Modulation of Galactic Cosmic Rays and Changes in the Solar Magnetic Field

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Abstract

We discuss the modulation of galactic cosmic rays over more than a 22-year magnetic cycle (solar cycles 20-23). We suggest that the cosmic ray intensity profile can be decomposed into a gradual component with superimposed medium-term modulation events with durations of the order of one year. The inverted profile of the cosmic ray intensity tracks rather well the interplanetary magnetic field (IMF) strength as observed near 1 AU. Coupling between the IMF strength (B) and the cosmic ray transport parameters leads to a conceptually simple modulation model in which the modulation process is linked to global variations of B. We also study the correlation between cosmic ray intensity and tilt angle. The slopes of the cosmic ray response to variations in tilt angle are similar for both magnetic polarities for tilt angles between about 25° and 60°. Systematic differences between polarity epochs are found around solar minimum for small tilt angles, in principal agreement with the existence of drift effects.

1 Introduction:

The current picture for the long-term modulation of cosmic rays (CRs) incorporates time-dependent heliospheric drifts, a few global merged interaction regions (GMIRs) per 11-year cycle (which are related to the so-called step decreases) and possible slow variations in the background transport coefficients (Wibberenz et al., 1998). The relative importance assigned to these effects varies from author to author. For instance, Burlaga and Ness (1998) argue that it is ultimately the strong magnetic fields and their associated fluctuations that produce the modulation of cosmic rays. Potgieter (1998) states that the main features of the 1977-1987 proton modulation cycle could be reproduced with a drift model combined with four GMIRs. GMIRs are interaction regions which extend 360° around the Sun in the ecliptic plane and close over the poles. They are considered to be related to sequences of coronal mass ejections (CMEs) which merge with other high speed flows at 10-15 AU (Burlaga et al., 1993). The extension to high latitudes is required because without a cosmic ray barrier in the heliospheric polar regions, there would be relatively unrestricted cosmic-ray flow from the poles toward the equatorial plane (Potgieter and le Roux, 1994). Recently, Cane et al. (1999a, b) have found that the cosmic ray profile tracks rather well the variations in the interplanetary magnetic field strength (IMF). They suggest that the appearance of "medium-term modulation events" in the cosmic ray profile is related to the generation of new magnetic flux at the Sun and is not an effect of merging in the outer heliosphere. Here, we suggest the decomposition of the solar cycle modulation into a smoothly varying component and superimposed events, and discuss the relation between cosmic ray intensity and tilt angle.

2 Observations:

2.1 Cosmic Ray Profiles and the IMF:

The lower part of Figure 1 shows the 22-year variation in the cosmic ray intensity as observed by (a) the Mt. Wellington neutron monitor (NM) (median energy ∼ 10 GeV) and (b) the GSFC experiments on IMPs 7 and 8. The IMP data (120-230 MeV proton intensities) have been normalised to the Mt Wellington count rate during the mid-1970s solar minimum period and, as well as possible, near the two solar maxima. The upper curve shows the average IMF at 1 AU. Note how the NM intensity profile is a mirror image of the magnetic field data. Vertical dashed lines indicate times of some IMF enhancements and concurrent medium-term cosmic ray decreases. Those in 1978, 1979, 1980/1981, and 1982 correspond to the 'steps' in ∼150 MeV data refered to by McDonald (1998), but at NM energies, the medium-term events do not look like 'steps'. In the papers by Cane et al. (1999a, b) it was shown that the IMF enhancements are directly related to variations in the solar open magnetic field as calculated by Y.-M. Wang from photospheric observations. Wang and Sheeley (1995) have shown how such observations can be used to predict solar-cycle variations of the IMF radial component. Note that such calculations do not include the contributions of CMEs.

