Proceedings of ICRC 2001: 3710 © Copernicus Gesellschaft 2001

ICRC 2001

Application of a simple propagating barrier model to the onset of cosmic ray modulation in solar cycles 20-23

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Abstract. The relationship between the evolution of the solar magnetic field and cosmic ray modulations at 1 AU on time-scales of ∼1 year is investigated using a simple model in which changes in the solar magnetic field propagate from the Sun and cause a change in the radial diffusion coefficient which is assumed to scale as some power of the IMF magnitude. The recovery in the cosmic ray density is modeled by a recovery time which physically is related to particle entry into the depleted regions of the heliosphere by drift and perpendicular diffusion. The model incorporates the observed variations of various solar and interplanetary parameters.

1 Introduction

It has been suggested that cosmic ray (CR) modulation is closely associated with the evolution of the solar magnetic field (e.g., Slavin and Smith, 1983; Cane et al., 1999, 2001; Belov, 2000 and references therein). We investigate this relationship during the ascending phases of solar cycles 20-23 and two "mini-cycles" in 1973-74 by numerical solution of a simple model (Wibberenz and Cane, 2000) in which increases in the solar magnetic field propagate away from the Sun and cause a reduction in the CR radial diffusion coefficient K, which is assumed to scale as some inverse power of the interplanetary magnetic field magnitude ($K \propto B^{-n}$). The recovery in the CR density, modeled by a "recovery time" (τ), occurs as particles flow (via drifts and perpendicular diffusion) into the depleted regions behind this "propagating barrier" which, because it is the result of a global change in the solar magnetic field, has a large extent in longitude and latitude. Using parameters related to the solar field, such as the IMF at 1 AU or tilt angle, as inputs to the model, the CR density for periods of ~ 2 years following modulation onset can be modeled reasonably successfully. The parameters τ and n are determined by fitting the predictions of the model to the observed CR densities. Whilst we recognize the simplicity of the model, the encouraging results confirm the important role of the evolving solar magnetic field for CR modulation.

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2 Model

We describe modulation of the CR density (U) in terms of a simple propagating barrier model (Wibberenz and Cane, 2000) in which regions of increased B are carried radially outward from the Sun. The model equation is:

$$\frac{dU}{dt} = -UG_rV\left(\frac{K}{K'(t)} - 1\right) - \frac{U - U_o}{\tau} \qquad (1)$$

where G_r = cosmic ray radial gradient, V = solar wind speed, τ = recovery time, and $U_o = U(t=0)$ is the initial condition. The disturbance

$$p(t) = \frac{K}{K'(t)} - 1 = \left(\frac{B'(t)}{B_o}\right)^n - 1, \qquad (2)$$

is the driving force for the CR depression. Here, $K/K'(t)$ is the ratio of the ambient to disturbed diffusion coefficients and n characterizes the CR response to variations in B. The integral incorporates the influence of solar wind magnetic fields beyond the orbit of Earth.

