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Cosmic ray modulation and the evolution of the solar magnetic field

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Abstract. The modulation of cosmic rays in the heliosphere is directly related to the structure and strength of the interplanetary magnetic field which at 1 AU is primarily caused by variations of the solar magnetic field. In this study we examine how the field evolves over timescales of months, and how the cosmic rays respond to these variations, for several interesting periods, including the onset of cycle 23. Also considered is the contribution of coronal mass ejections to the interplanetary magnetic field.

1 Introduction

It has been suggested that cosmic ray modulation is closely associated with the evolution of the solar magnetic field (e.g., Cane et al., 1999; Belov, 2000 and references therein). Wibberenz et al. (1999) emphasised that the modulation is composed of a gradual component and "medium–term events". These events lasting about a year, have previously been called "steps" and considered to be caused by merging processes beyond about 10 AU (Burlaga et al., 1993). However, Cane et al. (1999) showed that they were related to episodes of new open magnetic flux at the Sun.

Advances in our understanding of the evolution of the solar open magnetic flux and the interplanetary magnetic field (IMF) over time scales of months and years have been made by Wang and colleagues (e.g., Wang et al. (2000) and references therein). They conclude that "the large–scale magnetic field of the Sun, including the open flux that extends into the interplanetary medium, originates in active regions but is redistributed over the photosphere by differential rotation, super granular convection, and poleward meridional flow." In their studies, the photospheric field observations are combined with a potential field model, to determine open field regions and their field strength. A flux transport model (Sheeley et al., 1985) is used to show how the emergent flux decays and is transported to the polar regions, changing the solar polarity. They are able to show how the radial component of the IMF at 1 AU varies throughout the solar cycle, although the predictions are not very satisfactory near solar minimum, partially related to the difficulty in measuring the solar polar fields.

This paper illustrates how cosmic rays in the inner solar system respond to changes in the interplanetary medium which result from solar magnetic field changes. For a recent review of other basic aspects of galactic cosmic ray modulation, in particular related to drift mechanisms, see Potgieter and Ferreira (2001).

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2 Solar and interplanetary variations during medium–term events near solar minimum

Figure 1, bottom panel, shows the recovery phase of cosmic ray modulation for solar cycle 22 (Jan 1993 to Oct 1997). The cosmic ray variation is shown using data from the anti–coincidence guard on IMP 8. This detector provides a measure of the >60 MeV counting rate which is a sensitive measure of cosmic ray variations. Note the small decreases in early 1994 and late 1996 superimposed on the general recovery. These are examples of medium–term events. More significant medium–term events occurred in early 1973 and in 1974 (e.g. Richardson et al., this volume). The description by Wang et al. (1997) of the solar changes in 1996 would apply to each of these periods. A new active region complex developed near the solar equator after a period of relative inactivity. Wang et al. (1997) successfully model the warping of the heliospheric current sheet which resulted from the addition of low–order, non axisymmetric harmonic components of the photospheric field. The effects of photospheric activity depend on the strength of the erupting flux and its longitudinal phase relative to the background field. In an earlier paper Sheeley et al. (1989) describe how the eruption of flux can cause distortion of the polar hole boundary leading to fingers of open flux from polar coronal holes to form at lower latitudes and cause a deflection of the neutral sheet in the outer