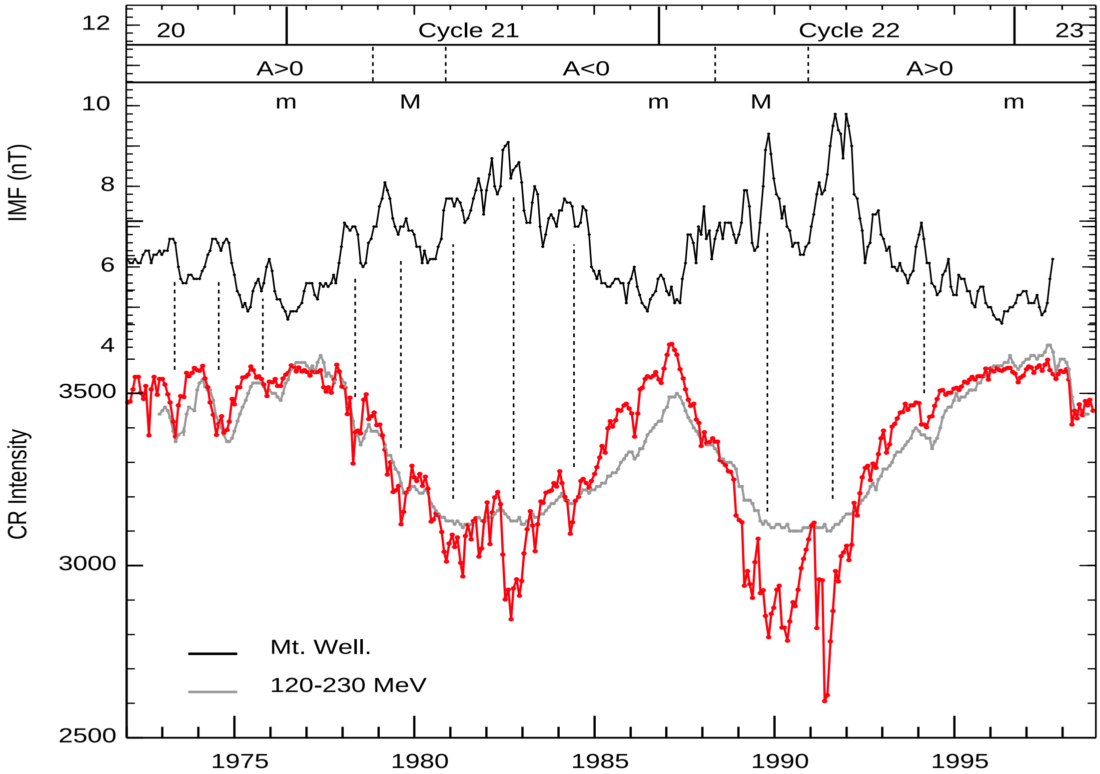

Figure 1: The lower two curves show the cosmic ray intensity at two energies at 1 AU. The upper curve is the interplanetary magnetic field. Carrington rotation averages are used. At the top of the figure the solar cycles and the approximate times of solar minima (m) and maxima (M) are indicated. A is the global solar field direction.

In Figure 1 it can be seen that for the period from late 1972 (when IMP data began) until the beginning of 1982 the two cosmic ray profiles track each other quite well, although the NM rate clearly had recovered earlier than the ∼180 MeV intensity at the end of cycle 20. The slower response of ∼180 MeV protons to heliospheric changes is particularly evident for the events of 1973 and 1974. Throughout the cycle, the lower energy channel is considerably smoother. In particular, several prominent events in the NM data close to solar maximum are essentially absent in the ∼180 MeV data. We note the different levels at the 1987 solar minimum. This probably arises because the lower energy particles recover more slowly and, in contrast to higher energies, do not reach maximum intensity before the new cycle sets in.

There must be a gradual component with an 11-year modulation, otherwise when medium-term events are sufficiently well separated, one would expect a profile as observed in the mid-1970s, where the CR intensity is the same before and after a medium-term event. In 1977-1980, the gradual component may be defined by joining the levels at the beginning and end of medium-term events. This technique cannot be applied objectively during part of the time near solar maximum, though the ~180 MeV intensity profile indicates the approximate behaviour.

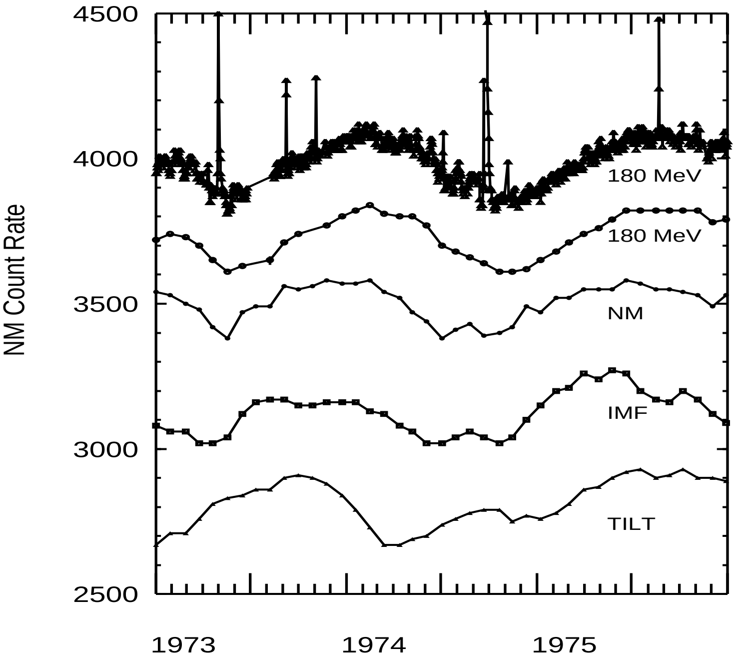

Figure 2: Variations in the cosmic ray intensity, the inverted IMF and the inverted tilt angle. The 180 MeV data is shown using daily (top profile) and solar rotation averages. Spike increases indicate CME activity.

