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Cosmic ray decreases and geomagnetic storms during 1975-1994

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Abstract : Ninety Cosmic ray intensity decreases ($\geq$ 4%) and geomagnetic storms with criteria such that planetary index $Ap \geq 30$, disturbance storm time index, $Dst \leq -$ 40nT have been investigated using neutron monitor data and solar geophysical data during the period 1975–1944 It has been observed that the majority of the i e 91% geomagnetic storms (GMS's) are associated with coronal mass ejection(CME's) The ejecta is intercepted only when the solar events, originates within 40° of the Sun's central meridian Further, it is not necessary that maximum number of GMS's should occur during the maximum activity period only. It is also observed that during 66% events the decrease in the cosmic ray intensity started a few hours later than the occurrence of GMS's at the Earth Further, statistically, it is observed that the sunspot numbers (SSN's) and solar flux are highly correlated during 21st and 22nd sunspot cycles The GMS's are better correlated with sunspot numbers during the even solar cycle as compared to odd solar cycle It is found that CME's transit time from the Sun to the Earth space lies between 1and 5 days

Keywords : Cosmic ray intensity, coronal mass ejection, geomagnetic storm, solar cycle, solar flux

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1. Introduction

Cosmic rays are energetic particles that are found in space and filter through our atmosphere. These are generally known as galactic cosmic rays. Ground based neutron monitors, at various locations on the Earth, for the last several decades, are regularly monitoring cosmic rays. Observations so far, show a long-term solar cycle effect, with cosmic ray neutron monitor intensity and its anti correlationship with sunspot numbers [1]. For short term effect, the relationship between solar variations with interplanetary plasma parameters and with cosmic ray decreases and geomagnetic storms (GMS's) have also been discussed in detail by various workers [2,3]. Solar wind

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plasma parameters vary considerably on different time scales Low density variations occur on the largest scale and are associated with fast flow from coronal hole and slow flow from vicinity of the streamer belt Further, the largest amplitude density variations occur on shortest time scales and are associated with slow flow

In the last few decades, various indices have been standardized representing various facets of the solar phenomena occurring on the various layers of the solar atmosphere, *i e* the photosphere, chromosphere and corona Currently, many solar parameters are available to the workers in the form of well defined indices for the investigation of solar terrestrial relationship These are sunspot numbers, 10 7 cm solar flux (or 2800 MHz radio emission), sunspot area, grouped solar flares *etc* For geomagnetic indices like *Ap* or *Dst,* the relevant interplanetary parameter is the *B* north south component of interplanetary magnetic field, (IMF) If B_z is negative geomagnetic storms occur because a connection gets established between solar wind plasma and in the geomagnetic tail, leading to auroral precipitation and equatorial ring currents, which affects variation in *Dst* When an interplanetary feature near the Earth is affects *Dst,* the cosmic rays also suffer modulations named as Forbush decreases in a matter of hours and almost coinciding with the variation in *Dst* and show a recovery within a few tens of hours Thus, the main phases of *Dst* storm are reasonably well related with cosmic ray decreases On the longer time scale, Burlaga *et al* proposed that fast coronal mass ejection contribute to the formation of a propagating diffusion region which propagates further out in the heliosphere, so that CR intensity never quite recovers at the Earth's orbit [4]

