1985A&A...152..199L

Astron. Astrophys. 152, 199–204 (1985)

ASTRONOMY
AND
ASTROPHYSICS

Some solar cycle phenomena related to the geomagnetic activity from 1868 to 1980

I. The shock events, or the interplanetary expansion of the toroidal field

J.-P. Legrand[1] **and P.A. Simon**[2]

[1] INSU-Saint Maur Cedex 94107, France
[2] UA 326, DASOP, Paris-Meudon Observatory, F-92195 Meudon Principal Cedex, France

Received April 24, accepted July 8, 1985

Summary. According to our previous analysis (Legrand and Simon, 1981), during 74% of the days the geomagnetic activity is the result of a steady wind flow occurring in the ecliptic plane. The present paper examined the remaining activity that we call the "transient activity" in order to separate the shock-events from a fluctuating wind flow supposed to be the two respective sources of that activity. We discussed a method of event recognition applied to the shock-event activity identified, on a Bartels diagram, by a SSC followed by a 3 day-jump of the geomagnetic activity level. Comparing our selected events with the ones obtained from the study of a series of solar wind data, we obtained a good agreement between both series. During the 112 year-interval under study, the shock-events contributed weakly to the geomagnetic activity (15%) during 8.5% of the days. Their rough relationship with the sunspot activity is rather weak ($aa = 0.048\,R$) and shows a large scattering on annual as well as on cyclical data. Outstanding jumps of shock-event activity occur currently once or twice a cycle, 2 years apart during the polar field reversal but not during the weakest cycles, i.e. those with a sunspot maximum number inferior to 50.

Key words: interplanetary medium – solar terrestrial relationship – shock waves – cosmic ray

1. Introduction

This series of papers is a continuation of our attempt (Legrand and Simon, 1981) to use improvements, produced during the last decades, of our knowledge of the Sun and solar corona, interplanetary medium and magnetosphere for a new study of long series of data. These series of data comprise geomagnetic data beginning in 1868 (Mayaud, 1973), auroral reports data beginning in 1780 (Legrand and Simon, 1985), and the well known series of relative sunspot numbers.

According to the geomagnetic data, we identify four categories of magnetospheric phenomena to which some specific solar origin can be either assigned or suggested.

1. One category of geomagnetic activity, the sudden commencement storm, is related to *a series of solar events* occurring in relationship with sunspot activity. These storms are the result of a sudden emergence in the interplanetary medium of the solar toroidal field, a kind of spatial enlargement of this field: we will call the related geomagnetic activity the shock-event activity.

2. The three other categories of geomagnetic activity, namely the "recurrent storms", the quiet days and the "fluctuating activity", are related to the distribution around the Sun, and for two of them around the solar equator, of several categories of corotating sources of solar wind. Any increase or decrease of such geomagnetic activity is not related to the occurrence or to the lack of occurrence of solar events but to *the rotation with the Sun of alternate sources* of the high and low speed wind which successively reach the Earth magnetosphere. We will call these three categories of geomagnetic activity of solar wind origin: the high speed wind stream activity, the low speed wind activity and the fluctuating wind flow activity.

Then, for each of these four classes of geomagnetic activity, we will discuss the sunspot activity relationship and the cyclical behaviour. During these long periods, there are series of cycles with very high activity level (cycles 18, 19, etc.) as well as quite low activity level (cycles 5, 6, 12 and 14). The study of the relationship between these separate categories of magnetospheric activity and the activity level of the related cycles shows quite new relationships between the activity level of sunspot cycles and several solar phenomena such as the occurrence of large interplanetary phenomena, the magnitude of the solar dipole, shortly before sunspot minimum, and the geometry of the heliosheet, at sunspot minimum.

2. Method of study

In a previous paper (Legrand and Simon, 1981), using a 110 year-long Bartels diagram of "*aa*" indices and SSC reports, we applied a method of data analysis for the identification and the study of two categories of *steady wind flow*: the slow undisturbed wind of "quiet days" and the stable high speed wind streams of the so-called "recurrent activity". These concerned respectively, for the quiet days, 35% of the activity level and 67% of the days, and for the stable high speed stream activity, 15% of the activity level and 7.1% of the days.

