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Forbush decreases in cosmic rays

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Abstract. Forbush decreases are one of the most important cosmic ray time-variations observed by ground-level neutron monitors. A detailed review of the characteristics of three different and distinct types of Forbush decreases is presented along with satellite observations. It is indicated that the interplanetary disturbances associated with Forbush decreases combine and merge with one another at larger distances from the sun and play a very important role in producing the long term solar cycle modulation of cosmic ray intensity.

Key words : cosmic rays—time variation—interplanetary disturbances

1. Introduction

The intensity of cosmic rays undergoes decreases some of which are described as the 'classical Forbush decreases'. These reveal a sudden decrease over a day (generally half a day) and recovery over many days, either to the original level or to a new level. There are other gradual decreases; we discuss all of them under the above general heading though it may not be quite appropriate to call them Forbush decreases according to the 'classical' definition.

Ideally the Forbush decrease is characterized by a very rapid decrease in the cosmic ray intensity which recovers gradually to the original level or to a new intensity level over several days. They are often associated with geomagnetic storms caused by solar flares (Sandstrom 1965; Dorman 1963). These are considered to be transient phenomena which do not corotate (recur). Hence we consider that the decreases are produced by cosmic ray particles interacting with the magnetized plasma clouds propagating outwards from the sun (Lindeman 1919; Chapman and Ferraro 1929; Alfven 1954). Note that some of the gradual decreases however do not fit the classical description of 'sharp' decreases.

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Morrison (1954, 1956) suggested that the magnetic field associated with Forbush decreases is turbulent and the cosmic rays diffuse into the cloud. The decrease in cosmic ray intensity is caused by diffusion to fill a cloud in a time smaller than the time it takes for the cloud to travel to a distance of 1 AU. Cocconi *et al.* (1958) as well as Gold (1959, 1962) have suggested that the magnetic field from the sun forms a magnetic tongue and the cosmic ray decrease is caused by scattering due to gradients within the magnetic field. Piddington (1958) proposed that a magnetic tongue detaches from the sun by magnetic reconnection, forming a closed bottle (or a bubble). Furthermore, Parker (1961) has shown that the interplanetary magnetic field could be compressed and distorted by a shock wave associated with the solar wind (Gold 1955) forming a shell of intense magnetic fields. the Forbush decreases in such cases are produced by the diffusion of cosmic rays through the shell (Parker 1963). This model explains that gradual Forbush decreases are similar to the one suggested by Morrison's turbulent magnetized plasma cloud.

Satellite observations have indicated the existence of hydromagnetic shocks and sheath behind the shocks consisting of compressed, distorted ambient magnetic fields. The observations have also indicated the presence of plasma clouds of limited angular extent having magnetic fields in them with higher strength than average. It has been found that these interplanetary shocks are driven by plasma clouds (Borrini *et al.* 1982). The present terminology is used for the total configuration of combination of shock, sheath and magnetized plasma clouds (interplanetary transients). The magnetic field configuration in plasma clouds has many forms; tongues and bottles have been suggested by a number of authors (Hundhausen 1972; Bobrov 1979; Pudovkin 1977, 1979; Garanios 1981; Sarris & Krimigis 1982). The association of a magnetized plasma cloud with a loop-like magnetic field configuration has been discussed by Burlaga *et al.* (1982). Again the magnetic field strength is higher than average and the satellite observations have indicated the presence of a magnetic loop (Burlaga & Behannon 1983).

It has been observed that the magnetic cloud moves with a speed greater than the ambient solar wind and the cloud density has been observed to be filamentary (Burlaga *et al.* 1981). The magnetic pressure in a cloud has been found to be higher than the thermal pressure (Klein & Burlaga 1982). The cloud has been preceded by a shock with a higher density, temperature and magnetic field strength between itself and the shock. A sheath has been observed consisting of compressed and disordered magnetic fields. Such a combination has also been earlier referred to, as the interplanetary transient.

