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Corotating high-speed solar-wind streams and recurrent cosmic ray modulation

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[1] We studied the solar magnetic cycle dependence of cosmic ray depressions due to the corotating high-speed solar wind streams (CSWS) during different polarity states of the heliosphere. The daily averaged cosmic ray intensity data from Climax, Oulu, and Thule neutron monitors together with simultaneous solar wind plasma and field data were subjected to the superposed epoch analysis with respect to CSWS start time. These analyses were carried out separately in different polarity states of the heliosphere $A < 0$ and $A > 0$ during solar minimum as well as during the periods of variable solar activity. Although the average variations in the solar wind velocity, IMF strength, and its variance are almost similar, the amplitudes of CSWS-associated cosmic ray depressions are quite different during different polarity epochs; they are larger during $A > 0$ than $A < 0$ periods. Further, correlation analysis between cosmic ray intensity and solar wind velocity during CSWS shows differences in their relationship during $A > 0$ and $A < 0$; they are much better during $A > 0$ than $A < 0$. Two other solar wind parameters, IMF strength and its variance, do not show a significant relationship with cosmic ray intensity change through the passage of these streams, although the initial depression coincides the enhancement of the two parameters. These results are discussed in the light of existing models of galactic cosmic ray modulation.

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1. Introduction

[2] Instruments on board satellites and spacecraft have been detecting the high-speed solar wind streams lasting for several days. The passage of these streams leads to several effects on the Earth and the interplanetary space. These streams are therefore of great importance for solar and heliospheric research. A high-speed stream is characterized by a large increase in the solar wind velocity lasting for several days. The beginning time, i.e., commencement of the stream, is taken at the time the velocity starts increasing toward the maximum. The long-lasting corotating high-speed stream (CSWS) exhibits an apparent tendency to recur at intervals of $\sim$27 days. In the corotating streams proton density rises to high values near the leading edge of the stream, the proton temperature varies in a pattern similar to that of the flow speed, and the polarity of the interplanetary magnetic field throughout the stream is almost constant (for more specific and detailed discussion on high-speed streams and their characteristics, see, e.g., *Lindblad and Lundstedt* [1981], *Lindblad et al.* [1989], *Mavromichalaki et al.* [1988], and *Mavromichalaki and Vassilaki* [1998]). Such corotating streams, upon reaching the detector (e.g., neutron monitor), are likely to produce slowly varying corotating depressions in cosmic ray intensity lasting for several days with amplitude $\lesssim 3\%$ at midlatitude stations.

[3] Interaction between a slow and the fast solar wind from coronal holes creates a corotating interaction region (CIR), a phenomenon brought out into prominence again by Ulysses observations. The effect of CIRs on cosmic rays received renewed attention in recent years, and it is now realized that the CIRs are much more dominant features in the heliosphere than previously anticipated. Thus the study of the effects of corotating high-speed streams on cosmic rays will be helpful in understanding the modulation of cosmic rays in the heliosphere.

[4] Galactic cosmic ray depressions due to CIRs and high-speed solar wind streams have been studied for many years. However, the relative contribution/role of corotating barrier, local structures within CIR, enhanced solar wind speed, and the direction of the global magnetic field in the modulation of galactic cosmic rays during the passage of a CIR and high-speed stream is still not fully understood. For a comprehensive review of the effects of CIRs and high-speed streams on energetic particles in the heliosphere, see *Richardson* [2004].

[5] Previous studies of cosmic ray depressions due to corotating high-speed streams [e.g., *Duggal and Pomerantz*, 1977; *Iucci et al.*, 1979; *Venkatesan et al.*, 1982; *Burlaga et al.*, 1984; *Mishra et al.*, 1990; *Badruddin*, 1993, 1997; *Yadav et al.*, 1994; *Richardson et al.*, 1996, 1999; *Alania et al.*, 2001; *Gil et al.*, 2005] have reached at different and

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sometimes even conflicting conclusions, probably due to near simultaneous variations in a number of parameters (e.g., solar wind speed, magnetic field fluctuations, and magnitude) within a stream. As a consequence of variations in these parameters, several processes could contribute in recurrent cosmic ray modulation. Changes in solar wind speed could cause variations in convection and adiabatic cooling, diffusion coefficient may change due to variation in turbulence level, and variation in field strength may be responsible for causing variations in particle drifts and diffusion coefficients. Models proposed to explain the corotating cosmic ray depressions have emphasized different processes [see *Richardson et al.*, 1996; *Richardson*, 2004].

[6] Recurrent cosmic ray modulation due to CIRs and high-speed streams have been studied using ground-based neutron monitors and spacecraft data [e.g., *Vershell et al.*, 1975; *Parker*, 1976; *Shah et al.*, 1978; *Iucci et al.*, 1979; *Duggal et al.*, 1981; *Venkatesan et al.*, 1982; *Tiwari et al.*, 1983; *Burlaga et al.*, 1984; *Mishra et al.*, 1990; *Yadav et al.*, 1994; *Shrivastava and Shukla*, 1994; *Kunow et al.*, 1995; *Richardson et al.*, 1996, 1999; *Badruddin*, 1997; *Zhang*, 1997; *Paizis et al.*, 1999; *Alania et al.*, 2001; *Reames and Ng*, 2001; *Gil et al.*, 2005, *Gupta and Badruddin*, 2005; *Singh and Badruddin*, 2005; *Venkatesan and Badruddin*, 1990; *Simpson*, 1998; *McKibben et al.*, 1999; *Richardson*, 2004]. However, such depressions in cosmic ray intensity have been associated with enhanced convection by high-speed solar wind [*Newkirk and Fisk*, 1985; *Iucci et al.*, 1979; *Richardson et al.*, 1996], diffusion in enhanced/compressed field region [*Burlaga et al.*, 1984; *Kota and Jokipii*, 1991], and/or particle drifts in large-scale heliospheric magnetic field [*Kota and Jokipii*, 1991, 2001; *Burger and Hitge*, 2004]. Further studies of CSWS associated modulation in the galactic cosmic ray intensity are therefore needed in order to obtain more insight into the modulation phenomena.

