THE EFFECT OF THE SOLAR FIELD REVERSAL ON THE MODULATION OF GALACTIC COSMIC RAYS

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ABSTRACT

There is now a growing awareness that solar cycle related changes in the large-scale structure of the interplanetary magnetic field (IMF) may play an important role in the modulation of galactic cosmic rays. To date, attention has been focussed on two aspects of the magnetic field structure: (1) large scale compression regions produced by fast solar wind streams and solar flares, both of which are known to vary in intensity and number over the solar cycle, and (2) the variable warp of the heliospheric current sheet. In this paper we suggest that another feature of the solar cycle is worthy of consideration: the field reversal itself. If the sun reverses its polarity by simply overturning the heliospheric current sheet (northern fields migrating southward and vice-versa) then there may well be an effect on cosmic ray intensity. However, such a simple picture of solar reversal seems improbable. Observations of the solar corona suggest the existence of not one but several current sheets in the heliosphere at solar maximum. This would be consistent with an interpretation of the field reversal in which the sun 'sheds' its old field and develops new field structures of the opposite polarity (like a dog shedding its winter coat). If this is the case then the effect on cosmic ray intensities can be considerable. We present the results of a simple calculation to demonstrate that the variation in cosmic ray intensities that will result can be as large as is actually observed over the solar cycle.

INTRODUCTION

For a number of years modulation theory has been frustrated in its efforts to account for the solar cycle variation in cosmic ray intensities by a lack of variation in such fundamental solar wind parameters as the interplanetary field strength, the solar wind velocity and the micro-scale turbulence of the magnetic field. Attention has recently turned to the effect of large-scale magnetic structures such as corotating interaction regions (Smith and Wolfe, 1976) and flare induced shock waves (Sonett et al., 1968). These are known to vary in both intensity and number over the solar cycle and recent studies have indicated that they can be expected to produce significant changes in cosmic ray intensity (Gall and Thomas, 1981, Thomas and Gall, 1982, 1983). There has also been interest in the effect of the variable warp of the heliospheric current sheet (Svalgaard and Wilcox, 1974), which has also been shown to be capable of modulating cosmic rays (Kota, 1979; Jokipii and Thomas, 1981).

There is now an indication in the Pioneer and Voyager data obtained in the outer heliosphere that the large solar flares occurring near solar maximum can produce almost circular belts of compressed field (Smith et al., 1983). These result in long-lived Forbush decreases of cosmic ray intensity (Van Allen 1979, Lockwood et al., 1980). It has been suggested that the large decrease in cosmic ray intensity near solar maximum may be due to a cascade of these long-lived intensity reductions (McDonald et al., 1981). The problem with this interpretation is that flare shocks do not produce such long-lived decreases in intensity at other times in the solar cycle. Furthermore, if the intensity is to be held at low levels for the long periods required it is necessary to suppress the latitudinal drift of cosmic ray particles. Otherwise particles reaching low latitudes can have gained access to the inner heliosphere from high latitudes where the compression effect of these flares is presumably much reduced. Whilst these may not be regarded as strong objections, it is certainly not clear at this time that solar flares are capable of producing the entire modulation effect. It is our suggestion that the apparent cascade effect of these shocks may be due to Forbush decreases (with standard recovery profiles) superimposed on a general downward trend in cosmic ray intensity produced by a different mechanism.

One obvious feature of solar maximum is that the magnetic field reverses polarity. Two-hemisphere models of the solar field interpret this as an increase in inclination of the heliospheric current sheet as solar maximum approaches at which time the current sheet becomes vertical and overturns (Saito, 1975; Kaburaki and Yoshii, 1979). Such a process will undoubtedly have an effect on cosmic ray intensities (Saito et al., 1977; Swinson et al., 1981). The major effect will be simply that a highly inclined current sheet will propagate into the outer heliosphere with very large latitudinal warps and is a simple extension of the analysis reported by Jokipii and Thomas (1981). It seems improbable, however, that the field reversal process is as simple as implied by the two-hemisphere models. The solar corona near solar maximum is extemely complex and suggests the existence of not one but several heliospheric current sheets. If this is the case then the simple picture of northern hemisphere flux migrating southward and vice-versa is implausible.

The model we present is based on the hypothesis that the solar field reverses by shedding the poloidal field of the previous solar cycle and developing a new field of the opposite polarity. This will imply the existence of closed field lines, for the periods near solar maximum, which will greatly impede cosmic ray access to the inner heliosphere.