The remaining activity was called the "transient activity". It concerned 50% of the activity level and 26% of the days. On our Bartels diagram (Legrand and Simon, 1981), that activity traces "irregular patterns" in which the most common feature is a random fluctuation of the activity level. Just a few "typical storms" have definite sudden storm commencement, and are followed by a main phase and end after several days by the return to a "quiet" pre-storm level: we will identify these events as "shock-events". They are superimposed on a series of *poorly defined events*. One can notice, among them, sudden storm commencements followed

---

Send offprint requests to: P.A. Simon

by no definite or very weak activity increases, short storminess intervals without sudden storm commencement, and weak and irregular increases of activity. We will identify this activity as a "fluctuating activity" i.e. a geomagnetic activity in which the fluctuation of activity is related *not* to some disturbance of wind flow by the sudden occurrence somewhere on the disk of solar event, but to *some change occurring at the wind sources themselves* such as a birth, a disappearance or a displacement of wind source.

Are the respective contributions to the geomagnetic activity of the shock-event activity and of the fluctuating activity changing during the cycle? In the previous paper (Legrand and Simon, 1981), we discussed a few points which can help us in the study of this problem. As the whole, the transient activity has some relationship with the sunspot activity: we found a correlation coefficient of 0.8 between the related annual data. However it seems that the contribution rate of each of these two sources, shocks and fluctuating wind, to the transient activity is *cycle phase related*: at sunspot maximum there is a close link between the transient activity level and the current sunspot number, whereas at the geomagnetic minimum, i.e. at sunspot minimum or in the following year, any similar link is questionable because it would involve a level of flare or "disparition brusque" activity which is not at all observed. One can conclude, as did Feynman (1982), that, at sunspot maximum, the transient activity is entirely sunspot activity related, whereas at geomagnetic minimum, it would be a "pure" solar wind phenomenon. We are in disagreement with this suggestion (Legrand and Simon, 1983). The analysis of the solar wind data (Burlaga and King, 1979; Legrand and Simon, 1981) shows that *at any phase of the cycle* some solar wind "stream" contributes to the transient activity. Unfortunately the solar wind data series form an intermittent survey of the interplanetary medium which cannot supply us with some definite evaluation of the variation of this contribution during the cycle.

In the present paper, we suppose that with our data analysis method (Legrand and Simon, 1981), we succeed generally in identifying the *steady flow* of the solar wind. But we feel that such a method is *not* appropriate to separate the "*fluctuating wind flow*" from the shock-event activity. On the other hand, we suppose that we could generally identify the contribution of the shock-event activity by using *a method of event recognition.*

3. The shock-event recognition

We select the shock-events according to a series of criteria that we discuss here. We begin with the results of a previous study showing that the "flare related storms" are of short duration (3 days) and follow a sudden storm commencement (Simon, 1956). For our shock-event selection we consider only the *three day-storms* with *a SSC on their first day.*

In a Bartels diagram, these storms are on a *background* resulting from the activity occurring on the few preceding and following rotations as well as, in the same rotation, on the neighbouring days. We selected only those storms with either an *outstanding level of activity* or a *definite increase* of activity in comparison with this background, i.e. events of any importance, even the weak ones, occurring on a quiet background and quite high activity events occurring during strongly disturbed periods.

On one side, few sudden commencement storms are stream-generated and, on another side, the stream activity could sometimes generate short storms (see for instance the equatorial stream activity occurring on the first quarter of 1971 in Fig. 3 in Legrand and Simon, 1981). As a consequence we rejected from our selection any series of storms showing a 27 day recurrence.

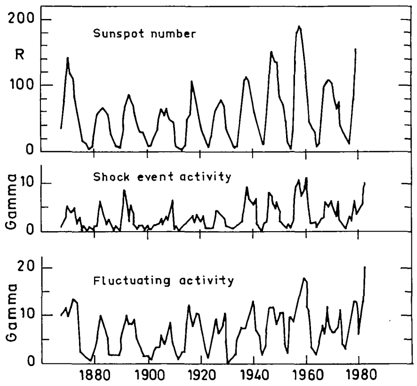

Fig. 1. The sunspot number, the levels of shock event activity and of fluctuating wind activity from 1868 to 1980

We must note that, according to the 3 above criteria, only 43% of the SSCs have been selected as the beginning of shock-events and that, by lack of SSC signature, 3 or 4 short intervals of high activity have not been selected as shock-events activity.

As a result we have the annual number of shock-events, we compute the annual level of shock-event activity (the annual sum of the 3 day-aa indices of the selected storms) and, after subtraction of the transient activity level, we obtain the remaining transient activity that we suppose to be of fluctuating wind flow origin (Fig. 1).