The decrease of cosmic rays are divided into four categories based on the decrease morphology and the behavior of different types of solar wind structure Classes 1 and 2 events are associated with strong, extensive shocks whose source region on the Sun can be determined by the rapid onset of solar particle flux at the time of solar flare event Such shocks are driven by fast, energetic coronal mass ejection (CME's) [5] These shocks lead to geomagnetic storms at various locations of Earth Class 1 events originate in solar events within about 50^0 of the central meridian [6] This is consistent with the interception of large ejecta which is directed in the general direction of the Earth [7] Class 2 events are associated with solar events farther from central meridian so that the ejecta do not encounter the Earth Class 3 events are similar to class 1 events in appearance, in that the N M and energetic particle data reach a minimum associated with the ejecta, but the associated energetic particle enhancements in space craft data do not extent above 60 Mev/amu [8] In these events, the associated shocks are usually not very energetic and that the CME's are slower and probably less extended than those associated with more energetic events [9,10] Onset of Class 4 events takes place more slowly and these have longer duration than the events associated with the other classes Class 4 events are associated with complex plasma regions including co-rotating high speed streams and ejecta [6]. In this study, the classification of solar wind structure associated with cosmic ray decreases (CR $\geq$ 4%) is expanded to include events which are associated with geomagnetic storms sudden commencements (SSC's) during the year 1975-1994 In principle, these structures can be inferred directly from *in-situ* solar wind plasma and magnetic field data However, such data are sufficiently complete to allow the solar wind structures to be classified in less than 60% of the events, whereas, the more complete energetic particle data can provide such information for a huge majority of the events We find that where simultaneous data are available, there is excellent agreement between the solar wind structures deduced from using the energetic particle data and by consideration of the solar wind data Furthermore, the particle data allow us to infer which events are likely to be energetic and therefore have identifiable solar regions The objective of this work is to study the energetic solar wind disturbances associated to SSC's with relatively, a reliable solar event association This will aid researchers making studies that require such information This paper is to identify unambiguously solar sources of geomagnetic storms with CR decreases ≥4%, with *Ap* > 30 along with *Dst* ≤ – 40nT based on a comprehensive set of solar, interplanetary, geomagnetic and cosmic ray decrease observations, CME's from the Sun cause solar wind disturbances in terms of magnetic field, speed and cosmic ray decrease, which in turn cause magnetic disturbances at the Earth These disturbances cause GMS's at various locations of Earth Geomagnetic storms have been found to be particularly sensitive to the presence of an intense southward interplanetary magnetic field that allows efficient energy transfer from the solar wind into the Earth's magnetosphere through magnetic reconnection [11–13] The aim of this work is to improve our understanding of the physical mechanisms responsible for CR decreases which may also lead to occurrence of geomagnetic storms In this paper, we concentrate on identifying solar sources for geomagnetic storms with *Ap* ≥ 30, *Dst* ≤ 40nT along with CR decreases ≥4% during 1975-9994

2 Data analysis

In the 20 year period from 1975 to 1994, 90 GMS's have been identified based on the *Dst* index < – 40nT, planetary index *Ap* ≥ 30 along with CR decreases ≥4% At the largest decrease, the variation between stations can be significant An example is the event of 15 February 1978, which is 24% at Mount Wellington but 19% at Deep River We use hourly data to determine the size and onset times of the decrease The size is obtained by dividing the minimum rates by the average rate observed for several hours preceding the onset of the decreases The *Dst* is derived from hourly horizontal magnetic variations in a network of near equatorial geomagnetic observatories The variation of the horizontal component of Earth magnetic field (*H*) on the ground are believed to be caused by the changes in the global high altitude equatorial ring current, which in turn depends on solar conditions Cosmic ray data are taken from mount Wellington neutron monitor. The *Ap, Dst* data and position of H_α solar flares have been taken from group listing in solar geophysical data We have examined simultaneously near Earth solar wind data from the National Space Science Data Center OMNI to see whether the solar wind conditions are consistent with our classification based on particle data In particular, we checked for evidence of ejecta material and other solar wind structures including co-rotating high-speed streams. To identify ejecta material, we primarily relied on the plasma temperature and the way it related to the expected temperature, determined from flow speed as described by Richardson and Cane (1995) [14] For solar wind data, we used designations related to the particle classes. If ejecta material is present within about 1 day following the shock or disturbance responsible for the onset of the CR decrease (transient flow plus ejecta designated as A), then we would expect the particle to be either class 1 or 3 If there are multiple shocks and ejecta or high speed streams the complex flow is represented by B A single disturbance with no ejecta following it, is labeled as C It can be seen that there is a very good agreement between *in-situ* solar wind and the particle data classes indicating that our method of inferring the solar wind structure from the particle data is generally valid However, it should be noted that the particle data provide additional information which allow us to determine the events most likely to be associated with an energetic solar event. Particle data indicate the presence of disturbances, which sometimes are not present in the solar wind data The example of this is the major shock off the east limb of the Sun on September 14, 1979, which produced no flow at Earth We note that a flare may occur anywhere under an associated CME [15] so that the direction of propagation of the CME may not be exactly outward from the flare location. For those events where a shock is detected at Earth and solar onset time has been determined, the transit speed of the shock is inferred from the time interval between the flare and the associated GME's. We used the particle only to define the solar event time and calculated a shock transit speed, putting the value in parentheses We have associated the Class 1 and Class 2 events with source regions on the Sun by relating the commencement of the lower energy particle event with the time of a solar flare. The associations of solar event are assigned on the basis of the onset time and intensity time profile of the low energy particle. The delay time is the time span between the start of CR decrease and the time of a SSC, a proxy for shock passage