Cosmic rays passing through such a configuration could be expected to diffuse in the sheath behind the shock and drift due to the gradient in the magnetic field. Further the motion of cosmic rays has been found to be governed by the magnetic cloud which expands at half the Alfven speed as it moves away from the sun (Burlaga & Bahannon 1983). This may also be controlled by the magnetic field pressure which may exceed the plasma pressure in a cloud (Parker 1957; Klein & Burlaga 1982). The time delay between the coronal mass ejection and the magnetic cloud arrival at the satellite gives the speed of the cloud; this is in agreement with the speed of the cloud directly measurable by satellite.

The observations have indicated a close correlation between the interplanetary shock and coronal mass ejection (Gosling *et al.* 1974; Sheeley et al. 1982 and Schwenn *et al.* 1982). Since the magnetic clouds and the interplanetary shocks are related to coronal mass ejections, which are in turn related to solar prominences, correlation between magnetized plasma clouds and prominences is also to be expected. This had been suggested by Lindeman as early as 1919 and Chapman & Ferraro in 1929. These relations are quite important for understanding the long-term 11-year variation of cosmic rays.

The Forbush decreases which are gradual and the interplanetary transients were also observed at a radial distance well beyond the earth's orbit by spacecraft Pioneer 10 and 11, Flare-associated shocks have been investigated by a number of authors (Intriligator 1977; Smith & Wolfe 1977, 1979; Smith 1983; Burlaga *et al.* 1981). They have analyzed multi-spacecraft observations of flows up to distances of 2 AU. A large Forbush decrease observed at 16 AU by Pioneer 10 and at 7 AU by Pioneer 11 have been discussed by Van Alen (1979) and Pyle *et al.* (1979). The size of the cosmic ray decreases at such large distances was comparable to that of corresponding Forbush decreases observed by a ground-based nautron monitor. The duration however appeared larger at greater radial distances from the sun; this may be attributed to the superposition of several effects (von Rosenvinge *et al.* 1979). The decreases propagated away from the sun at a constant speed of 960 km s^{-1} in this case and extended over at least 160° longitude. It is important that a detailed analysis of transient flows and decreases with data observed over a large radial distance from the sun is needed for a better understanding of the processes controlling these variations.

2. Corotating Forbush decreases and the 27-day variations

The existence of recurrent interplanetary streams with the 27-day periodicity corresponding to the average solar rotation was invoked by Neugebauer *et al.* (1986) to explain the observation of recurrent geomagnetic storms. The existence of a 27-day variation in galactic cosmic ray intensity with their relation with recurrent interplanetary streams has been known for many years (Mayer & Simpson 1954; Sarabhai *et al.* 1954; Monk & Compton 1939). The cosmic ray 27-day variations are shown to be correlated with the speed of the recurrent streams. These can also be treated as simple recurrences of corotating Forbush decreases. The recurrent stream is also called a corotating stream because it appears to corotate with the sun as seen from the earth. The study of the 27-day cosmic variations essentially implies an understanding of the relation between corotating Forbush decreases and corotating streams.

A correlation between corotating Forbush decreases and corotating enhancements in the interplanetary magnetic field strength has been first observed by Barouch & Burlaga (1975). They have shown the drifts associated with gradients in the magnetic fields with corotating Forbush decreases. A correlation between magnetic field increases and reduction in cosmic ray intensity has been studied by Duggal *et al.* (1983) and their results also has shown that the reductions in the magnetic field sometimes have been associated with increases in cosmic ray flux.