[7] In this paper we have studied the GCR depressions due to corotating streams, using cosmic ray data of Climax (geographical latitude 39.37°N, longitude 106.18°W, cutoff rigidity = 2.97 GV), Oulu (geographical latitude 65.02°N, longitude 25.50°E, cutoff rigidity = 0.61 GV), and Thule (geographical latitude 76.60°N, longitude 68.80°W, cutoff rigidity = 0.00 GV) neutron monitors, during different polarity states of the heliosphere ($A > 0$ and $A < 0$) in minimum as well as varying solar activity conditions. We have used daily averaged GCR intensity data, as such averaging eliminates the effects of ever present daily variations (amplitude ~0.4%) from the cosmic ray intensity data.

[8] Present investigation has been carried out for (1) four periods of different solar magnetic conditions (two $A > 0$ and two $A < 0$ epochs) during four solar activity minimum periods when transient streams are almost absent, and (2) the same number of polarity periods with varying solar activity. Solar activity minimum periods are 1964–1965 ($A < 0$), 1975–1976 ($A > 0$), 1985–1986 ($A < 0$), and 1995–1996 ($A > 0$), while the extended periods with varying solar activity are 1964–1969 ($A < 0$), 1971–1979 ($A > 0$), 1981–1989 ($A < 0$), and 1991–1996 ($A > 0$). Although later periods contain the periods of higher solar activity, we have removed the period from our analysis when large-amplitude transient effects (e.g., Forbush decreases) are observed in GCR data.

2. Result

2.1. Minimum Solar Activity

[9] In order to study the cosmic ray modulation due to the corotating high-speed streams, we have applied the method of superposed epoch analysis on neutron monitor data as well as solar wind plasma/field data, namely solar wind velocity (V), proton temperature (T), density (N), IMF strength (B), and its variance (σ_B). Enhancements in V, B, T, and N are helpful in identifying the interaction region formed due to interaction of high-speed stream with the slower stream in interplanetary space. Moreover, suggested processes of modulation of GCR intensity are associated with V (convection), B, σ_B (diffusion), and the direction of B in large-scale heliosphere (drifts).

[10] In Figures 1a and 1b we have plotted the superposed epoch analysis results of the daily averaged data of GCR intensity I (%) at Climax NM, solar wind velocity V (km/s), field magnitude B (nT), its variance σ_B (nT), plasma temperature T (K), and density N (/cc) during four solar minimum periods. Epoch (zero day) corresponds to the day of start of high speed stream. It is seen from these figures that (1) GCR intensity decreases during the corotating streams showing corotating modulation. (2) The parameters N, B, and σ_B peak on zero day indicating the formation of interaction region. (3) The speed of the streams peaks on 2nd/3rd day and then decreases slowly in several days time. (4) Days of minimum intensity are almost coincident with the days of maximum speed in the stream.

[11] Table 1 summarizes the GCR intensity decrease (%) as observed at three neutron monitors located at Climax, Oulu, and Thule and peak values of solar wind parameters V, B, σ_B, N, and T, the values obtained from superposed epoch analysis of daily average data. The enhancement in speed ΔV and the ratio B_2/B_1, where B_2 is the compressed field strength in interaction region and B_1 is the normal field on preceding day, has also been tabulated together with these parameters. The parameters N and T show the physical conditions within the stream while parameters V, B, and σ_B can be related to modulation processes. It is inferred from this table and Figures 1a and 1b that corotating decrease amplitude is larger during $A > 0$ than $A < 0$ epoch. An examination of peak values of various parameters ratio B_2/B_1 and velocity increase (ΔV), given in Table 1, does not show any systematic difference in their values between $A < 0$ and $A > 0$ epochs.

[12] In order to check the statistical significance of GCR depressions, obtained from superposed epoch analysis, we have adopted the the t-test based procedure illustrated by *Singh and Badruddin* [2006] and tested the results, both during minimum and variable solar activity periods. The results of the statistical analysis are shown in Figure 2. In this figure, vertical bar represents 95% confidence limit of minimum intensity, middle horizontal line is the mean value of the intensity, and the region between upper and lower horizontal lines represent 95% confidence interval of mean intensity. If the vertical bar enters in 95% confidence interval of mean intensity, then depression in cosmic ray intensity is insignificant at this level with respect to mean value. If it does