3. Results and discussion

There are a total of 90 events studied in the twenty years investigation period from 1975-1994. The distribution of the 82 events in classes 1 to 4 and the average size of events in each classes are given in Table 1. The class represents the solar wind structures inferred to cause the cosmic ray decrease and occurrence of GMS's. Class 1 event is related to shock plus ejecta while class 2 events indicates shock only Class 3 events are related with shock plus ejecta but are less energetic than class 1. Class 4 represents complex event including a co-rotating high speed stream. Class 1, 2 events are associated with energetic CME's while class 3 events are associated with less energetic CME's. Seven events are related with class 2* (>60 Mev count rate) which are not shown in Table 1. One event is associated with strong shock near the Sun. The distribution of events on the basis of two indices *(Dst, Ap)* have been shown in the Table 2.

Table 1. The Distribution of events (associated with GMS's) by class on the basis of CR decreases during the period 1975-1994

Class	Number of events	Mean size% (CR decreases)
1	29	9 5
2	22	6 0
3	28	5 7
4	03	6 0

Table 2. Distribution of events associated with GMS's on the basis of *Dst* and *Ap* indices with CR decrease 4% during the period 1975-1994

Category of GMS	*Dst* index	No of events	*Ap* index	No of events (GMS's)
Minor	-50 nT $\leq Dst \leq -40$ nT	03	$30 \leq Ap \leq 50$	30
Major	-100 nT $\leq Dst \leq -50$ nT	33	$50 < Ap < 100$	36
Severe	$Dst < -100$ nT	54	$Ap > 100$	24

Similar classification has been made by earlier workers [3,16] It is clear from the Table 2 that, there are significant differences between sets of minor and severe GMS s defined by the two indices This result agree with earlier findings [17]. Further, the classification of events has been performed on the basis of kind of flow in Table 3 In Table 3, ---------- designation means that there are insufficient data From Table 3 we conclude that maximum number of events are associated with class A (either

Table 3 Classification of events on the basis of kinds of flow during the period 1975-1994

Class	Kind of flow	Number of events
A	Transient flow plus ejecta	39
B	Tranransient flow and no ejecta	5
C	Complex flow and/ or high speed stream	10
D (Unknown)	--	36

class 1 or class 3) Furthermore there are a large number of events (36) in which kinds of flow is unknown and they are named as D due to insufficiency of data. Figure 1(a,b) shows the distribution of the shock *i e* magnitudes of CR decrease (in %) of class 1 and class 2 events as a function of helio latitude and longitude. The solid circles indicate class 1 events and open circles indicate class 2 events Figure 1(a) clearly demonstrates that the ejecta is encountered (class 1, class 2) if the CME's originate within 35° helio latitude region. It is apparent from Figure 1(b) that the ejecta is encountered (class 1 events) if the CME's originate within about 50° of helio longitude. The distribution in Figure 1(b) suggests that the maximum latitudinal and longitudinal extent of ejecta at 1 AU is about 35° and 90° respectively. This is similar to the average latitude span of a group of very energetic CME's [5] which occurred close to the limbs, suggesting that CME's/ejecta do not expand in longitude during propagation