It has been observed that in addition to the magnetic field strength the corotating Forbush decreases are also influenced by small-scale magnetic field fluctuation of the directions. The amplitude of the field fluctuations are more when the speed of the stream is high (Belcher & Davis 1971; Behannon & Burlaga 1981; Barnes 1979) and the cosmic ray intensity is reduced by diffusion in these disturbances (Morrison 1954; Morfill *et al.* 1979). The relative importance of the speed of the stream, the magnetic field strength, and the field fluctuations on the cosmic ray variations have not been established. Since the enhancement in the magnetic fields is correlated with the velocity profiles and the fluctuations in the magnetic field, the cosmic ray variations should reveal correlations

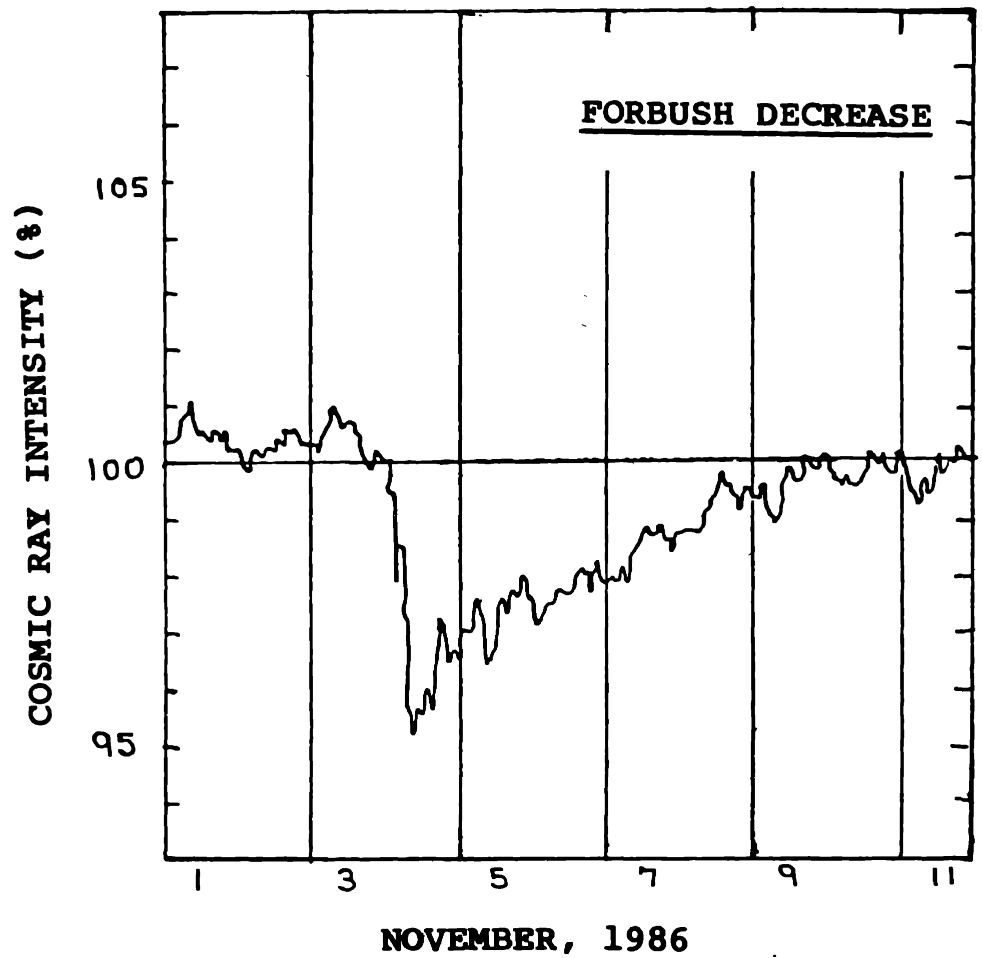

Figure 1. A cosmic ray classical Forbush decrease recorded by the Calgary super neutron monitor during 1986 November 1-11.

amongst all the three parameters. Thus an understanding of the magnetohydrodynamics of the corotating streams and the measurements of the three parameters as a function of radial distance from the sun is essential for a better understanding of the recurrent Forbush decreases.

