play any role in the coupling mechanism, or if any, a minor one in comparison with the one of the spatial distribution of the solar sources themselves. Therefore they postulate that the source of the seasonal effect is the average latitudinal distribution of the solar sources of the geomagnetic activity, a distribution which is supposed to reach its peak at the highest heliolatitudes.

In addition a mechanism suggested by Russell and McPherron (1973) contains both equinoctial and axial elements. The southward *Bz* component of the interplanetary magnetic field as measured in solar magnetospheric coordinates is modulated by the tilt of the Earth's axis relative to the ecliptic pole and the tilt of the dipole axis to this rotation axis, as well as by the Sun's axis of rotation to the ecliptic pole.

As pointed out above, the number of disturbed days at the origin of this semi-annual variation is rather small and, in addition, as shown on figure 9, the distribution of the *Aa* indices is far from being Gaussian. Thus one cannot succeed to definitely separate the « peaks » occurring on 5 March or on 6 September which concern the maximum heliolatitude of the Earth from the ones on 21 March or on 21 September which concern the terrestrial phenomenon of the equinoxe itself and from the ones on 5 April and on 6 October which concern the Russell-McPherron mechanism (see for instance Green, 1984).

Consequently other ways than the date of the peak of the seasonal effect should be used in order to identify the proper mechanism of some seasonal effect. For instance Berthelier (1976) has shown that a diurnal component of the geomagnetic activity is in phase with the diurnal rotation of the Earth dipole : therefore, on the average, some equinoctial mechanism is in operation in the geomagnetic activity. According also to Berthelier (1976) the Russell-McPherron mechanism can only explain a small part, if any, of the semi-annual variation of the wind activity.

Our analysis of this long series of *Aa* indices gives the possibility of studying the separate semi-annual variations of selected categories of geomagnetic activity.

If we consider our set of shock events, their monthly distribution does not show any seasonal effect. This distribution « at random » is in agreement with the one of the SSCs and of the relevant Forbush effects (fig. 20). But if we consider separately the severe storms and the associated « low latitude » aurorae (fig. 21) they show a definite seasonal effect with a modulation of ± 80-90 %. Taking into account the quasi hemispheric shape and the interplanetary size of the shock waves themselves, the heliolatitude of the Earth cannot play a decisive role in the seasonal distribution of the shock activity. Therefore this seasonal effect shows that several items contribute together to the coupling process of the shock events. At first the southward orientation of the *Bz* component which, in our data set, occurs at the time of the

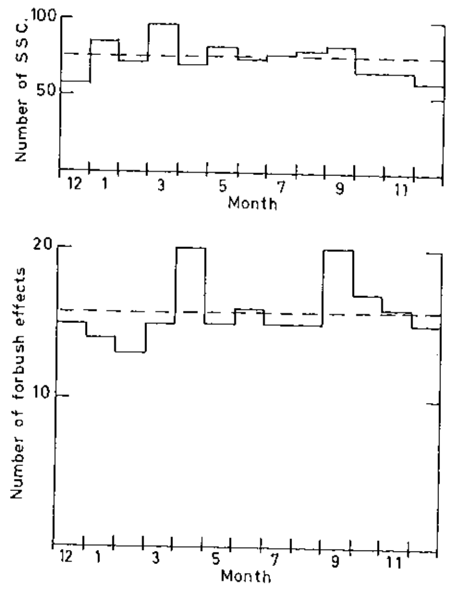


Figure 20
*Monthly distribution (top) of* 898 SSCs (1868-1905) *and (bottom) of* 191 *Forbush decreases of amplitude larger than* 3 % *recorded at the Mount Washington neutron monitor* (1955-1984).

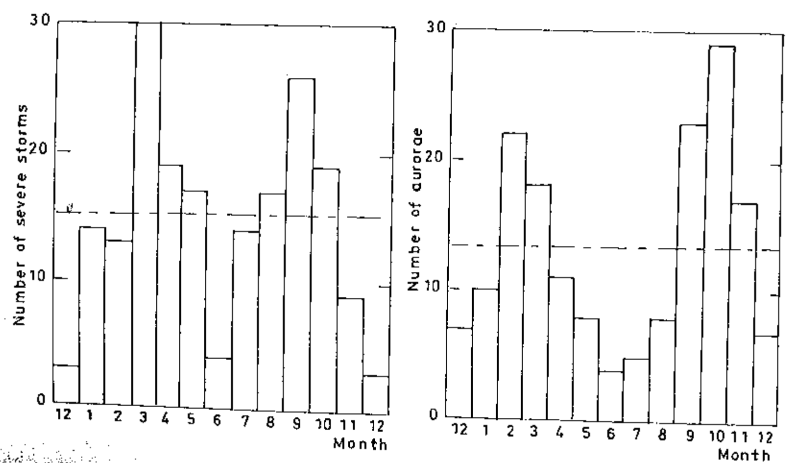


Figure 21
*Histogram of the monthly distribution (left) of* 192 *severe storms* (*Aa* > 100 nT) (1868-1980) *and (right) of* 162 *« low latitude » aurorae* ($\Phi \leq 47°$) *associated with shock events* (1716-1972).

shock transits for 45.5 % of the events. Then, depending on the equinoctial mechanism, the level of the disturbance depends upon the direction of the Earth dipole what explains the occurrence of only 15.4 % of severe storms.