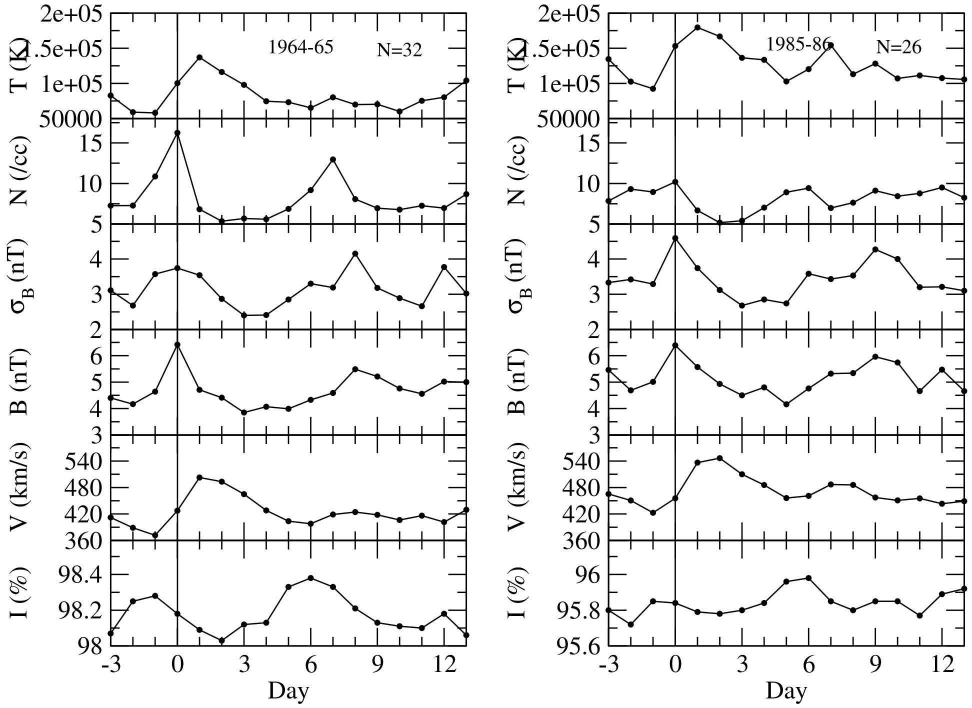

Figure 1a. Superposed epoch analysis results of daily averaged GCR intensity observed at Climax neutron monitor and solar wind plasma/field data; zero day corresponds to the arrival date of CSWS for the minimum period (1964–1965) and (1985–1986), when A < 0.

not enter in this interval then results are significant at that level. As shown in Figure 2, during minimum solar activity periods the corotating depressions in GCR intensity are statistically significant only during A > 0 epoch. Here it may be worth mentioning that *Burger and Hitge* [2004] developed a steady-state three-dimensional (3-D) modulation model using a divergence-free Fisk-Parker hybrid heliospheric magnetic field and investigated the ~26-day recurrent variation using this model. Their simulation results indicate that the hybrid field reduces intensities compared to the Parker field when A > 0; when A < 0, the global effect of the hybrid field are almost negligible.

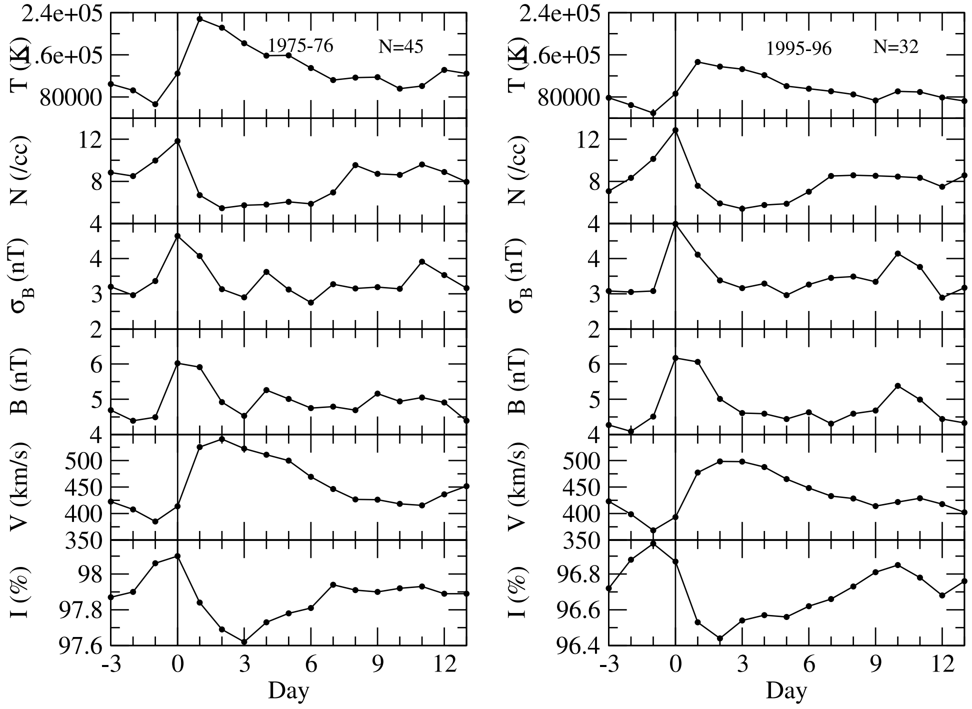

Figure 1b. Same as Figure 1a for the minimum period (1975–1976) and (1995–1996), when A > 0.