A MODEL FOR SOLAR REVERSAL

Figure 1 is a schematic representation of a possible mechanism by which the solar magnetic fields may reverse. The three diagrams represent a time sequence. The top diagram shows the interplanetary field (solid lines) as it may appear above the solar corona at a time well before solar maximum. The circle does not represent the sun, but the source surface of the interplanetary magnetic field, located at 2 or 3 solar radii. Thus, all field lines are open at this time. The middle diagram illustrates the situation near solar maximum with isolated regions of opposite polarity now existing in the two hemispheres separated from the background field by additional current sheets. The dashed lines represent new field lines, associated with the developing current systems, which are drawn into the interplanetary medium by the outflowing solar wind. The hypothesis is that as the new regions of opposite polarity grow they push the old flux towards lower latitudes where it is ultimately shed from the sun. Evidence for the existence of these localised regions of anomalous polarity at

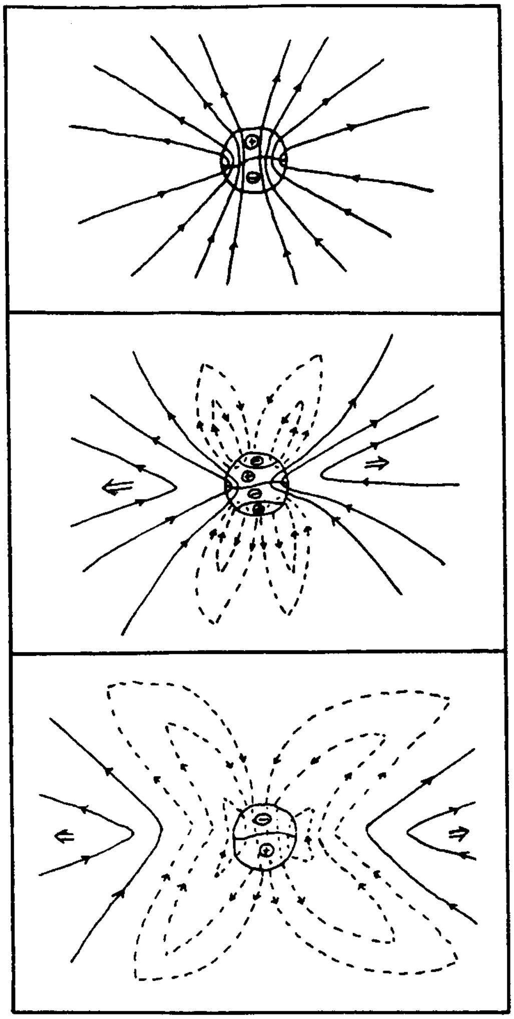

Figure 1. A schematic representation of a model for the solar field reversal. The upper panel shows meridian plane projections of field lines above the solar corona prior to solar maximum (the circle represents the IMF source surface, not the sun). The middle panel shows the field geometry during the reversal period with new current systems and current sheets on the sun producing new magnetic flux (dashed lines). The lower panel shows the situation shortly after the reversal is completed with the new flux having completely displaced the old. The radial distances in these diagrams have been greatly foreshortened.

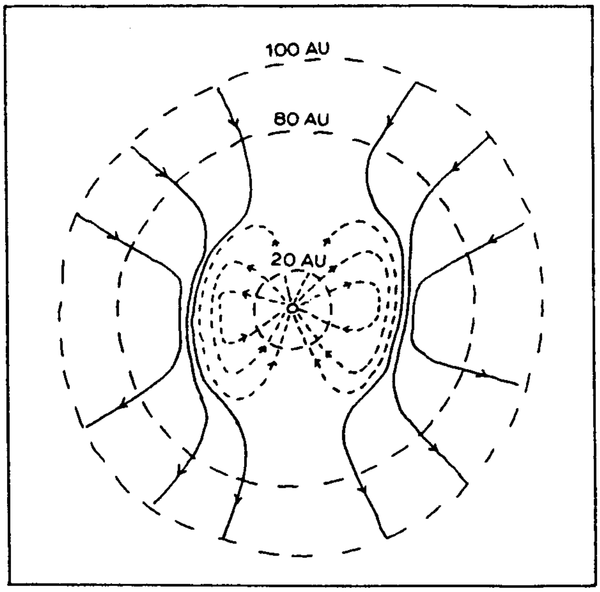

Figure 2. A meridian plane projection of a simple model for the heliospheric field, shortly after solar maximum, containing the essential features of the lower panel in Figure 1.