Though τ and n are considered as free parameters, they are related to properties of the interplanetary medium. The CR decreases are diffusion-dominated, n describing the sensitivity of the CR response via the coupling between K and B. The recovery time τ is partly drift-dominated. Thus, consideration of these two parameters may help disentangle the relative importance of drift and diffusion effects for CR modulation. Wibberenz and Cane (2000) inferred $n \sim 2.5 \pm 1.0$ and $\tau \sim 52 \pm 10$ days for neutron monitor (NM) observations during the 1974 mini-cycle using an analytical solution incorporating an approximation to $B'(t)$, and assuming G_r = 0.7%/AU (Chen and Bieber, 1993). They noted that the immediate response of the CR intensity to the first passage of the propagating barrier suggests that variations in $K_\parallel$ are responsible. For NM energies, quasi-linear theory predicts $K_\parallel \propto B^{-2}$ if magnetic field fluctuations $(\delta B)^2$ scale with B^2, in good agreement with their solution. Here, we solve equation (1) numerically and incorporate the observed variations in solar-rotation averages of V and $B'(t)$, as well as the possibility that the $K - B$ relationship evolves with changing solar activity levels. For example, when solar activity is low, full modulation models suggest that the CR intensity is rather insensitive to K (Potgieter and Ferreira, 2001), concurring with observations indicating that the CR intensity shows little response to variations in B when $B \leq 5.8$ nT (Wibberenz et al., 2001a). Thus, we consider solutions where either (a) $n(t)$ = constant, and $p(t) = 0$ if $B(t) < 5.8$ nT, or (b) $n(t) = \alpha(t)/j$, where α is the tilt-angle of the heliospheric current sheet (courtesy of T. Hoeksema) which is low around solar minimum. This is not meant to imply that the tilt-angle controls the relation between the IMF turbulence (via the magnitude of B) and the diffusion coefficient, but provides a convenient way of relating the variable role of the change in K to the evolving solar activity. The integration time-step is 1 day and the resulting intensities are averaged over solar-rotation intervals to compare with rotation-averages of the observed cosmic ray intensity. For the results in the next section, a radial cosmic ray gradient of 0.7%/AU is assumed. The effects of temporal changes in G_r (Chen and Bieber, 1993) are briefly discussed below.

3 Results

Figure 1 shows solar rotation averages of B, and the cosmic ray intensity (black curves with dots) observed by the Mount Wellington neutron monitor (cut-off rigidity 2 GV), during the onsets of cycles 20 - 23 and for two mini-cycles in 1973 and 1974. The same vertical scale is used in each panel, though the duration varies. Considering first cycle 21 (top right-hand panel), the best fit to the data (that minimizing the squared differences between the observed and model intensities, shown by the red curve in Figure 1) for Carrington rotations 1662 - 1680 (December 1977 - May 1979) has $n = 1.4, \tau = 102$ days. If n depends on α, we obtain $j = 47^o, \tau = 119$ days. For cycle 22, fitting between CRs 1791 - 1822 (July 1987 - December 1989), the best fit incorporates the tilt-angle and has $j = 40^o$, $\tau = 319$ days. The constant n assumption does not give a satisfactory fit. The onset of cycle 23 also cannot be adequately fitted by a constant n solution because B first increased significantly in late 1997, whereas the major CR modulation onset was delayed until April 1998 (e.g., Wibberenz et al., 2001a, Cane et al., 2001). However, other parameters such as the tilt-angle, the equatorial dipole component of the source surface magnetic field, and the low-latitude open flux, only started to deviate significantly from solar minimum conditions in early 1998 (Wang et al., 2000). Hence, this delay does not conflict strongly with the proposal that the evolving solar magnetic field plays a role in CR modulation (see also Cane et al., 2001). In fact, a similar, though less pronounced, delay occurred at the onset of cycle 21. From examining cycles 21 and 23, Wibberenz et al. (2001a) concluded that modulation onset in $\boldsymbol{A} > 0$ epochs (where $\boldsymbol{A}$ is the direction of the solar global field) requires the solar field to have evolved sufficiently such as to give both $B(1\text{ AU}) > 5.8$ nT (as discussed above) and $\alpha > 35^o$. We can fit the onset of cycle 23 reasonably well by assuming that n is parameterized by α, the best fit being $j = 31^o, \tau = 31$ days.