2.2 The mini-cycle of 1974:

The detailed analysis of selected medium-term modulation events provides further insight into the modulation process. Figure 2 includes the so-called mini-cycle of 1974. We see that the cosmic ray decrease in the NM data commences with a delay of not more than one month relative to the inverted IMF decrease, and that the substructure in the IMF profile (two minima in the second half of 1974 in the inverted IMF profile) are also reflected in the cosmic ray behaviour. Both the NM and ~180 MeV data show a recovery phase soon after the IMF has passed its maximum magnitude in November 1974. Finally we note that the onset of the event is not accompanied by CME activity, as indicated for example by an absence of major particle events in the uppermost curve in Figure 2. We see that the mini-cycle partially mimics a scaled-down 11-year cycle.

2.3 Tilt Angle Correlations: A prediction of drift theory is that the CR intensity should respond differently to changes in the inclination of the heliospheric current sheet when the Sun is in different magnetic polarity states (A). The work of Smith (1990) seems to support this prediction, but Cane et al. (1999a) argued that straight lines were fitted to data that actually consisted of sections of different slope. We have found that for tilt angles between 60° and 20° the CR intensity is correlated with tilt angle with the same slope for both signs of A apart from a short period in the recovery phase of cycle 22. We find a larger separation between the upper and lower branches of the correlation curves for cycle 21 compared to cycle 22. It is not yet clear to what extent differences in behaviour between alternate cycles is caused by an intrinsic property of the Sun. We have studied the slopes a in the relation $C = aT + b$ where C = NM count rate, T = tilt angle. At tilt angles below about 30° $a = -1.2 \pm 0.3$ for the transition from cycle 22 to 23. This same (flat) behaviour is found at the onset of cycle 21, $a = -1.2 \pm 0.4$. In contrast, the slope is much steeper in the transition from cycle 21 to 22, $a = -9.9 \pm 1.5$. Note that the tilt angle, which has been determined by J.T. Hoeksema, does not have a physical meaning near solar maximum where there are multiple current sheets and the solar field is very complex.

3 Discussion and Summary:

We suggest that cosmic ray modulation can be decomposed into a gradual component and superimposed medium-term modulation events. The gradual component results from the gradual variation of the background cosmic ray transport parameters, scaled with the variation of the IMF magnitude B. The events vary in size and duration and are not restricted to periods around solar maximum. They correspond to periods of global magnetic field enhancements originating at the Sun and carried out with the solar wind. These field enhancements are conceptually similar to GMIRs except that they result not from merging processes beyond about 10 AU, but from the generation of new (open) magnetic flux at the Sun. Study of the isolated event during the mini-cycle of 1974 shows that the initial cosmic ray decrease is not connected with increased CME activity. Near 1 AU we find a good anticorrelation between the IMF magnitude B and the CR intensity on the time scale of one solar rotation. Also, Burlaga and Ness (1998) show that many features of the IMF as a function of space and time scale with B. Thus, a coupling of the cosmic ray transport coefficients with the field magnitude B may provide a conceptually simple, first-order model for cosmic ray modulation.

The temporal development of the solar source surface magnetic field, combined with solar wind speed variations, determines the distribution of $\vec{B}$ throughout the heliosphere. Not all spherical harmonic components of the solar field will vary in the same way during a solar cycle. The resulting latitudinal variation of B will be important in order to understand the (charge and energy dependent) recovery phases of the events (Potgieter and le Roux, 1994).

Predictions from drift theory limit the close coupling between the tilt angle and cosmic ray intensity to tilt angles below about 30°. Thus, the correlation of the CR intensity with the inverted tilt angle between 60° and 20° is remarkable. We believe that, for increasing tilt angle, its absolute size is a measure for the complexity of the general solar magnetic field, and that tilt angle increases occur at the times of the generation of additional open magnetic flux. This does not seem to be coupled in general with the rate of CMEs. Inspection of the tilt/CR relation for small tilt angles shows that the slope of the correlation is different for A>0 and A<0 epochs. Combined with recent simultaneous Ulysses observations of electrons ($q = -1$) and protons ($q = 1$) during the present A>0 epoch (Heber et al., 1999) one finds that the correlation varies with the product qA, in general agreement with predictions from drift theory.

References

Burlaga, L. F., McDonald, F.B. and Ness, N.F. 1993, J. Geophys. Res. 98, 1

Burlaga, L. F., and Ness, N.F. 1998, J. Geophys. Res. 103, 29719

Cane, H.V., Wibberenz, G., Richardson, I.G. and von Rosenvinge, T.T. 1999a, Geophys. Res. Lett. 26, 565

Cane, H.V., Wibberenz, G., and Richardson, I.G. 1999b, Proc. Solar Wind Nine (New York:AIP)

Heber, B., et al., 1999, Geophys. Res. Lett., accepted for publication

McDonald, F.B., 1998, Space Sci. Rev. 83, 33

Potgieter, M.S. and le Roux, J.A. 1994, ApJ 423, 817

Potgieter, M.S., 1998, Space Sci. Rev. 83, 147

Smith, E.J. 1990, J. Geophys. Res. 95, 18731

Wang, Y.-M. and Sheeley, N.R., Jr., 1995, ApJ 447, L143

Wibberenz, G., le Roux, J. A., Potgieter, M. S., and Bieber, J. W. 1998, Space Sci. Rev 83, 309