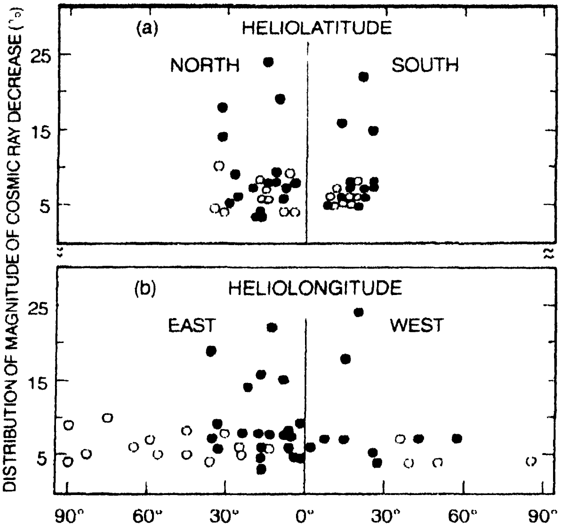

Figure 1. Distribution of events with $Ap \geq 30$, $Dst \leq -40$ nT alongwith CR intensity decrease ≥ 4% (a) helio latitude and (b) helio longitude during the period 1975–1994.

from the Sun assuming similar extents in latitude and longitude. Another indication of the extent of ejecta comes from the fact that two ejecta which caused >4% CR decrease in 21st February and 17th April, 1994 were also observed apparently through Ulysses satellite data which at that time was at 60° south of ecliptic and at 3.5 AU [18]. Thus, one may conclude that ejecta expand at high latitudes in these cases to extend beyond 60° from the ecliptic, as suggested by Gosling *et al* [18]. On the other hand, preceding the April 1994 decrease, the soft X-ray telescope on Yohkoh observed a very long lasting, spatially extended event [19] and a possibility is that there is more than one mass ejection, *e.g.* one directed at Ulysses and at Earth. It is also evident from the Figure 1(a,b) that the distribution of class 1 and 2 event sizes as a function of solar event latitude and longitude, has a pronounced peak near the central meridian. This is to be expected, since shocks are strongest at the nose so that the effect of the shock on the cosmic ray density will be greatest for central meridian events. The effect of the ejecta is also likely to be greatest for these events, since the Earth is more likely to penetrate well inside the ejecta. This expectation has been shown to be correct by a multi space craft study of several large, shock associated decreases [8,20]. The asymmetry in the distribution of class 1 events in Figure 1(a,b) (*i.e.* greater number of northern [18] versus southern [11] events and eastern [20] *versus* western [9] events) has been known for many years [21]. Since the distribution of class 2 events is asymmetric, this means that the shock effect is certainly asymmetric. This is to be expected because the draping field lines around the ejecta lead to an asymmetry in the post shock compression region [22] where the cosmic rays experience increased scattering. Asymmetry of class 1 events is suggests that the ejecta show asymmetry. This is consistent with expectations, since there is no obvious reason for the ejecta to be asymmetric about the event longitude as well as latitude

Our conclusions are not consistent with the conclusions of Iucci *et al.* [23] that the second steps of Forbus decrease are asymmetric. However, one must question the analysis since they find second steps for decreases originating at all longitudes, whereas our observations suggest that they should only be present in events originating within 40° of central meridian

Yearly occurrence of number of events with greater than 4% cosmic ray decrease related to GMS's have been plotted histographically for the period 1975-1994 in Figure 2. Further, the best fit lines between the yearly occurrence of sunspot numbers and the numbers of events associated with GMS's have been plotted in Figure 2(a,b) for the 21st and 22nd solar cycle, respectively. It is apparent from Figure 2 that