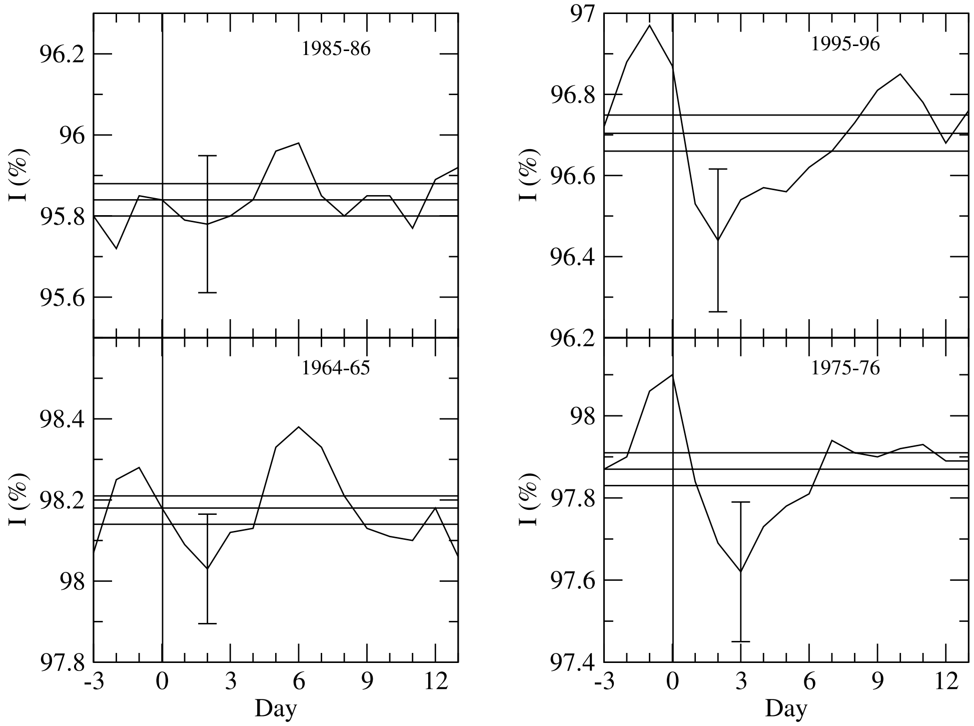

Figure 2. Statistical test applied to cosmic ray intensity changes due to CSWS in four solar minimum periods, two $A < 0$ (1964–1965, 1985–1986) and two $A > 0$ (1975–1976, 1995–1996) epochs. Depressions during $A > 0$ are statistically significant at 95% confidence level, as vertical bars do not enter in the area between horizontal lines (95% confidence interval of mean value).

[13] *Iucci et al.* [1979] observed that during the passage of high-speed streams, maximum depression in cosmic ray density was correlated with the maximum speed inside the stream and with the magnitude of the increase in solar wind speed above the stream leading edge. *Richardson et al.* [1996] also observed similar relationship with solar wind but a weak positive correlation. The relationship between maximum depression in GCR and maximum solar wind velocity of high speed stream, were examined by dividing events into $A < 0$ and $A > 0$ epoch by *Richardson* [2004]. Their plots show considerable scatter in data points and weak correlation in both the epochs; however, the correlation is better in $A > 0$ epochs compared to $A < 0$ epochs. *Singh and Badruddin* [2005] studied the relationship between cosmic rays and solar wind velocity during corotating streams both during $A > 0$ and $A < 0$ epochs. They have found better correlation in $A > 0$ epoch as compared to $A < 0$ epoch.

[14] We have done correlation analysis of intensity variation with various parameters V, B, σ_B observed during four solar minimum periods; the correlation is good with solar wind velocity only, that too during $A > 0$ epochs (see Table 2). Scatterplots between the variation in GCR intensity and solar wind velocity along with the best fit linear curves during different epochs in solar minimum conditions are shown in Figure 3.

2.2. Variable Solar Activity

[15] In order to see whether the polarity-dependent effect in corotating decrease amplitude can be observed only during solar minimum periods or during other periods also, we have made similar analysis of the data during variable solar activity periods of $A < 0$ (1964–1969, 1981–1989) and $A > 0$ (1971–1979, 1991–1996). The results of superposed epoch analysis are shown in Figures 4a and 4b and the peak values of various parameters, the ratio B_2/B_1, speed difference ΔV along with the depressions in GCR intensity are summarized in Table 3.

[16] It is seen from Figures 4a and 4b that as in minimum periods, modulation due to the corotating high-speed streams is stronger in $A > 0$ (1970s and 1990s) epochs. The plasma and field parameters, listed in Table 3, do not show any systematic difference in their values during $A > 0$ and $A < 0$ periods.

[17] Adopting the same procedure as in Figure 2, we have tested the significance of depressions observed during variable solar activity periods (see Figure 5). The depres-

Table 1. GCR Intensity Depression, %, and Peak Values of Various Solar Wind Plasma and Field Parameters Due to Corotating High-Speed Streams During Minimum Solar Activity Periods

	ΔI									
Periods	Climax	Oulu	Thule	V	B	σ_B	N	$T \times 10^5$	B_2/B_1	ΔV
1964–1965 ($A < 0$)	0.25	0.27	0.27	500	6.5	3.8	12.0	1.35	1.38	129
1975–1976 ($A > 0$)	0.48	0.43	0.77	540	6.2	4.7	12.0	2.25	1.34	155
1985–1986 ($A < 0$)	0.07	0.12	0.13	540	6.4	4.6	10.0	1.75	1.27	124
1995–1996 ($A > 0$)	0.53	0.65	0.48	500	6.2	5.0	13.0	1.40	1.37	130