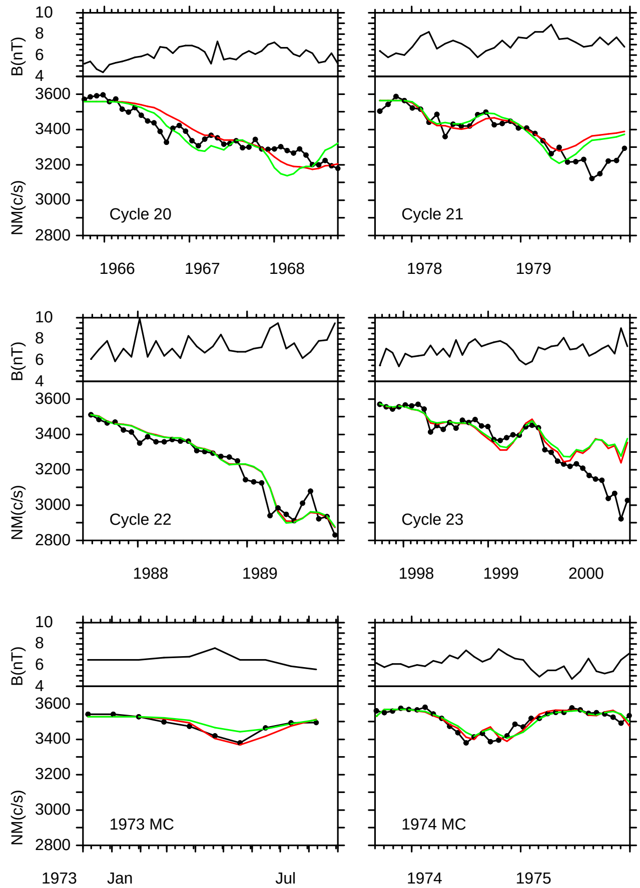

Fig. 1. Fits of the propagating-barrier model to solar rotation averages of the CR intensity observed by the Mount Wellington NM during the onsets of solar cycles 20-23 and "mini-cycles" in 1973 and 1974. Best fits (red curves) have $j = 96^o, \tau = 494$ d (cycle 20); $n = 1.4, \tau = 102$ d (C21); $j = 40^o, \tau = 319$ d (C22); $j = 31^o, \tau = 31$ d (C23); $n = 3.9, \tau = 75$ d (1973 MC) and $n = 3.1, \tau = 28$ d (1974 MC). Green curves show fits assuming $n = 2.0$ or $j = 38^o$ ($\sim$maximum-$\alpha/2$), with $\tau = 116$ d (C20), 82 d (C21), 284 d (C22, nearly identical to best fit), 40 d (C23), 120 d (1973 MC) and 48 d (1974 MC).

The values of n and τ inferred for the various intervals in Figure 1 from the best fits to the NM data assuming constant or variable n are summarized by the circles in Figure 2. (For the variable n fits, $n = 75^o/j$ is plotted since $0 \leq \alpha \leq 75^o$). We also show results for the two mini-cycles. For cycle 21 and the 1974 mini-cycle, results for both constant and variable n are shown because either assumption gives a reasonable fit to the observations. Overall, the values of n are

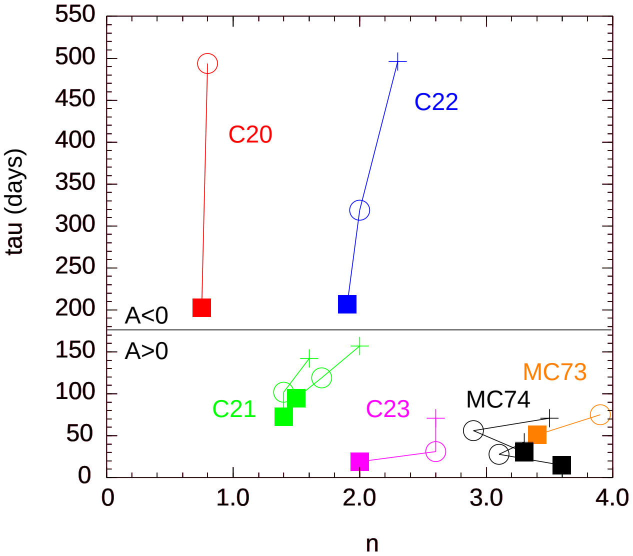

Fig. 2. Summary of the values of n or $n = 75/j$ and τ giving the best fits to the onsets of cycles 20-23 and the 1973 and 1974 mini-cycles. $+$ = IMP 8 guard; $\circ$ = MTW NM; square = HUA/HAL NM. Note the longer recovery times when $\boldsymbol{A} < 0$.