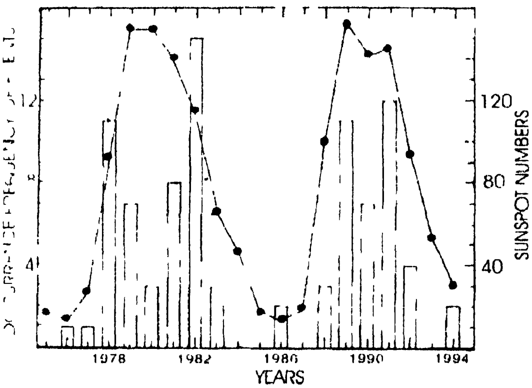

Figure 2. Yearly occurrence of events related with GMS's with $Ap \geq 30$, $Dst \leq -40$ nT along with CR intensity decrease $\geq 4\%$ and SSN's, plotted histographically during the period 1975-1994

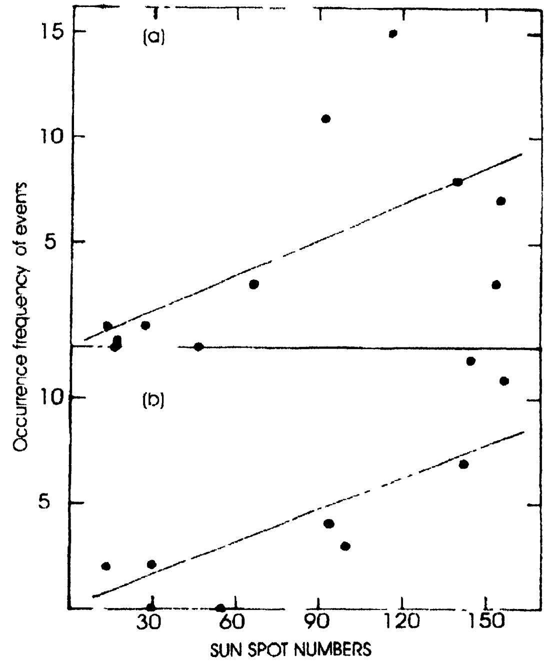

Figure 2(a,b). The best fit lines between the yearly occurrence of SSN's and number of events associated with GMS's (a) 21st solar cycle and (b) 22nd solar cycle for the period 1975-1994.

the occurrence rate of cosmic ray decreases is clearly related to the solar cycle. The correlation coefficient between SSN's and GMS's during 21st and 22nd solar cycles are 0 67 and 0.86 respectively which shows that SSN's and GMS's are more correlated in 22nd solar cycle as compared to 21st cycle. One peculiar result has been obtained during year 1982 and 1991 when SSN's decreases rapidly while GMS's increases significantly as shown in Figure 2. Further more, it is observed from Figure 2 that maximum number of events associated with GMS's have occurred during the year 1978, 1982, 1989 and 1991, while all these years are not years of maximum activity. Thus we conclude that, it is not necessary that maximum number of event with decrease ≥4%, $Ap \geq 30$ along with $Dst \leq -$ 40nT associated with GMS's have occurred during maximum activity years [24]. It is apparent from Figure 2 that there is one year almost near each solar minimum having no decrease ≥4%. For example, there are no events in 1987, when the long terms modulation for 22nd sunspot cycle commenced, supporting the proposal that drifts rather than ejecta, played a more important role in the modulation process at this time [25]. The absence of events in year 1987 provides evidence of a close association between ≥4% cosmic ray decrease events and fast ejecta. Though the CME rate observed by the solar maximum mission (SMM) coronograph increased monotonically from 1985 to 1989, there is a lack of fast (>800 km/sec) CME's in 1987 [26]. The effect at solar disc can be seen in the CME rate from 1979 to 1981, as observed by the solar wind coronagraph. This showed a maximum in 1980/1981 [27,28] but the highest rate of fast CME's have been observed in 1982, the year in which the maximum rate of cosmic rays decrease in 21st solar cycle occurred. This result is consistent with Howard *et al.* [27]. Also, it is remarkable that there is a local minimum in 1980. Thus, sunspot cycle dependence of cosmic ray decrease is related, not surprisingly, to the rate of fast CME's. Statistically, it is found that the CME's transit time from the Sun to the near Earth space falls in between 1 and 5 days and coarsely depends on the initial speed of CME's. This result is consistent with earlier findings [29–32].