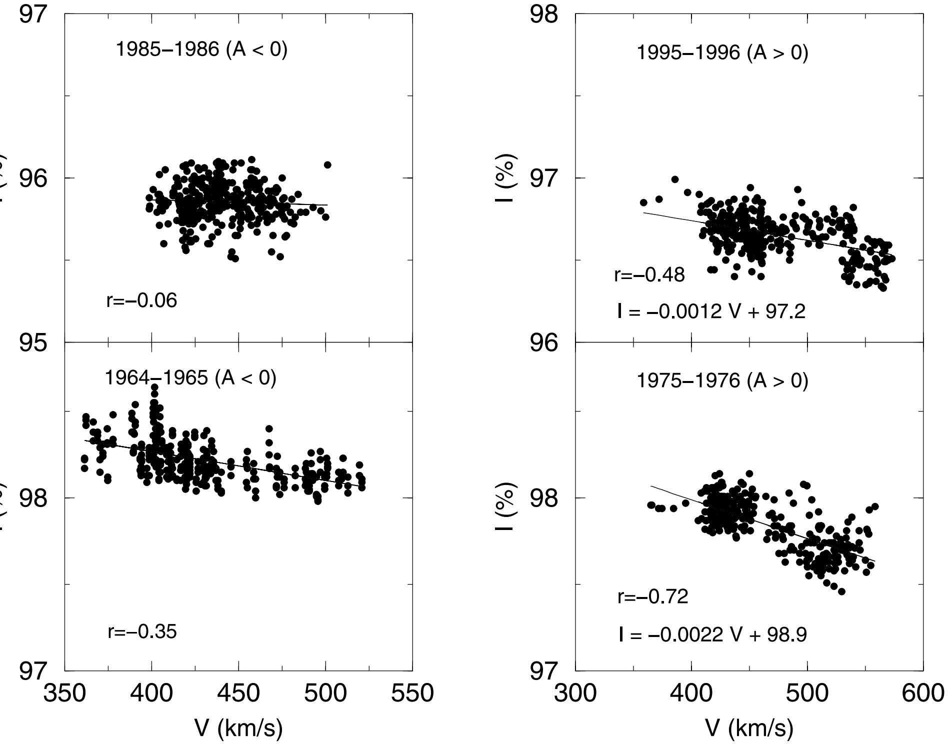

Figure 3. Relationship between GCR intensity and solar wind velocity during CSWS observed in minimum periods 1964–1965, 1975–1976, 1985–1986, and 1995–1996.

sions during variable solar activity periods are also found to be statistically significant during A > 0 epochs.

[18] From the correlation analysis between variation in GCR intensity and various parameters V, B, σ_B during different polarity epochs in variable solar activity periods (see Table 4), we found that correlation of GCR intensity was good during 1970s and 1990s (A > 0) with solar wind velocity only.

[19] The scatterplot of GCR intensity with solar wind velocity during high-speed steams is shown in Figure 6. It

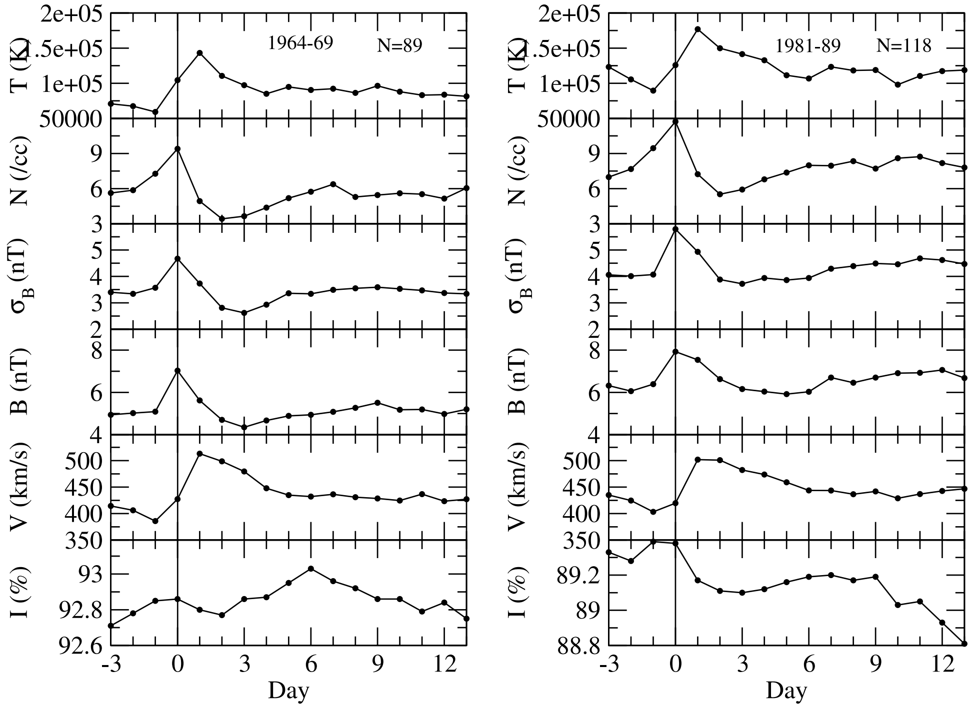

Figure 4a. GCR intensity and solar wind plasma/field data; zero day corresponds to arrival date of CSWS in variable solar activity period (1964–1969) and (1981–1989), when A < 0.

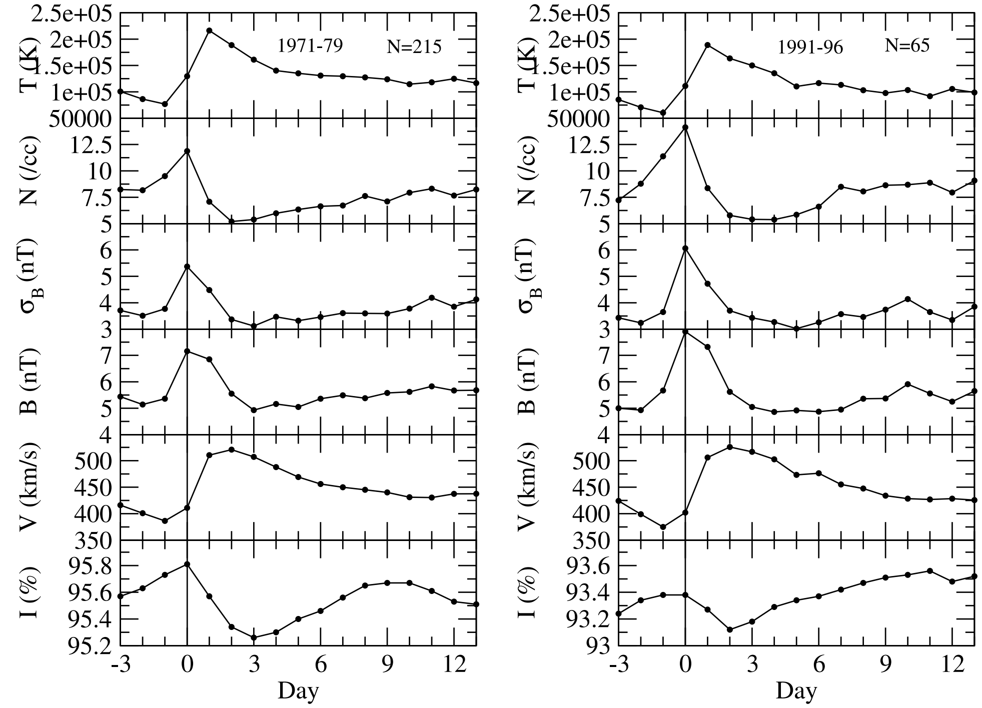

Figure 4b. Same as Figure 4a for variable solar activity period (1971–1979) and (1991–1996), when A > 0.