reasonably consistent with the $n \sim 2$ suggested theoretically and the Wibberenz and Cane (2000) analytical result ($n \sim 2.5 \pm 1.0$) for the 1974 mini-cycle. An interesting feature is the longer recovery time inferred for cycle 22 than for cycles 21 and 23 and the mini-cycles. We interpret this as a consequence of the change in CR drift pattern caused by the opposite directions of the solar global magnetic field $\boldsymbol{A}$ at the onsets of sucessive solar cycles (e.g., Potgieter and le Roux, 1994). Cosmic ray entry into the inner heliosphere from over the poles when $\boldsymbol{A} > 0$ (as during the onsets of cycles 21 and 23, and the mini-cycles) occurs more rapidly than from along the equatorial current sheet when $\boldsymbol{A} < 0$ (onset of cycle 22), leading to shorter recovery times when $\boldsymbol{A} > 0$.

In cycle 20 (top-left panel of Figure 1), the increase in B was rather weak, yet a CR depression still occurred, apparently contradicting the proposal that the interplanetary magnetic field influences CR modulation (e.g. Hedgecock, 1975). We have fitted the model to data for CRs 1503-1543 (January 1966-January 1969). Unfortunately, there are no B observations for CRs 1504-1508, and α (from Mt. Wilson) is only available from CR 1517. We therefore interpolated between the available B or α data, and assumed that α increased linearly from 20^o between CR 1503 and the start of α observations. Although the lack of complete observations must limit the ability of the model to reproduce the CR intensity, a fair fit implying the expected long recovery time (since $\boldsymbol{A} < 0$) is obtained (Figure 1). We conclude that CR modulation in cycle 20 is a consequence of the long recovery time which allows modulations associated with modest increases B to combine to produce an extended CR depression. The longer recovery time when $\boldsymbol{A} < 0$ may contribute to the tendency for distinct "steps" to be less evident during the onsets of cycles 20 and 22 than in cycles 21 and 23.

We might expect n to be relatively constant from cycle to cycle because it is determined by particle diffusion processes. The green curves in Figure 1 show fits using $n = 2.0$ (or equivalently, $j = 75^o/2.0$), since this has some theoretical basis. These are generally nearly indistinguishable from the best fits. The corresponding values of τ are listed in the figure caption. Note that as solar maximum is approached, the model solutions deviate from the observations, in particular when $\boldsymbol{A} > 0$. The physical origin of this feature will be discussed below.

The effectiveness of the propagating barrier is influenced by the size of the radial CR gradient (Equation 1). However, G_r varies during the solar cycle, and may be larger during the ascending phase than the 0.7%/AU assumed above (Chen and Bieber, 1993), enhancing the effectiveness of the barrier. If we incorporate $G_r(t)$ from Chen and Bieber (1993) for the onset of cycle 21, we obtain a best fit of $n = 0.8, \tau =$ 103 days (cp. $n = 1.4, \tau = 102$ days if G_r 0.7%/AU). Unfortunately, Chen and Bieber only estimated G_r for the complete ascending phases of cycles 20 and 21, and it is not clear whether their results can be applied directly to other cycles. Nonetheless, the general effect of an increase in G_r as solar activity increases will be to reduce the dependence of K on B required to fit the observations.

We have also applied the model to observations of CRs from the Huancayo or Haleakala neutron monitors (cut-off rigidity 13 GV) and to > 60 MeV particles observed by the anti-coincidence guard of the Goddard particle experiment on IMP 8. Since radial gradients apparently decrease with increasing energy (e.g., Gerasimova et al., 1999), for HUA/HAL we assumed a gradient of 0.35%/AU, i.e. one half of that used for lower energy NM data. For the guard, we assumed a gradient three times larger, i.e. 2.1%/AU. The values of n and τ giving best fits for the guard (crosses) and HUA/HAL (filled squares) during the intervals of interest are shown in Figure 2 (lines connect data for the same interval). Note that while there is little change in n (with these choices of G_r), τ decreases with increasing energy, consistent with the expectation that higher energy particles will fill in more rapidly behind the propagating barrier.