4. Discussion of the method of shock-event selection

By the analysis of an appropriate period of solar wind data, i.e. a period without or with just a few gaps in the survey, we can check the reliability of our method of identification of shock-events. We can compare our selection of shock-events from the geomagnetic data with the one obtained from the wind parameters themselves. In addition, we can identify, in between the shock-events, the fluctuations of the wind flow which actually generate the "fluctuating activity".

On one side, the wind data themselves have been published by the WDC-A for Rockets and Satellites (King, 1977, 1979) and, on the other side, Lindblad and Lundstedt, applying to these data the Burlaga criteria (Burlaga and King, 1979) published a list of shock-events and wind-streams (Lindblad and Lundstedt, 1981, 1983). We limited our checking to 13 months of the years 1967 and 1968, a sunspot maximum period with shock-events superimposed on a fluctuating wind-flow activity and without any important data gap.

First of all, our *shock-event recognition* from our Bartels diagram is questionable only for *less than 10% of the shocks*: it supplies us with an evaluation of the uncertainty of our results.

Then the transient activity, outside of the shock-event activity, is *solar-wind related.* Its annual level confirms that, *even at sunspot maximum,* the wind related activity is an important part of the geomagnetic activity. Obviously this wind is not a steady wind-flow but we will discuss its "fluctuating" properties in the paper devoted to this topic (Paper III).

1985A&A...152..199L

5. Results

1. During the 112 years under study, the shock-events occurred during just 8.5% of the days and generated only 15% of all the geomagnetic activity. This quite new result shows that *most of the geomagnetic activity,* i.e. 85% of the occurring activity *is of solar-wind origin.* It concerns 91.5% of the days.

Most of this wind has a steady flow (50% of the activity, 74.1% of the days) and the related activity can give piece of information on the "stable" or slowly varying components of the solar environment. The remaining activity which has a fluctuating origin emphasizes the variability of the solar atmosphere. This fluctuating wind-flow occurring during 17.5% of the days generates 35% of the activity.

2. In our previous analysis of the "transient activity" (Legrand and Simon, 1981) we pointed out that, at low sunspot number, the level of the transient activity was much too high to be related to the sunspot activity. According to our new analysis we have now two components of the transient activity: the shock-event activity which, at low sunspot number, always remains very weak and the "fluctuating wind-flow" activity which obviously is not controlled by the sunspot activity (see Fig. 2). One can notice that, in comparison with the shock wave activity, at low sunspot number, this last activity can reach quite a high level (see for instance the level of activity in 1954 and 1977 and our discussion in Legrand and Simon, 1981).

3. The main interest of the shock-event activity is the study of this category of activity during the *past cycles,* those for which we do not have any flare report or lists of disparitions brusques. Of course, with the discovery of coronal transients during the SKYLAB program and with the new series of data of the SMM and the Solwind experiments, the solar origin of shock-events is now an open question that we will not discuss here (see for instance Hewish, 1985, who rejects most of the parent flare identifications related to the large storm disturbances). We will just discuss here the shock-event occurrence in relationship with the sunspot cycle, i.e. the interplanetary expansion of the toroidal field.

One can note that a statistical study of the so-called "parent flares" of the SSCs was the first work to suggest that the associated shock waves had a large angular size (Caroubalos, 1964). The observation of the flare related radio Type II bursts confirmed the large angular size of the associated coronal disturbance (Wild and Smerd, 1972). Recently the observation in the interplanetary medium, by radio source scintillation, of the travelling disturbance showed this property of the solar shock-waves (Hewish, 1985). It means that our sample of geomagnetic shock-events is the result of a *permanent monitoring* of events occurring in the "*central part*" of the solar disk, probably between 60 degrees East and 60 degrees West.

It emphasizes the important difference existing between the activity of solar wind origin and the shock event activity. The solar wind reaching the Earth has to be guided by the external solar field from its source in the corona to the ecliptic plane. During each solar rotation, the Earth *successively "visites"* a series of wind sources selected by this external solar field. The shock-event activity is a permanent survey of all the shock phenomena occurring at any place in the "central part" of the solar disk. The shock-events supply us with a sample of the related solar events, whatever they might be, appropriate to study their cycle occurrence.