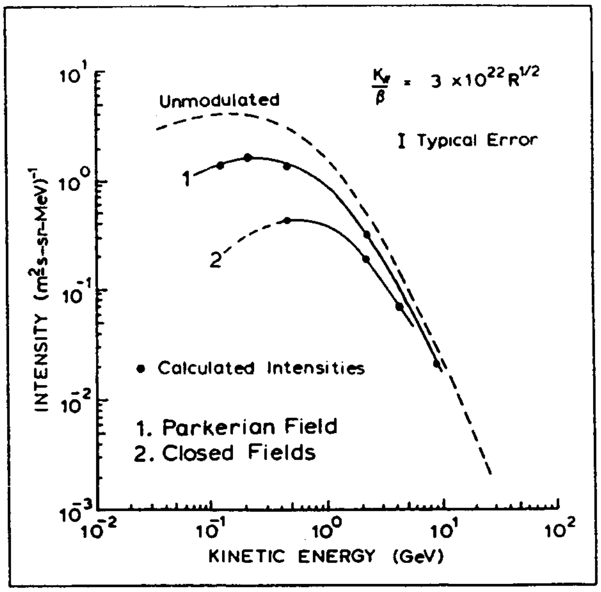

Figure 3. Results of a numerical calculation of cosmic ray intensities at 1 AU in a simple spiral (Parkerian) field and in the closed field geometry of Figure 2. The diffusion coefficient is quoted for 1 AU (R is rigidity in GV).

solar maximum has been reported (Hoeksema et al., 1982). The lower panel illustrates the situation shortly after solar maximum when the new polarity regions have spread completely over both hemispheres, establishing the new solar cycle, with the old field lines now completely shed from the sun. This model for the reversal of the IMF polarity is not inconsistent with dynamo models for the 22 year solar cycle (e.g. Babcock, 1961; Stix 1976). If the bulk of the IMF reversal takes place on a time scale of order one year then the new flux will not have had time to convect to the heliospheric boundary and the field lines in the inner heliosphere at this time will therefore be closed.

This model may be over simplified, there may be more than one region of anomalous polarity which develops in each hemisphere and the flux shedding process, if it occurs, will probably be spasmodic and patchy (i.e. coronal transients or localised bubbles). However, topologically there are only two possible interpretations for the solar reversal process. Either field lines migrate over the solar surface or, alternatively, new flux emerges and displaces the old. Reconnection processes may be expected to play a role in the reversal but if isolated regions of opposite flux do develop on the sun it will not be possible for the field lines in these regions to reconnect with the old field from the opposite hemisphere.

A SIMPLE NUMERICAL MODEL

The magnetic field geometry near solar maximum resulting from the process outlined in the previous section would be quite complex. In this section we outline a greatly simplified model for the field geometry shortly after solar maximum, for which solutions for the cosmic ray intensity at 1 AU can be determined by numerical integration techiques. The objective is to determine if the existence of a closed field line configuration in the inner heliosphere is capable of providing cosmic ray modulation of the required magnitude.

Figure 2 displays the model schematically. The diagram shows only the meridian plane components of the field. Over most of the diagram the azimuthal component is dominant and the field geometry is close to an Archimedian spiral, with a flat current sheet in the equatorial plane. For computational simplicity the outer boundary of the heliosphere is taken to be spherical and is located at 100 AU. Inside 20 AU the field is a pure Archimedian spiral given by the equations:

$$B_r = A \frac{B_o}{r^2} \tag{1a}$$

$$B_\phi = A\, B_o \frac{\Omega \sin\theta}{r V_w} \tag{1b}$$

$$B_\theta = 0 \tag{1c}$$

where V_w is the solar wind velocity, Ω the solar rotation frequency and B_o is chosen to give a 5 nT field at 1 AU. $A = \pm 1$, chosen to give outward fields in the northern hemisphere and inward in the southern hemisphere. This region represents the new field after the reversal process is completed.

Outside 80 AU the field equations are identical, but A is chosen to give inward field in the northern hemisphere and outward in the southern hemisphere. This region represents field from the previous solar cycle which has now been completely shed from the sun but which has not yet convected to the model boundary.

Between 20 and 80 AU is the transition region representing the period during which the field reversal occurred. This corresponds to a reversal period of approximately eight months. A simple method of closing the internal and external field regions is given by the divergence free expressions:

$$B_r = A\,B_o\,\frac{(r - r_o)}{r^2 \Delta r} \tag{2a}$$

$$B_\phi = A\,B_o\,\frac{\Omega \sin\theta\,(r-r_o)}{r V_w \Delta r} \tag{2b}$$

$$B_\theta = A\,B_o\,\frac{(\cos\theta - 1)}{r\,\Delta r \sin\theta} \tag{2c}$$

where r_o is the interface between old and new flux located at 50 AU and Δr is the half-width of the transition region, 30 AU. This model actually corresponds to a field on the sun in which the radial component dies away linearly and builds up again in the opposite direction. Although not a representation of the true situation it contains the essential features: separate regions of old and new flux, closed fields in the inner heliosphere and a field geometry which is almost Parkerian (except very near the interface). The magnitude of the north-south component as this structure convects past 1 AU would be approximately 1/10th nT. The effect of the radial component of the field diminishing over the reversal period may be unrealistic but will have the consequence of providing easier access of cosmic rays to the inner heliosphere and so will weaken the overall modulation rather than exaggerate it.