A corotating stream has its origin in a coronal hole (Hundhausen 1977) with a limited azimuthal extent and a thin boundary near the sun (Rosenbauer *et al.* 1977; Schwenn *et al.* 1978; Burlaga 1979). As a consequence of the solar rotation, the faster plasma overtakes the slower plasma streams ahead of it (which is emitted from more westerly solar longitude). Consequently the material between the faster and slower plasma streams is compressed. Further the magnetic field is frozen to the highly conducting plasma, it is enhanced at the leading edge of the profile of the stream speed showing naturally a correlation between field strength and speed of the recurrent stream. The temperature increases and as a result, a pressure wave is formed ahead of the stream (Burlaga & Ogilvie 1970) due to the kinematic processes related to the sun (Burlaga & Barouch 1976). The pressure wave tends to expand and corotate forward, leading to a reverse shock formation at the boundary of the pressure wave. The existence of a corotating shock at the orbit of the earth was depicted by Burlaga (1970). The presence of a corotating shock wave beyond 1 AU has also been established from Pioneer data (Hundhausen & Gosling 1976) and confirmed by Voyager data (Gazis 1983).

The magnetohydrodynamic models of the corotating streams have been extensively studied (Steinolfson *et al.* 1975; Dryer *et al.* 1978; Goldstein & Jokipii 1977; Whang 1981; Pizzo 1982). Using the satellite observations of stream profiles on the satellite Helios, it has been found that the boundary of the streams are relatively thin, the density is low and the temperature high for the streams. At the front of the streams it has been observed that there is enhancement of the density, temperature and field strength due to the compression. A reverse shock is formed behind the interface and a forward shock is formed ahead of the interface beyond 1 AU. The satellite observations at 1 AU have confirmed this and have shown agreement with the predictions of theoretical profiles.

Models of evolution of the corotating streams beyond 1 AU has been reviewed by Pizzo (1983) and Gosling (1981). The radial evolution of the corotating flows can be observed as a growing pressure wave bounded by a forward shock and a reverse shock. As the shocks drift apart, the pressure waves expand which in turn accelerate the material in a large region ahead of the streams and decelerate the streams. At large distances the streams erode and the dominant features are the pressure waves. The diminution of the streams with heliospheric distance was demonstrated by Mihalov & Wolfe (1979) and Collard *et al.* (1982) using Pioneer data and confirmed by Gazis (1983). Using Voyager data Burlaga *et al.* (1982) have shown the existence of large corotating pressure waves in the absence of fast corotating streams beyond the orbit of the earth.

The observations on corotating streams have shown that the amplitude of the streams decreases with solar radial distances whereas the magnetic field strength increases. Thus it is possible to determine the effects of bulk speed, field strength and field fluctuations on the corotating Forbush decreases. The observations made by Burlaga *et al.* (1982) have shown that the cosmic ray intensity decreases are correlated with the bulk speed and the enhancement of magnetic fields. The Voyager 1 observations have indicated that at a distance of 8 AU the amplitudes of the streams have been small whereas the amplitudes of the fields have been large. Satellite observations at large, radial distances and ground-based observations have demonstrated the importance of stream velocities and magnetic fields in the 27-day modulation of cosmic rays.

The large-scale structure of the heliosphere when the stationary corotating streams have been dominant (Burlaga *et al.* 1983) has shown that near the sun the corotating streams are dominant. Farther away from the sun the nonlinear pressure waves grow and the streams are observed to have eroded so that the corotating pressure waves are observed to be dominant. The stream parameters restructure themselves as a result of dynamical processes and the information about the source is lost. The pressure waves expand, and beyond 25 AU the pressure waves between the streams interact and the individual streams lose their identity. This results in a wave interaction zone in which the corotating Forbush decreases lose their identity and are no longer similar to the one occurring inside 10 AU. Thus we may expect a difference in the structures of cosmic ray variations at large distances from the sun.