4. As shown in Fig. 1, the statistical distribution of the shock-events follows a *cyclical behaviour* which is illustrated by the distribution of the "severe storms" (192 sudden commencement storms with a daily $aa > 100\,\gamma$, Fig. 3). This series of outstanding events forms an unquestionable sample of shock-events. Most of them (88%) occur during the six year-interval beginning in the year preceding the sunspot maximum year. The peak of the severe storm distribution is *not* at sunspot maximum but in the first year of this interval and a secondary peak can be noticed in the third

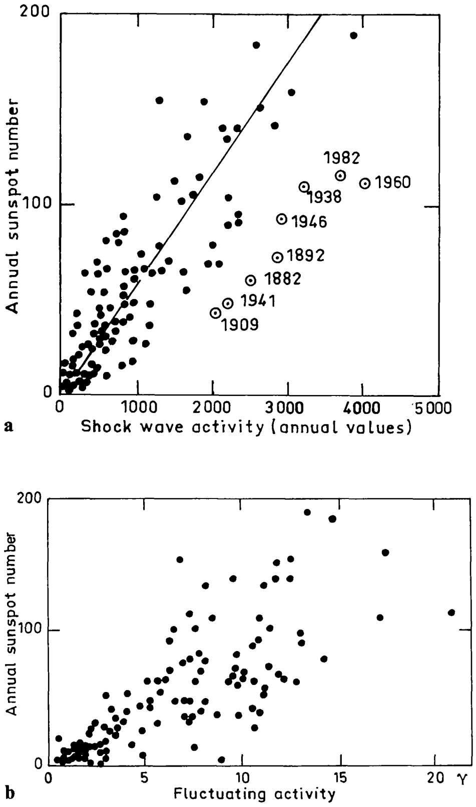

Fig. 2. The distribution of **(a)** the shock event activity and **(b)** the fluctuating wind activity versus the current sunspot number (annual values). The numbered years are those with an outstanding level of shock activity

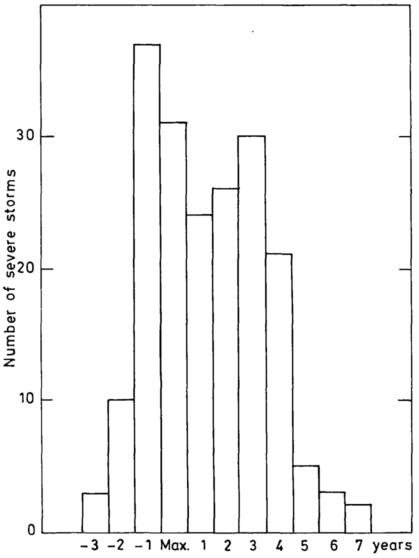

Fig. 3. Distribution on years on boths sides of the sunspot maximum year of 192 severe storms

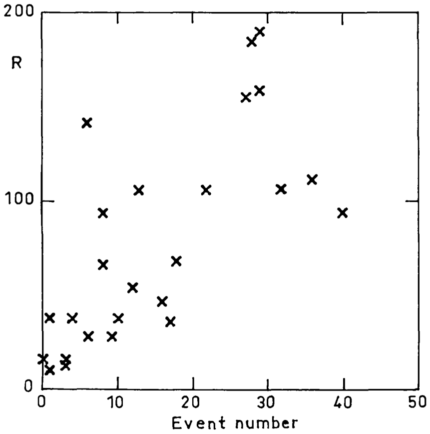

Fig. 4. Annual number of outstanding flares occurring between 1954 and 1979 versus the current sunspot number. Outstanding flares are selected according to the Experimental Comprehensive Flare Index (CFI > 9) (Dodson and Hedeman, 1971, 1975, 1981)

year after the sunspot maximum year, i.e. the two peaks are 2 years apart on the polar field reversal. As this 6 year-interval is just one half of the solar cycle and that the peaks occur at both ends of the interval, we cannot expect a close relationship between the all shock-event activity and the current sunspot number.

5. That is confirmed by the Fig. 2a on which we displayed the annual level of shock-event activity versus the related sunspot number. Even if we can identify some "rough" link between both categories of activity ($aa = 0.048\,R$), this relationship is loose and cannot be used to evaluate, for instance, from an annual sunspot number, the related level of shock-event activity.