In the numerical calculation of the cosmic ray intensity at 1 AU, which is described in the next section, we have compared the results obtained in this model with those obtained in the simple spiral field which will exist well away from solar maximum. It is clear that particles will have easier access to the inner heliosphere in the simple spiral field configuration. Particles move in the heliosphere under a combination of diffusive propagation along the field lines and particle drifts. In spiral fields both the field lines and the drift patterns extend to the heliospheric boundary. In a closed field topology exactly the opposite is true. Not only are the field lines closed but, since particle drifts are divergence free, the drift patterns are also closed. Therefore the particles obtain no help from either process and can gain access to the inner heliosphere only by scattering perpendicularly to the field, across the interface between one field region and the other.

NUMERICAL METHOD AND RESULTS

The method used involves full numerical integration of the equation of motion (3) for individual cosmic ray protons.

$$\frac{d\vec{P}}{dt} = e(\vec{E} + \frac{\vec{v} \times \vec{B}}{c}) \quad (3)$$

where P, v and e are the particle momentum, velocity and charge; B the magnetic field and E the convection electric field. The effect of scattering by magnetic field irregularities is represented by introducing small random angular perturbations in such a way that the desired diffusion coefficient is obtained. The diffusion coefficient is allowed to increase in the outer heliosphere such that the mean free path and particle gyroradius have a fixed ratio. Perpendicular scattering is also implicit in this method with the particle scattering typically one gyroradius perpendicular to the field in each parallel mean free path. This leads, in these calculations, to a perpendicular diffusion coefficient approximately 10% of the parallel coefficient. The trajectory of a given particle is obtained by integrating backward in time, starting at 1 AU until the particle reaches the model boundary at 100 AU. A power law in total energy is assumed for the cosmic ray phase space density at the boundary. By direct application of Liouville′s theorem each particle gives an independent estimate of the phase space density at 1 AU (at a given particle energy) and by averaging over a large number of individual estimates we obtain a representative value for the omnidirectional intensity at 1 AU. This method has certain advantages over a more traditional numerical solution of the transport equation. Firstly, adiabatic focussing and gradient and curvature drifts are automatic consequences of full trajectory integration and we therefore avoid the unphysically large velocities that can result from first order approximations. Secondly, current sheets and other discontinuities are also dealt with automatically without the need for continuity conditions. The primary advantage is that it can deal with three-dimensional field configurations, although that is of little advantage here, as our model has azimuthal symmetry. The method has been compared with traditional solutions of the transport equations in simple spiral fields and complete agreement is obtained. Further details of this method are given in Thomas and Gall (1983).

Figure 3 displays the cosmic ray intensities obtained as a function of particle energy for simple Parkerian fields and for the closed field line model outlined above. The same diffusion coefficients were used for both calculations. The calculated intensities are subject to errors due to the finite number of individual estimates of the phase space density. A typical error bar is displayed. The difference in the two curves is indeed comparable to the observed variation in cosmic ray intensity over the solar cycle.

DISCUSSION AND CONCLUSION

The mechanism by which the sun reverses polarity is crucial for understanding the solar cycle modulation of galactic cosmic rays. One possible mechanism we suggest is that the sun may completely shed the magnetic flux from the previous cycle and develop a new magnetic field of the opposite polarity. If this is the case then a closed field line topology will exist in the heliosphere for the periods near solar maximum. We have quantitatively investigated the effect of an extremely simple closed field model, representing the heliospheric field shortly after solar maximum, and find the effect on cosmic ray intensities to be comparable to that observed.

We have performed our analysis at just one particular time in the solar cycle shortly after the field reversal has been completed. It is clear, however, that the effect will begin substantially earlier (when the reversal process begins and new flux loops begin to appear in the inner heliosphere) and will not disappear until all of the old flux has been shed and has convected to the heliopause. Thus, the intensity reduction can be expected to persist for several years. It will also display the familiar hysteresis effect.

Our primary objective in this paper is to give a general indication of the effect that closed field configurations may have on cosmic ray intensities in the heliosphere, using reasonable estimates for the particle diffusion coefficient and overall size scale of the interplanetary magnetic field. In reality the field configuration at this time may be very complicated, but if regions of closed field do exist then there may be large effects on cosmic ray intensities which cannot be ignored.

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