appears that the response of the GCR intensity to solar wind enhancements is apparently reduced in A < 0 epochs. However, the exact cause of this apparent reduction in the response of GCR to solar wind enhancements is not clear. It may be due to epoch dependent transport coefficients [*Richardson et al.*, 1999] and/or some other unknown reason. It will be interesting to understand which model [e.g., *Richardson et al.*, 1999; *Kota and Jokipii*, 2001; *Burger and Hitge*, 2004] can quantitatively better explain the epoch dependent corotating modulation in GCR (weaker in A < 0 and stronger in A > 0).

3. Discussion

[20] The recurrent modulation of GCR must have its origin in the solar wind and interplanetary magnetic field (IMF). This is because all the basic modulation processes, namely, particle convection, diffusion, drift, and adiabatic deceleration are controlled by the properties of magnetic field fluctuation, large-scale IMF structures and the solar wind velocity. How the recurrent modulation contributes to the global modulation and, if so, by which mechanism is still not solved completely [*Simnett et al.*, 1998].

[21] As regards the structure(s) responsible for corotating depressions, previous studies, have associated the onset of recurrent modulations with various structures. They include stream leading edges, magnetic sector boundaries, and magnetic field enhancements, etc. Using high-time resolution guard data, *Richardson et al.* [1996] concluded that recurrent modulations at 1AU typically commence at the leading edge of the high-speed stream or at the enhancement in field turbulence in the CIR (which often occurs at the stream leading edge). The cosmic ray density also tends to be anticorrelated with the solar wind speed, suggesting that increased cosmic ray convection plays a major role in the production of recurrent cosmic ray depression, with the enhanced turbulence following the interface also contributing.

[22] *Barouch and Burlaga* [1975] have found that for corotating streams observe at 1 AU, there is a strong correlation between the cosmic ray intensity and the strength of the magnetic field; intensity decreases when the region of enhanced field moves past a spacecraft. This can be interpreted in terms of small diffusion coefficient in the stronger fields of corotating interaction regions. At larger distance from the Sun, near 10 AU, observations of the interaction and coalescence of two corotating streams leading to formation of compound stream were presented by *Burlaga et al.* [1984, 1985]. *Burlaga et al.* [1985] found a simple correlation between the quantity B/Bp and the count rate of particles $\geq$ 75 MeV/nucleon derived from Voyager 2 data; B is the total magnetic field strength measured by the spacecraft and Bp is the mean Parker spiral magnetic field. Several large enhancements in B/Bp were observed to be associated with interaction regions which probably resulted from interaction of two or more distinct flows. During the passage of these regions, cosmic ray intensity decreased at

Table 2. Correlation Coefficient Between Cosmic Ray Intensity and Various Solar Wind Parameters During Corotating High-Speed Streams Observed in Solar Minimum Periods

Periods	Polarity	I Versus V	I Versus B	I Versus σ_B
1964–1965	A < 0	−0.35	−0.11	−0.26
1975–1976	A > 0	−0.72	0.11	−0.07
1985–1986	A < 0	−0.08	0.10	−0.05
1995–1996	A > 0	−0.48	0.28	0.10

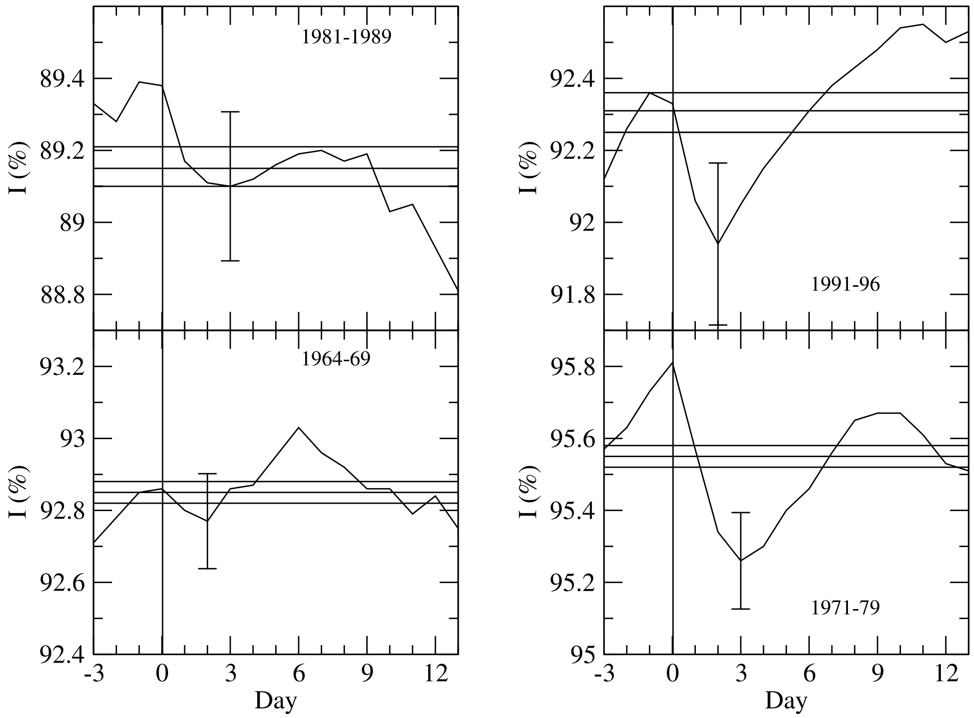

Figure 5. Statistical test applied to GCR intensity depressions due to CSWS in two A < 0 (1964–1969, 1981–1989) and two A > 0 (1971–1979, 1991–1996) shows that depression during A > 0 are statistically significant at 95% confidence level but not in A < 0.