The scattering is quite large and in Fig. 2a we identified the few years during which this category of activity reached a *specially high level.* It occurred once or twice a cycle either in the year preceding the sunspot maximum year, or in the third or fourth year after this one. One must point out that this "outburst" of the shock activity occurs also during weak activity cycles. In 1882, during a weak activity cycle ($R_{\max} = 63$) and in a year of moderate sunspot activity ($R = 60$), the shock activity reached about the same level as it did at the high sunspot peak of 1947 ($R = 152$). Similar outburst can be noted on separate events. The largest severe storm of this series occurred on September 25, 1909 with an *aa* index reaching 546 γ during the first 12 hour-interval of the storm. The sunspot peak reached only 63 and the annual sunspot number was equal to 44. Such a large scattering can also be noted on the cycle distribution of large flares, as we can notice in Fig. 4, in which are displayed, from 1954 to 1979, the annual numbers of flares having a Comprehensive Flare Index larger than 9 versus the related annual sunspot number (Dodson and Hedeman, 1971, 1975 and 1981). There are obviously outstanding rich flare-years followed by poor ones and vice versa. Concerning large flares, this "chaotic" distribution is related to their serial occurrence, such as, for instance, in August 1972. The shock-events have the same property.

6. The list of severe storms includes their dates of occurrence. One can notice that they show a quite *definite seasonal effect* (Fig. 5). There is a poor chance of severe storm occurrence in June or December but a very high chance in March and September. We did not study the distribution of all the shock events, but it is clear that no seasonal effect can be noted on the SSC occurrence. We did not notice any so large seasonal effect in the other categories of geomagnetic activity. Obviously this seasonal effect has a terrestrial origin. The average direction of the Earth dipole is perpendicular to the sun-earth line in March and September and reaches its maximum inclination of 23 degrees in June and December whereas one cannot see what kind of seasonal effect could be related to the occurrence of shock-event sources on the solar disk. McIntosh (1959) already attributed to this fact the seasonal effect that he pointed out in the annual variation of the geomagnetic activity. Boller and Stolov (1970) have shown that the probability of occurrence of Kelvin-Helmholtz instabilities at magnetopause increases when $\cos^2\psi$ decreases, where ψ is the angle between the earth dipole axis and the Earth-Sun line. Such instabilities are thought to represent a likely mechanism for the transfer of solar wind energy into the magnetosphere. Berthelier (1976), Mayaud (1977) have shown that this mechanism explains both the annual and the diurnal variation of the geomagnetic activity. The McIntosh effect is the most likely explanation of this annual variation of the shock event activity. We will see (Simon and Legrand, 1985) that a different mechanism can be proposed to explain the seasonal effect of the high speed wind activity.

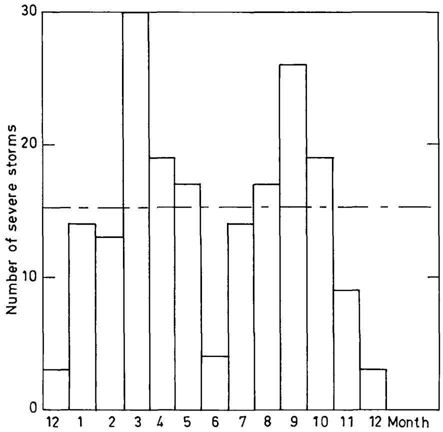

Fig. 5. Monthly distribution of severe storms occurring between 1868 and 1980

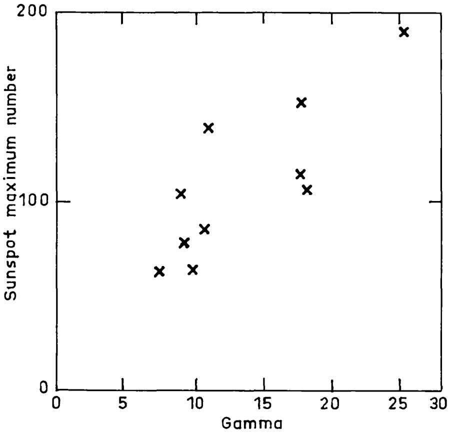

Fig. 6. Shock activity by cycle versus the related sunspot maximum number

7. Now comparing the sum of the shock-event activity *during the entire cycle* with the related maximum sunspot number, we also see a quite weak relationship (Fig. 6). Of course cycle 19 had the largest activity but, for instance, a series of cycles peaking between 139 and 64 has about the *same level of shock-event activity.* Now, if we consider the number of severe storms by cycle, it