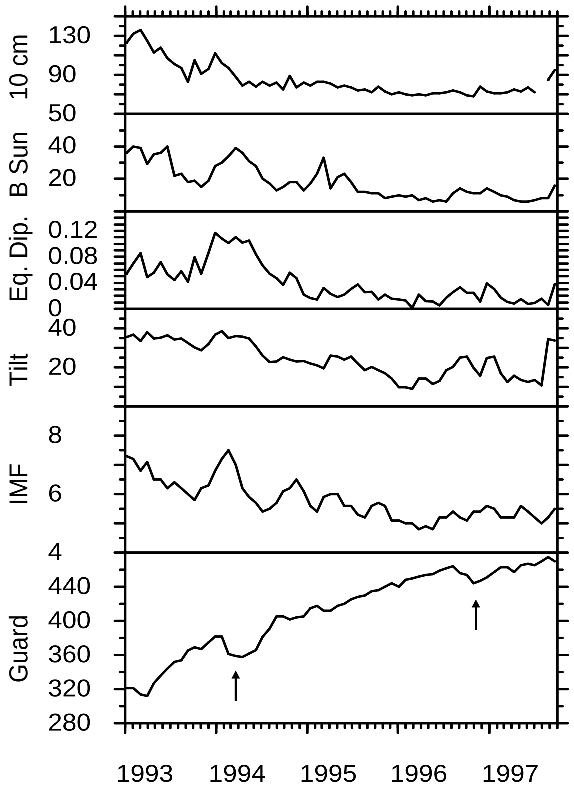

Fig. 1. Carrington rotation averages of some solar parameters (the 10 cm flux, the mean field of the Sun as a star, the equatorial dipole field at the source surface), the 'tilt angle' of the heliospheric current sheet, the IMF and the cosmic ray count rate at energies >60 MeV. Two medium–term events are indicated by arrows.

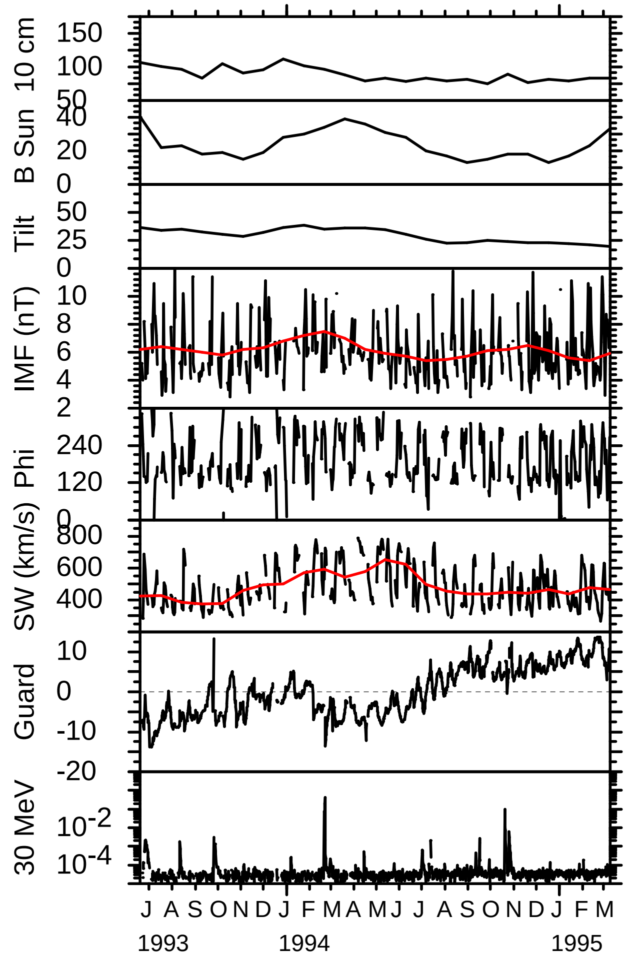

Fig. 2. The medium–term event of 1994. The top three panels show solar parameters for each Carrington rotation. The next two panels show the IMF strength and its azimuthal angle (daily averages).Carrington-rotation averaged field strength is also shown. The solar wind and its rotation average is shown in the next panel. The bottom two panels show particle intensities in two energy ranges (>60 and ∼30 MeV) from IMP 8.

corona. Such a finger formed in August–September of 1996. The consequences at 1 AU of this activity were an increase in solar wind speed *and* an increase in the interplanetary magnetic field. Thus the expected response in the cosmic ray intensity is an increase in the size of the recurrent decreases and a gradual decrease and recovery over the time scale of about a year. It takes about a year for the erupted flux to either be annihilated or to reach the polar regions.

The upper panels of Figure 1 illustrate some of the solar and interplanetary variations associated with the cosmic ray changes. The 10 cm solar flux is a good indicator of overall solar activity and the eruption of new photospheric flux. The mean field of the Sun (B Sun) in panel 2 provides a measure of the unbalanced flux in the Earthward solar hemisphere. Panel 3 shows the equatorial dipole component of the field at the source surface (the surface beyond which all field lines are open to the interplanetary medium). Except near solar maximum, the source surface field is primarily dipolar so changes in the IMF are mainly determined by the equatorial dipole field. The next panel is the 'tilt angle' of the heliospheric current sheet as determined by J. T. Hoeksema for each Carrington rotation. The increases in the mean field, the equatorial dipole and the tilt angle are manifestations of the processes described above. The increase in the IMF during the events of 1994 and 1996 can be seen in panel 5. Running means over 3 solar rotations are used here which partly simulate the integrating effect of cosmic rays of the outward propagating barriers of reduced diffusion coefficients which are connected with the IMF enhancements.