a rate proportional to (B/Bp-1). There observations led *Burlaga et al.* [1985] to conclude that cosmic ray intensity is more closely related to the magnetic field strength and magnetic turbulence than to the stream profiles and that the results are consistent with the idea that cosmic ray modulation is produced by diffusion process in which particles are scattered by magnetic field fluctuations in magnetohydrodynamic turbulence.

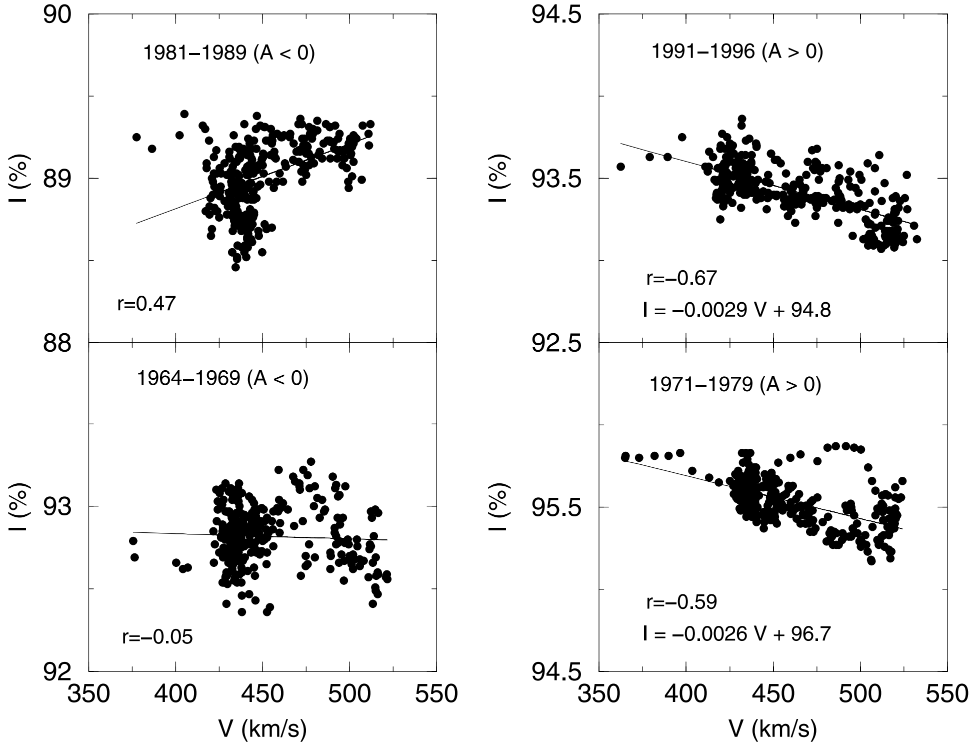

Figure 6. Relationship between GCR intensity and solar wind velocity during CSWS observed in periods 1964–1969, 1971–1979, 1981–1989, and 1991–1996.

Table 3. GCR Depression, %, and Peak Values of Various Solar Wind Plasma and Field Parameters Due to Corotating High-Speed Streams During Varying Solar Activity Periods

	ΔI									
Periods	Climax	Oulu	Thule	V	B	σ_B	N	$T \times 10^5$	B_2/B_1	ΔV
1964–1969 ($A < 0$)	0.09	0.19	0.19	520	7.0	4.6	9.5	1.50	1.38	128
1971–1979 ($A > 0$)	0.55	0.55	0.63	525	7.4	5.4	11.9	2.25	1.33	135
1981–1989 ($A < 0$)	0.28	0.35	0.34	510	8.0	5.8	11.8	1.75	1.18	098
1991–1996 ($A > 0$)	0.39	0.54	0.42	530	8.0	6.0	14.8	1.35	1.39	151

[23] A later study [*Richardson et al.*, 1999] reported that the amplitude of recurrent cosmic ray modulations in the inner heliosphere at solar minimum exhibits a dependence on 22-year global solar magnetic field polarity cycle. However, these authors commented that the reason for this epoch-dependence is unclear at present as high-speed streams and CIRs do not appear to be necessarily stronger in $A > 0$ epochs. Earlier, *Kota and Jokipii* [1991] suggested that polarity dependence in corotating depressions might be expected if CIRs introduce enhanced particle scattering at low latitudes. However, stronger modulations would then be expected when cosmic rays enter the heliosphere along the equatorial regions (i.e., in $A < 0$ epochs) than when they enter over the poles ($A > 0$) [*McKibben et al.*, 1999]. This is the opposite dependence to that which is actually observed. However, a later modeling by *Kota and Jokipii* [2001], by including a southward displaced heliosphere current sheet, show results that were in quantitative agreement with the observed results, i.e., stronger modulation in $A > 0$ epoch. If effects due to local diffusion are predominant, then no A-dependence would be expected. In this case, another possibility is that the particle transport parameters have a solar-field dependence [e.g., *Chen and Bieber*, 1993; *Bieber*, 1998] such as to enhance the effect of cosmic ray convection in $A > 0$ epochs. A further complication is that the stream configuration may also play a role since large recurrent depressions can result from the combined effect of depressions in multiple, interacting streams [*Richardson*, 2004].