The distribution of the sizes of class 1, 2 and 3 events *versus* the transit speed of the associated shock have been shown in Figure 3. Solid sphere, hollow sphere and

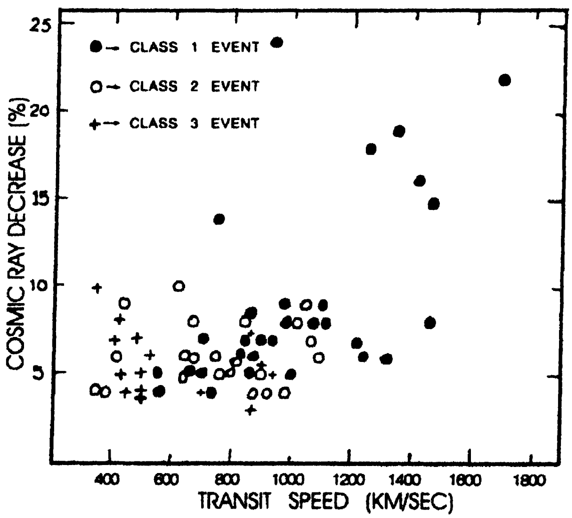

Figure 3. Distribution of sizes of class 1, 2 and 3 events *versus* the transmit speed during the period 1975-1994.

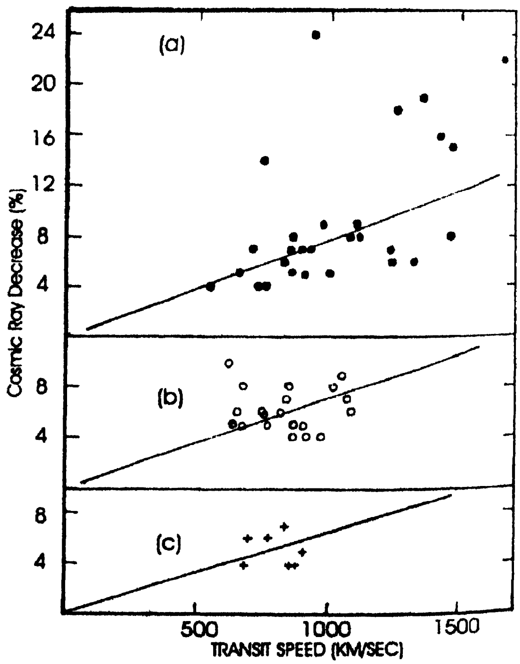

Figure 3(a,b,c). The best fit lines between transit speed and CR decreases (in %) of class 1, 2 and 3 events in (a) class 1 events, (b) class 2 events and (c) class 3 events for the period 1975-1994 plus sign indicate class 1, 2 and 3 events respectively. The best fit lines between transit speed in cosmic ray decreases of sizes of class 1, 2 and 3 events have been plotted in Figure 3(a,b,c), respectively. In Figure 3(b,c) all events have not been shown due to insufficiency of transit speed data. It is apparent from Figure 3 that there is a weak correlation between size of decrease and transit speed. Overall, the transit speed is not a good indicator of the size of the decrease because the ejecta also contribute to the decrease. The event of 24 March, 1991 is of interest because of related activity seen at Ulysses. We have associated the long duration solar event at 13°E on 23 March, 1991 with this decrease, resulting in a transit speed of 1700 km/second for the shock. We think it unlikely that shock seen at the Earth is same as that seen on 25 March at Ulysses [33] which is then at about 2.5 AU, 55°E of the Earth. We proposed that the shock and ejecta detected at Ulysses on March 25 are associated with the impulsive event at 28°E late on March 22, with the implied transit speed of this shock then being 1900 km/second. Since the solar event is impulsive, this CME may have been narrow and therefore may have missed the Earth [14]. This study concludes that major solar wind disturbances (about 50–60% of ≥4% Cosmic ray decreases with $Ap \geq 30$ along with $Dst \leq -40$ nT) originate with an identifiable solar event, which, in nearly all cases includes a long duration flare on soft X rays and $H\alpha$ flares.