In Figure 2 the event of 1994 is shown in greater detail. The solar wind speed (SW) has been added as well as the >30 MeV energetic particle count rate. It can be seen that there are 27 day variations (corotating decreases) in response to the solar wind speed variations. Richardson et al. (1996), and earlier Iucci et al. (1984), showed that the predominant influence on corotating decreases is the increased solar wind speed. The higher speed streams during the medium-term events result from the fact that the Earth is placed further inside the streams because of the tilt of the heliospheric current sheet. But note that the corotating decreases are clearly superimposed on a longer term decrease i.e. the medium–

term event. We attribute this decrease to the increased IMF, which can be seen in the Carrington rotation averages (red curve in Fig. 2), and have shown how a simple model can predict these decreases based on the IMF observations (see Wibberenz et al., 2001; Richardson et al., this volume).

Low energy (<∼100 MeV) increases, such as can be seen in the 30 MeV data in the bottom panel of Figure 2, result when a fast coronal mass ejection (CME) occurs at the Sun. Mass ejections set up the right conditions for particle acceleration and then the shocks driven by the CMEs may further accelerate these particles. There was a very energetic CME event in Feb. 1994 (about 2 rotations after the start of the medium–term event). At the time of the 30 MeV increase there is a sharp narrow decrease in the guard data. This is a Forbush decrease caused by the CME when it arrived at Earth. Another Forbush decrease can be seen in April 1994. This is a common feature in the medium–term events; there is often an increase in CME activity several months after the start of the event and sometimes in the late recovery stage. A probable explanation is that many CMEs occur because of the sheared fields that result from differential rotation in the months following newly emerged flux. Though not illustrated here, there were no energetic events at the time of the 1996 event.

3 The onset of cycle 23

As solar activity increases and the polar fields decrease in size, much of the open flux originates in smaller, lower latitude coronal holes. Although the holes are smaller, the fields are much stronger and so the IMF increases (Wang et al., 2000). The increases are incremental as new active regions develop and mature; the changes in the average IMF are on ∼1 year time scales. Figure 3 shows data for 1997-1999 (in similar format as Figure 2). The rotation-averaged field is shown because of the extended time scale. The dashed curve shows the IMF measured at Ulysses (adjusted to 1 AU) for comparison. It can be seen (indicated by vertical lines) that four successive medium–term cosmic ray events occurred, commencing in Sept. 1997, April 1998, Nov., 1998 and Aug. 1999. Each was preceded by structural changes in the interplanetary medium and at the Sun as indicated by the rapid variations of the parameters in Figure 3.

Note that the solar wind speed does not increase much during these medium–term events. This is because the field from small coronal holes expands considerably from the photosphere to the source surface and the wind speed far from the Sun is inversely correlated with the coronal flux tube expansion (Wang and Sheeley, 1990). Note that the decrease in the mean solar field and the IMF in mid-1999, which caused a slight recovery of the cosmic ray rate (most obvious in the neutron monitor rate), was not accompanied by a decrease in the 10 cm flux. Rather there was an increase in the 10 cm flux and a corresponding increase in the CME rate, as indicated by the 30 MeV solar particle events in June 1999 in the lowest panel and confirmed from LASCO coronagraph