[24] Two basic kind of recurrent phenomena in the solar wind and interplanetary magnetic field have been observed. One is the corotating interaction region which is the result of compression between slow and fast stream. The other recurrent phenomena is the heliospheric current sheet (HCS) that is usually tilted from the solar equator. The association between the passage of fast streams and crossing of HCS in the ecliptic plane at 1 AU (sector structure) has also been examined [e.g., see *Rangarajan and Mavromichalaki*, 1989; *Mavromichalaki et al.*, 1999].

[25] To account for the observed corotating decreases in GCR intensity and their various features, models have been developed, however, emphasis differ from one model to the other so far as the physical processes mainly responsible for this phenomenon are concerned. *Iucci et al.* [1979] and *Badruddin and Yadav* [1985] suggested the enhanced convection of cosmic rays by high-speed streams. *Richardson et al.* [1996] modeled enhanced convection process in a steady state convection-diffusion model and suggested that the amount of particle scattering (and hence particle radial mean free path) is likely to vary from stream to stream. *Badruddin et al.* [1985], *Newkirk and Lockwood* [1981], *Newkirk and Fisk* [1985], and *Badruddin and Ananth* [2003] proposed that recurrent cosmic ray modulation near ecliptic arise because of latitudinal cosmic ray density gradients that are arranged about a tilted heliospheric current sheet. *Reames and Ng* [2001] noted that peak intensities occurred near north-south crossing of HCS and valley near south-north crossing of HCS, inconsistent with simple particle gradient organized around the current sheet. *Barouch and Burlaga* [1975] suggested that enhanced drifts of particles out of the region of enhanced magnetic field associated with CIR may cause the cosmic ray depression associated with high-speed streams. *Kota and Jokipii* [2001], in their 3-D drift modulation model including CIR, assumed that particle scattering increases with the magnetic field ($\kappa \propto \lambda \propto 1/B$) in the vicinity of CIR. The model of *Scholer et al.* [1979] incorporates changes in the solar wind parameters and magnetic field turbulence in CIRs. *Kota and Jokipii* [2001] in their simulation considered a southward displaced heliospheric current sheet to account for 22-year variation in corotating decreases. Solutions to a 3-D transport equation including drifts, obtained by *Gil and Alania* [2001], predicted that the phase of the 22-year variation may reverse at larger distances in the heliosphere so that larger variations are seen when $A < 0$. However, all the proposed various models are far from perfect (for a critical assessment of various models, their merits, and demerits, see review by *Richardson* [2004]).

[26] More recently, *Burger and Hitge* [2004] developed a divergence free Fisk-Parker hybrid heliospheric magnetic field and studied the effect of such field on galactic cosmic rays by solving numerically the 3-D steady state Parker transport equation. They investigated ∼26-day recurrent intensity variations of both protons and electrons and their latitudinal intensity gradient for both solar magnetic polarity epochs ($A < 0$ and $A > 0$). Their simulation results show that the amplitude of recurrent variations is directly proportional to the latitudinal intensity gradient both for protons and electrons. They found common linear relation both for protons and electrons and in both polarity epochs ($A < 0$ and $A > 0$), in agreement with observational studies [*Zhang*, 1997; *Paizis et al.*, 1999]. However, with drift switched off in the code, electrons and protons obey different but still linear relationship, indicating that drifts may be important for corotating modulation. While *Burger and Hitge* [2004] do not show results for recurrent variations in the ecliptic plane, they show that at high latitudes the amplitude is always significantly larger when particles enter the heliosphere through the polar regions of the Sun compared to when they enter through the ecliptic region; protons enter

Table 4. Correlation Coefficient Between Cosmic Ray Intensity and Various Solar Wind Parameters During Corotating High-Speed Streams in Varying Solar Activity Periods

Periods	Polarity	I Versus V	I Versus B	I Versus σ_B
1964–1969	$A < 0$	−0.05	−0.49	−0.53
1971–1979	$A > 0$	−0.59	0.61	0.35
1981–1989	$A < 0$	0.47	−0.07	0.13
1991–1996	$A > 0$	−0.67	0.08	−0.19

through the polar regions during A > 0 epochs. Therefore if recurrent variations due to a Fisk-type field is present near the Earth, one would expect that the amplitudes would be larger for protons during A > 0 epoch than during A < 0 epoch.

[27] The models with corotating interaction regions, including dynamical, compressed magnetic field, may explain onset of corotating depressions due to enhanced particle scattering at low latitudes. However, the observed polarity dependent effects in cosmic ray depressions is hard to explain from these models. However, if particle transport parameters have solar polar dependence [e.g., *Chen and Bieber*, 1993] in such a manner that there is enhanced effect of transport parameters in A > 0 epochs, convection-diffusion models, as proposed by *Richardson et al.* [1999] might explain the corotating depressions. One may also expect that a global model in which the large-scale structure is controlled by drift effects in conjuction with diffusion, convection, and energy change, and small-scale structure is caused by diffusion effects in corotating structures may produce the observations [*Simnett et al.*, 1998]. However, 3-D drift models [*Kota and Jokipii*, 2001] could produce the observed polarity dependence when a southward displaced HCS was considered. However, the potential of Fisk-field [*Fisk*, 1996] in the study of corotating decreases should also be explored.

4. Conclusion

[28] GCR depressions due to CSWS are significantly larger during A > 0. Correlation analysis between cosmic ray variation and solar wind velocity during high-speed streams shows much better correlation during A > 0 as compared to A < 0 epochs. Whether this reduced response of cosmic rays to solar wind enhancement is due to different paths of cosmic rays entering in the heliosphere during A < 0 and A > 0 (through equatorial region and polar regions respectively) or due to polarity dependent transport coefficients is not clear yet.

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