3. Long-lasting Forbush decreases

The long-lasting decreases and their contribution to the 11-yr cosmic ray modulation was originally proposed by Lockwood (1958, 1960, 1971). The occurrence of sequence of closely spaced Forbush decreases due to magnetic storms has been known in the literature for many years (Sandstorm 1965). Long-lasting Forbush decreases can have the cosmic ray intensities decreased over as long as a month indicating the succession of several Forbush decreases. The cosmic ray decreases last long because the subsequent Forbush decrease occurs before the first Forbush decrease recovers. The interplanetary magnetic field strength remains high at times of the largest cosmic ray decreases. In fact, the first decrease is not fast and does not necessarily exhibit the 'classical' Forbush decrease. These events are also found to be associated with sudden commencement (SSC) of geomagnetic storms and the passage of interplanetary shocks. Based on the observations, Barouch & Burlaga (1975) have concluded that the long-lasting transient magnetic field enhancements and cosmic ray storms are caused by the passage of several magnetized plasma clouds following one after another.

The study of recurrent streams associated with 27-d variations also have shown that the system of tranisent flows and corotating flows lasting for more than one solar rotation mainly contribute to the long-term variation of cosmic ray intensity. It has been observed that a system of transient flows could follow a system of corotating flows and vice versa (Burlaga *et al.* 1982). A system of corotating flows observed by Voyager 2 has indicated the presence of stream interfaces as well as absence of shocks. There follows a system of corotating flows three months later, which is identified by the presence of shocks and the absence of stream interfaces. The system of corotating flows has produced corotating Forbush decreases but no net reduction in the cosmic ray intensity occurs. The system of transient flows on the other hand has produced a permanent reduction in the cosmic ray intensity.

Similar observations made by McDonald *et al.* (1982) and Burlaga *et al.* (1982, 1983) have established the existence of corotating flows lasting over at least two solar rotations which modify cosmic ray intensity profiles but do not cause any reduction in the cosmic ray intensity. The observations have also indicated the presence of a system of transient flows associated with shocks lasting for nearly two solar rotations which causes a net reduction in cosmic ray variations and the possibility of two kinds of flows co-existing side by side.

The above observations can be explained as follows. The sun and the interplanetary medium can exist in one of two states. The first is a quiet state where the solar wind consists of only corotating flows but no transients while the sun is associated with only coronal holes but consequently no active regions. The other state is a disturbed state in which the solar wind is associated with transient flows but no corotating streams and the sun has many sources of active regions, which eject random magnetized plasma clouds but do not have any sources of stationary flows. Assuming that the sun is in the quiet state for many months the solar wind will have a stable spiral geometry. When the sun goes into the disturbed state, emitted magnetized plasma and shocks will fill up the region and form a shell moving outward with a velocity of 400-500 km s^{-1}. Assuming the sun to return to the quiet state after two solar rotations the shell will be followed by an ordered spiral configuration. In such a situation the spacecraft would observe a sequence of corotating flows followed by a sequence of transient flows and again corotating flows. Such satellite observations have been made and the existence of shells of turbulent magnetic fields has been extensively discussed by Morrison (1954, 1956) and Lockwood (1971).

A shell produced by a system of transients can lead to a long-term reduction in cosmic ray intensity. It may be supposed that all such long-term reductions in cosmic ray intensity are caused by shells, and spacecraft observations may be used to confirm such a hypothesis. Further it is also necessary to examine the magnetic fields associated with large-scale shells and compare them with magnetic fields accompanying a system of corotating flows. Goldstein *et al.* (1983) have studied the power distribution of magnetic field fluctuations during observations of transient flows and corotating flows. The presence of largescale magnetic loops, tightly wound helices, and small fluctuations for the two cases were examined by Mattheus *et al.* (1982) and Mattheus & Goldstein (1982). For the corotating interval the power spectra showed large power for ~ 10 days interval which corresponds to the pressure waves associated with the interaction regions of corotating flows. The power spectra during corotating interval showed more magnetic helicity of low frequencies and the field amplitude and direction can be described by a power law. Thus the spectral signatures of the two classes of interplanetary flows have shown distinct features. Their relation to the compressible MHD flows needs to be further explored. Thus a study of Forbush decreases in cosmic ray intensity is important and elucidates cosmic ray modulation.

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