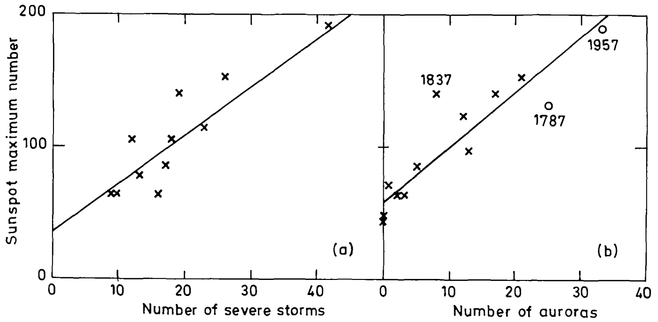

Fig. 7. Number by cycle of **(a)** severe storms and **(b)** auroras of mid-low latitude (below 50 degrees) versus the related sunspot maximum number

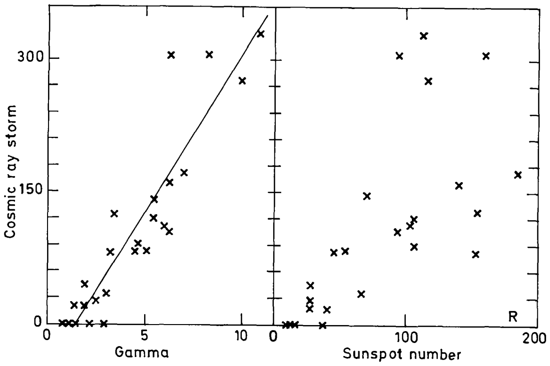

Fig. 8. The annual amplitude at Kerguelen Island of cosmic ray storms with a decrease >5% versus **(a)** the related shock event activity and **(b)** the related sunspot number (1958–1982)

suggests some inferior boundary for the low cycles which have no severe storms during the cycles peaking between 40 and 50 (Fig. 7). A result concerning low latitude auroras confirms this conclusion. The low latitude auroras, observed at geomagnetic latitude below 50 degrees, are well-observed events currently noted in the contemporary historical chronicles. They are shock-associated events and their low latitude occurrence is the result of the high level of magnetospheric disturbance. No low latitude aurora has been reported between 1792 and 1831, i.e. during the lowest known cycles, peaking in 1804 and 1816 with a sunspot peak of respectively 46 and 47.

6. Shock-events and cosmic ray cycle modulation

There is some agreement among scientists to link the time profile of the cosmic ray cycle modulation to the number and the importance of the shock related Forbush decreases (see for instance Perko and Fisk, 1983; Lockwood and Webber, 1984; Burlaga et al., 1984). But they generally believe that the occurrence of Forbush decreases is closely linked to the level of sunspot activity. We will now show that this is not the case but that the Forbush decreases are more closely linked to the shock event activity than to the current sunspot number.

In order to check the reliability of our above identification of the shock-event activity, we compared our annual level of shock activity with the amplitude of the flux decreases of all the cosmic storms, so-called Forbush decreases, occurring during the same year. For that purpose, we computed, from 1958 to 1982, the annual sum of the sudden flux decreases occurring at the beginning of the cosmic ray storms having a well definite shape, i.e. with a 5% or more decrease of the flux level. We used the neutron monitor data of Kerguelen Island supplemented, after some normalisation, for the interval 1958–1964, by the data of Deep-River.

We see a close link between both series of events, i.e. a close statistical link between the amplitude of a series of geomagnetic phenomena and the one of the related cosmic ray storm series (Fig. 8). Of course both categories of phenomena are entirely different ones: during a Forbush decrease, the shock wave plays the role of a shield diverting the cosmic ray flux (Thomas et al., 1984), whereas the geomagnetic activity is related to the interaction of the shock wave with the Earth magnetosphere. However this link should explain the irregular shape of the cosmic ray cycle modulation, its lack of phase relationship with the sunspot number curve (Hatton, 1980), all properties of the shock-event activity discussed above. A good illustration of this link occurred during the present cycle. The sunspot maximum occurred in 1979 whereas the cosmic ray minimum was in 1982, with a three-year delay on the sunspot peak, but at the peak of the shock-event activity.

The abundance of the Carbon 14 in the Earth atmosphere is a physical consequence of the flux of the cosmic ray particles passing through the interplanetary medium. If the cosmic ray modulation is linked as we suggest to the shock-event activity, the abundance of any radioactive atom should have the same time behaviour as the shock activity, i.e.:

1) A poor link if any with the sunspot cycle activity.