The case of the wind stream activity is entirely different from this last one. At the Earth orbit the solar wind flow is a permanent phenomena intermittently disturbed (8.5 % of the time) by the shock wave occurrences. Consequently any statistical study of the geomagnetic activity concerns mostly the wind activity. Having in mind the geometrical parameters involved in the wind activity (section 3.2 above), the close correlation established by Svalgaard (1977) between the *am* indices and the wind velocity (fig. 2) suggests that the main source of the semi-annual variation of the geomagnetic activity is a latitudinal distribution of the wind velocity, i.e., that variation depends on the axial mechanism.

The analysis by Green (1984) of the distribution of the *Aa* indices confirms this hypothesis. On one hand, as pointed out above (section 4.2), the distribution of the quiet and disturbed day patterns shows separate peaks, occurring at the equator and at a latitude of 6-7°, for the slow and fast wind sources respectively (fig. 9, top). On the other, the annual amplitudes of the semi-annual variation (fig. 9, bottom) show the high variability of the annual latitudinal distribution of the slow and fast wind sources.

Our above description of a geomagnetic activity cycle and of its close link with the activity level of the sunspot cycle supplies us with a mechanism in order to explain this high degree of variability. On one side, during the geomagnetic cycle, the sources of geomagnetic disturbance are successively (fig. 10) the high speed streams and, from the sunspot minimum, both the fluctuating activity and the shock events. They have separate contributions to the semi-annual variation. For instance most of the high speed streams are at the origin of a semi-annual variation but, in few cases, an equatorial stream takes place, as on 1930, which does not generate any seasonal effect.

On the other side, these components of the geomagnetic cycles reach levels which depend separately (fig. 11) upon the activity level of a sunspot cycle delayed by 5-6 yr on the geomagnetic activity cycle. In our data set, the sunspot maximum numbers vary from 63, on 1883 and 1905, to 190, on 1957, i.e., by a factor of 3.

Therefore the latitudinal and longitudinal distributions of the wind velocity depend of so many parameters that they might explain the high variability of the semi-annual variation of the geomagnetic activity.

Of course it raises the problem of the coupling mechanism. A frozen-in magnetic field is carried in the solar wind. In the large scale wind structures, at the origin of the distribution of the various categories of geomagnetic activity, take place turbulent motions at the origin of the radio scintillation phenomena used in the interplanetary study of the solar wind. These last small scale structures are at the origin of the rotation of the *Bz* component of the field. Their relationships with the wind velocity have not been studied. Berthelier (1976) has shown that, during the two years under study, the *Bz* component has a quasi Gaussian distribution in polarity and in intensity. In addition, the level of activity, shown by the *am* index, increases with the intensity of the south polarity *Bz* component. Svalgaard (1974) established that the variance of the interplanetary field intensity increases with the wind velocity. We have shown that the daily distribution of the south *Bz* component does not change drastically with the level of activity (fig. 14). It suggests, but does not prove, that, generated by the wind turbulence, the intensity of the *Bz* component, which is the key parameter of the magnetospheric wind coupling, depends upon the wind velocity.

Whatever might be the mechanism, according to this large data set, the main source of the semi-annual variation of the wind stream activity is the latitudinal distribution of the wind structures. The coupling depends upon a small scale phenomenon, both the polarity and the intensity of the *Bz* component. However to this « dominant » axial mechanism is superimposed a diurnal effect related to the direction of the terrestrial dipole (Berthelier, 1976) and possibly some weak additional effect of the Russell-McPherron mechanism, a phenomenon of large scale origin.

Finally, according to the seasonal effect, in the case of a shock, the degree of coupling might depend upon the direction of the Earth dipole and, in the case of a wind stream, the level of activity depends mainly upon the wind velocity itself.

As a conclusion of this section 5, we see that if we study separately for the shock and the wind stream activities, on one hand, the latitudinal distribution of the auroral activity and the related level of the geomagnetic disturbance and, on the other, their « seasonal » effects, they supply us with new pieces of information on the separate roles of the Earth magnetic field in the magnetosphere coupling processes at work in these two separate classes of geomagnetic phenomena.

## 6. CONCLUSION

We classified the geomagnetic phenomena amongst two classes : the shock events and the wind stream activity. Taking into account the close correlation occurring between the *aa* indices and the wind velocity, we selected three groups of wind streams : the slow wind, the high speed wind and the fluctuating velocity wind.

The main results of the analysis of a centennial series of geomagnetic data are as follows.

The sunspot activity is not a frequent source of the geomagnetic activity which is at 91.5 % of the time under the control of the solar wind velocity.

The distribution of the activity in the recurrence patterns depends upon the size of the patterns : the bigger the patterns, the higher the average level of activity in the case of disturbed days, and the lower in the case of quiet days. In addition the peak in heliolatitude of the distribution of the disturbed and quiet day patterns take place at 6-7° of latitude and at the equator respectively.

According to the cyclical distribution of these categories of activity, one can identify a cycle of geomagnetic activity in which the three components of the wind activity are closely linked to the activity level of a sunspot cycle. However the sunspot cycle has a delay of about 5-6 yr on the relevant geomagnetic cycle.

Taking into account the latitudes of associated aurorae, one can notice that, at the same latitude, the flux of particles injected in the ionosphere is larger in the case of a shock than in the case of a stream. In addition, the latitude of the shock aurorae can reach lower latitudes than the ones of the stream aurorae and the relevant storms can reach higher levels than the one of any wind stream activity.

This difference of role of the Earth magnetic field in the magnetospheric couplings of both categories of disturbances is also noticeable in the study of their seasonal effects. In the case of a shock, the degree of coupling depends upon the direction of the Earth dipole and, in the case of the wind stream activity, the level of activity depends mainly upon the wind velocity itself.

In a second paper (Part II) we will study the solar sources of the geomagnetic activity, their cyclical behaviour and their links to the sunspot cycle.

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