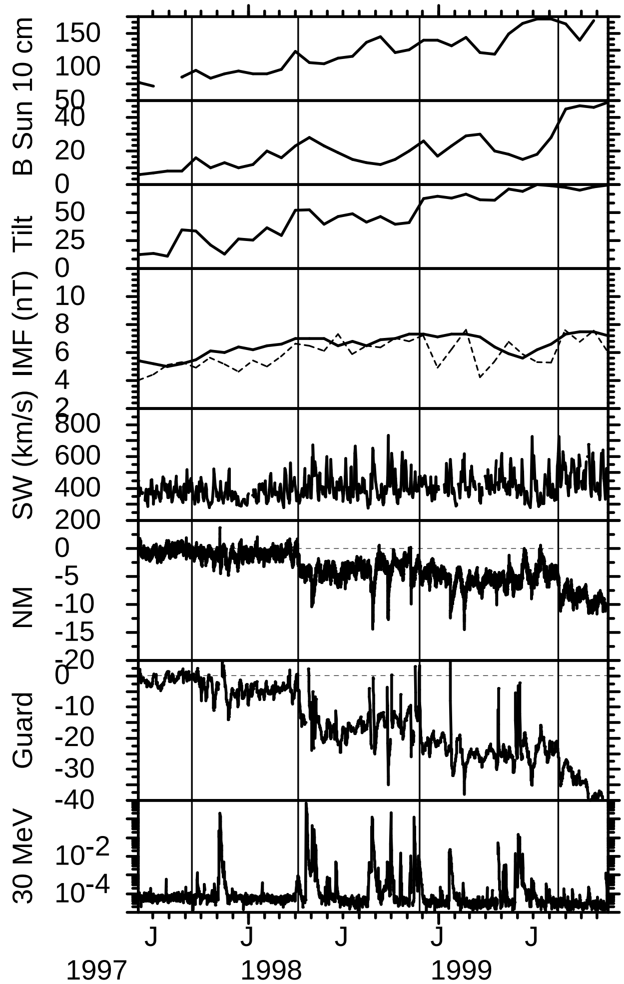

Fig. 3. Similar format as Fig. 2 but also including the count rate from the Mt. Wellington neutron monitor and magnetic field from Ulysses mapped to 1 AU. The vertical lines indicate the start times of four medium–term events.

observations (O. C. St Cyr, private communication). Thus the CME rate and cosmic ray modulation were clearly not related at this time.

4 After solar maximum?

At solar maximum there is a decrease in the open flux at the Sun because activity occurs at all heliolongitudes and so the equatorial dipole does not increase. After solar maximum, in cycles 21 and 22, there was an increase in the open flux and the IMF because the decaying remnants of low–latitude active regions were longitudinally separated, thus increasing the equatorial dipole. Cosmic ray modulation was maximum at these times and *not* at solar maximum when the photospheric magnetic flux, and the CME rate were at a maximum. In cycle 20 there was a relatively large increase in the IMF in 1974 almost 4 years after solar maximum and this caused the so-called ‘mini cycle’ of modulation. Since the behaviour after solar maximum depends on the location of the active regions and how asymmetrically they are distributed, a pronounced maximum in the IMF will not necessarily occur after each solar maximum. But based on long term studies of geomagnetic activity, the IMF usually does increase after solar maximum and so it is likely that there will be an increase in cosmic ray modulation in the 2001-2002 time frame. From the cosmic ray record it can be seen that there were two broad minima around 3 of the last 4 solar maxima.

5 Summary and Discussion

In this paper a number of features of cosmic ray modulation at 1 AU have been illustrated and a description given of how the evolving solar magnetic field, and of that component which escapes to the interplanetary medium, causes these features. The purpose of this paper was to point out that there is a reasonable explanation for the medium–term modulation events in terms of solar variations. In another paper it is shown how a simple model incorporating the changing IMF can account for the $\sim$1 year cosmic ray modulation events seen at 1 AU (Richardson et al., this volume). Note that a direct comparison of the increasing IMF and the decreasing cosmic ray count rate at the onset of cycle 23 does not show a particularly tight anti-correlation. However, when the field is integrated and the drift effects considered, a satisfactory fit can be achieved (see Wibberenz et al., 2001 and Richardson et al., this volume). The obvious 27–day recurrent decreases that occur during events away from solar maximum are a natural consequence of low-latitude extensions of polar coronal holes which result from newly emerged solar magnetic flux. A number of researchers have been struck by the recurrent decreases and tried to determine how they could contribute to the medium–term event. Kondoh et al. (1999) noted that since the 1994 medium–term decrease started at the same time as the increased recurrent variations it could not be caused by a merging process beyond 1 AU. However the interaction regions that form at the leading edges of the high speed streams are balanced by rarefaction regions so are unlikely to cause a sustained decrease anyway i.e because they cause no increase in the mean IMF. It is the additional magnetic flux which causes the medium-term modulation. The recurrent events are just a signature of the solar magnetic field reorganisation.

We also presented data that suggests that CME activity often occurs in the mid or late stages of these solar episodes and is not always an integral part of medium–term events. It is unlikely that CMEs are an important component in long–term modulation. Furthermore, we have pointed out that CME activity maximises at sunspot maximum which is not when maximum cosmic ray modulation occurs.

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