Yearly occurrence of solar flux 10.7 cm (or 2800 MHz radio emission) with SSN's [34] have been plotted in Figure 4 during 21st and 22nd solar cycles and further the best fit lines between yearly occurrence of SSN's and solar flux have been plotted in Figure 4(a,b). for the 21st and 22nd solar cycle respectively. The correlation coefficient between SSN's and solar flux has been calculated and are found to be 0.99

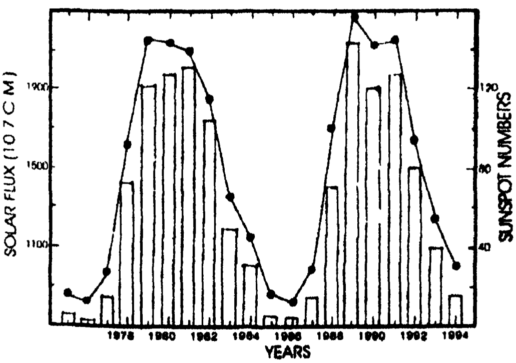

Figure 4. Yearly occurrence of solar flux with SSN's, plotted histographically during the period 1975–1994.

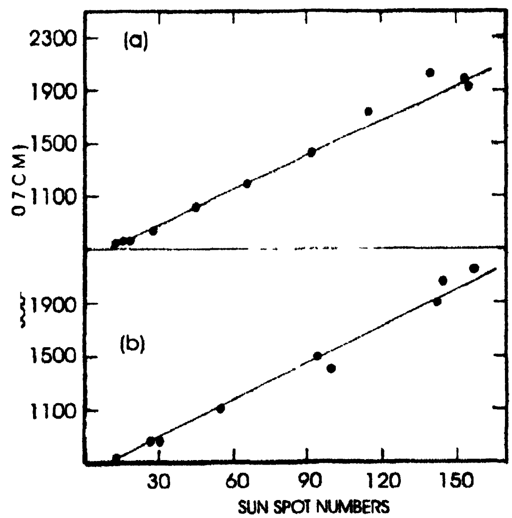

Figure 4 (a,b). The best fit lines between yearly occurrence of SSN's and solar flux : (a) 21st solar cycle and (b) 22nd solar cycle for the period 1975–1994.

for both 21st and 22nd solar cycle, which shows that solar flux and sunspot numbers are highly correlated as shown in Figure 4 and Figure 4(a,b) Similar result obtained by Mishra *et al* [35] from detailed study of SSN's and 10 7 cm solar flux can be used as they will yield the same result because SSN's and 10 7 cm flux are highly correlated

One final aspect of this paper is the study of solar wind disturbances causing GMS's, which are well associated with solar events Many researchers have attempted to learn about solar wind disturbances by making association with solar events [15 31] However, some of these studies have not considered energetic particle data and as a result, some of these associations may be incorrect As for example, Bothmers [36] and Rust [37] have attempted to relate the rotation of magnetic field in magnetic clouds with the twist of the magnetic field in eruption of particular prominences in the Sun Clearly, the conclusion of such studies will be more reliable if the associations have a higher probability of being correct This study will be more useful in determining the sources of cosmic ray decrease detected in the outer heliosphere in relation to GMS's [38] Furthermore, the weak relationship between solar parameters is not well understood presently In future studies this fact seems to be quite important in understanding the choice of solar parameter for studies of terrestrial phenomena

4. Conclusions

The following conclusions have emerged from the present investigations

(i) The majority of the events *i.e* 91% GMS's are caused by coronal mass ejections

(ii) The ejecta is intercepted only when the solar event originates within 40° of the Sun's central meridian

(iii) It is not always necessary that maximum number of events occur during the maximum activity period.

(iv) Statistically, it is observed that during 66% events, the decrease in CR intensity started few hours later than the occurrence of GMS at the Earth

(v) GMS's are highly correlated with SSN's during the even solar cycle as compared to odd solar cycle

(vi) SSN's and solar flux are highly correlated during even as well as odd solar cycle

(vii) Statistically, it is found that the CME's transit time from the Sun to the near Earth space lies between 1 and 5 days.

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