2) A lack of large event, i.e. a very weak cosmic ray modulation, during low activity cycles ($R_{\max} < 40-50$).

3) An irregular distribution of the modulation during any cycle.This result makes questionable the current evaluations of the secular behaviour of the solar activity done according to the observed abundance of the Carbon 14 or any other radioactive atom.

7. Conclusion

The contribution of shock-events to the geomagnetic activity is weak and scarce. The related activity shows a seasonal effect which has a terrestrial origin, the so-called McIntosh effect which is related to the annual variation of the angle between the Earth dipole axis and the Earth-Sun line.

However it supplies us with a reliable survey of that category of active during the past cycles. The shock events have a cycle behaviour such as the largest events, the severe storms, occur during a 6 year-interval beginning in the year preceding the sunspot maximum year. As a consequence their link with the current sunspot number is rather weak whatever would be the level of activity of the related sunspot cycle. The largest events could occur during weak activity cycles but, however, according to the low latitude auroras, no large event occurred during a 40 year-interval with 2 cycles peaking respectively at $R = 46$ and 47. Once or twice a cycle, the level of shock activity could reach "abnormally" high values. Incidentally we pointed out that the Forbush decreases are more closely linked to the shock-event activity than to the current sunspot number. This last result makes questionable the reliability of the evaluation of the secular behaviour of the solar activity done according to the observed abundance of the Carbon 14.

Finally, we see that the study of shock-event geomagnetic activity according to a long series of geomagnetic and aurora data supplies us with some new pieces of information on the relationships between the interplanetary expansion of the toroidal solar field and the sunspot cycle.

References

Berthelier, A.: 1976, *J. Geophys. Res.* **81,** 4546

Boller, B.R., Stolov, H.L.: 1970, *J. Geophys. Res.* **75,** 6073

Burlaga, L.F., King, J.H.: 1979, *J. Geophys. Res.* **84,** 6633

Burlaga, L.F., McDonald, F.B., Ness, N.F., Schwenn, R., Lazarus, A.J., F. Mariani: 1984, *J. Geophys. Res.* **89,** 6579

Caroubalos, C.: 1964, *Ann. Astrophys.* **27,** 333

Dodson, H.W., Hedeman, E.R.: 1971, Report UAG-14, NOAA, Asheville

Dodson, H.W., Hedeman, E.R.: 1975, Report UAG-52, NOAA, Asheville

Dodson, H.W., Hedeman, E.R.: 1981, Report UAG-80, NOAA, Asheville

Feynman, J.: 1982, *J. Geophys. Res.* **87,** 6153

Hatton, C.J.: 1980, *Solar Phys.* **66,** 159

Hewish, A.: 1985, Artificial Satellites (in press)

King, J.: 1977, Interplanetary Medium Data Book, NSSDC/WDCA, Goddard Space Flight Center, Greenbelt, Maryland

King, J.: 1979, Interplanetary Medium Data Book, NSSDC/WDCA, Goddard Space Flight Center, Greenbelt, Maryland

Legrand, J.P., Simon, P.A.: 1981, *Solar Phys.* **70,** 173

Legrand, J.P., Simon, P.A.: 1983, *J. Geophys. Res.* **88,** 8137

Legrand, J.P., Simon, P.A.: 1985, *Ann. Geophys.* (submitted)

Lindblad, B.A., Lundstedt, H.: 1981, *Solar Phys.* **74,** 197

Lindblad, B.A., Lundstedt, H.: 1983, *Solar Phys.* **88,** 377

Lockwood, J.A., Webber, W.R.: 1984, *J. Geophys. Res.* **89,** 17

Mayaud, P.N.: 1973, *IAGA Bull.* No. **33**

Mayaud, P.N.: 1977, *J. Geophys. Res.* **82,** 1266

McIntosh, D.H.: 1959, *Phil. Trans. Roy. Soc. London, Ser. A* **251,** 525

Perko, J.S., Fisk, L.A.: 1983, *J. Geophys. Res.* **88,** 9033

Simon, P.: 1956, *Ann. Astrophys.* **19,** 122

Simon, P.A., Legrand, J.P.: 1985, *Astron. Astrophys.* (in press)

Thomas, B.T., Gall, R.: 1984, *J. Geophys. Res.* **89,** 2991

Wild, P., Smerd, S.F.: 1972, *Ann. Rev. Astron. Astrophys.* **10,** 159