4 Summary and Discussion

A simple propagating barrier model using observations of parameters characterizing the solar magnetic field as input reproduces the CR intensity during the ascending phases of solar cycles 20-23, as well as the 1973 and 1974 mini-cycles, reasonably successfully. The best fits to NM observations imply $K \propto B^{-n}$ with values of $n \sim 0.8 - 4$ which may be reduced if time-varying radial gradients are taken into account. These results are consistent with the $n = 2$ suggested by Wibberenz and Cane (2000), suggesting that $B - K$ relationships required to fit the model to the observations are physically plausible.

The model solutions imply significantly longer recovery times when $\boldsymbol{A} < 0$ (e.g., the onsets of cycles 20 and 22) than when $\boldsymbol{A} > 0$ (e.g., cycle 21, 23 onsets and 1973-4 minicycles), which may be related to the dependence of particle drift patterns into the inner heliosphere on $\boldsymbol{A}$. Recovery times also decrease for higher energy particles, which can more rapidly populate the depleted region behind the propagating barrier. The shorter recovery times in $\boldsymbol{A} > 0$ epochs lead to higher correlations between variations in B and the CR density and may contribute to the more pronounced "steps" as the intensity declines. In $\boldsymbol{A} < 0$ epochs, the CR density falls more steadily without prominent steps, and is less well correlated with B. We also note that τ cannot attain very small values (say $<<$ a solar rotation period) since the integrating effect of the barrier would then be so weak that the CR intensity would follow individual solar rotation averages of the IMF, in contrast to observations (see the discussion in Wibberenz et al., 2001b). Since in general, smaller recovery times require stronger variations of K to result in CR modulation, this also implies that there is an upper limit to the value of n.

Figure 1 shows that the fits depart from the observations at some point as solar maximum is approached, most clearly when $\boldsymbol{A} > 0$. We interpret this "solar maximum effect" as an indication that the heliospheric magnetic fields have significantly departed from their solar minimum configuration. For example, in cycle 21, both solar poles had the same polarity during the second half of 1979, and the field reversed in early 1980. This is the period when drift effects tend to fade out. Thus, in an $\boldsymbol{A} > 0$ epoch, τ tends to increase with time (hence, the observed intensity eventually falls below that predicted by the model) because particle drifts from the poles contribute less and less to the recovery. Starting in an $\boldsymbol{A} < 0$ epoch, the change from drift to no-drift effects leads to a reduction in τ. As further time elapses, particle drifts will start to respond to the reversal of the magnetic field. This means that, within a single cycle, recovery times will be different during the ascending and descending phases. A consequence of such factors, which influence the relationship between B and the CR intensity over the solar cycle, is that a simple correlation analysis is unlikely to be able to determine the degree to which B and the CR intensity are actually related.

The success of this simple model is a further indication that CR modulation on timescales of ~ 1 year is driven by expanding shells of enhanced magnetic field arising from global changes of the solar magnetic field. In an alternative model (e.g., Burlaga et al., 1993), modulation occurs by the formation of "global merged interaction regions" (GMIRs) by the interaction of systems of transient flows in the outer heliosphere. In both cases, the physical mechanism is a propagating barrier. However, the results presented here suggest that this barrier is already present in the inner heliosphere, rather then being formed by essentially random processes well beyond 1 AU. Further evidence supporting this view is provided by the observations of Richardson et al. (2000). They found that the increase in average B at 1 AU as solar activity levels increase, which is incorporated into the model, must be caused by a global variation of the heliospheric magnetic field because it is observed in *all* regions of the solar wind at 1 AU, including corotating streams and slow solar wind. It is not simply the result of the addition of magnetic flux from transient structures which might then go on to generate GMIRs in the outer heliosphere.

Acknowledgements. IGR was supported by NASA grant NCC 5-180. The HUA/HAL NM data were provided by the University of Chicago National Space Science Data System supported by Science Foundation Grant ATM-9912341.

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