Corotating Variations of Cosmic Rays Near the South Heliospheric Pole

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Three-dimensional simulations of the heliospheric modulation of galactic cosmic ray protons show that corotating variations in the intensity can persist to quite high heliographic latitudes. Variations are seen at latitudes considerably higher than the maximum latitude extension of the heliographic current sheet, in regions where the solar wind velocity and magnetic field show no significant variation. Similar conclusions may apply also to lower energy particles, which may be accelerated at lower latitudes. Cosmic ray variations caused by corotating interaction regions present at low heliographic latitudes can propagate to significantly higher latitudes.

Observations of periodic variations of the cosmic ray intensity, associated with corotating regions in the solar wind, are a useful diagnostic of the modes of transport of cosmic rays. Kunow *et al.* (*1*) and McKibben *et al.* (*2*) reported such variations in the flux of relativistic protons observed from the Ulysses spacecraft at heliospheric latitudes where no corresponding variations were seen in the magnetic field and solar wind, and Simpson *et al.* (*3*) found such variations to extend to −80.2°. Sanderson *et al.* (*4*) and Simnett *et al.* (*5*) also reported similar variations, but for particles having much lower energies (1 to 10 MeV). The variation of the lower energy particles was not seen beyond about −70°. The unexpected persistence of corotating cosmic ray variations to the highest latitudes traversed by Ulysses has not yet been explained. Here we suggest that it is a straightforward consequence of a global model of cosmic ray modulation, which has previously explained a variety of observations at lower latitudes.

The transport of cosmic rays in the heliosphere involves a number of physical effects: diffusion, convection, guiding-center drifts, and energy change. Global modeling suggests that the drift terms play the most important role in the large-scale, 11-year variation [see, for example, (*6*–*10*)], particularly during the years around a sunspot minimum. Notable successes have been the prediction of various observed 22-year solar magnetic cycle effects and the correlation between the magnetic field and the rate of change of the cosmic ray intensity associated with corotating interaction regions (CIRs).

Here we examine the latitudinal and longitudinal behavior of a global, three-dimensional, time-dependent model of cosmic rays and energetic particles that contains a realistic, corotating solar wind configuration. Emphasis is on the 13-day and 26-day corotating variations and how they vary with latitude.

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The distribution function $f(\mathbf{r}, p, t)$ of cosmic rays of momentum p at position $\mathbf{r}$ and time t satisfies the equation (*9*, *11*)

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left(\kappa_{ij}\frac{\partial f}{\partial x_j}\right) - V_{w,i}\frac{\partial f}{\partial x_i} - V_{d,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\left(\frac{\partial f}{\partial \ln p}\right) \quad (1)$$

where κ_{ij} is the diffusion tensor, $\mathbf{V}_w$ is the (radial) wind velocity, and the guiding-center drift velocity $\mathbf{V}_d$ is given in terms of the local magnetic field $\mathbf{B}$, the particle speed w, and charge q by $\mathbf{V}_d = (pcw/3q)\nabla\times(\mathbf{B}/B^2)$, where c is the speed of light.

The large-scale magnetic field (*12*, *13*) consists of an Archimedean spiral, with the field pointing in one direction in the northern heliospheric hemisphere and in the opposite direction in the southern. The fields are separated by a thin current sheet that is nearly equatorial near sunspot minimum. The magnetic field direction changes sign at each sunspot maximum with the northern field at present directed out from the sun.

Observations (*14*) show that the solar wind velocity increases with heliomagnetic latitude λ_{mag} from around 350 or 400 km/s near the current sheet ($\lambda_{mag} = 0$) to nearly 800 km/s for $\lambda_{mag} \gtrsim 20°$. Solar rotation results in regions of fast solar wind overtaking previously emitted slower solar wind, which together form CIRs. Shocks form closer to the sun if the transition from slow to fast wind is sharper, and farther out (or do not form at all) if the transition from slow to fast wind is more gradual.

Our code computes a wind model based on this picture. We assume that at the sun, the current sheet is a plane inclined at an angle α to the equator and that the wind varies with λ_{mag}, with a specified functional form, corresponding to a low speed V_{min} = 350 km/s at the magnetic equator and V_{max} = 750 km/s at the poles

$$\mathbf{V}_w = \left[V_{max} - \frac{V_{max} - V_{min}}{1 + \left(\dfrac{\sin\lambda_{mag}}{\sin\lambda_*}\right)^8}\right]\hat{\mathbf{e}}_r \quad (2)$$

where $\lambda_* = 15°$ is the transition latitude and $\hat{\mathbf{e}}_r$ is the unit vector in the heliocentric radial direction. Because transverse stresses are small, we neglect the transverse velocities and solve the radial momentum equation, including the pressure and magnetic forces. This calculation is followed until it settles into a corotating pattern. Therefore, only corotating phenomena are considered.

The structure beyond the solar wind termination shock is uncertain, and we simply assume that there is a shock transition at some specified radius R_{sh}. Beyond this, the radial velocity drops by 1/4 and falls off as $1/r^2$, out to an outer spherical boundary where f takes on a specified "interstellar" value. We use the same form for the diffusion tensor as that in our previous modeling efforts (*9*).

Jokipii and Kóta (*7*) suggested that the magnetic field over the poles would have increased large-scale fluctuations and that this might help explain certain features of the observations of cosmic rays. Smith *et al.* (*13*) reported an increase in variance at large scales as Ulysses moved to higher latitudes. We incorporate a modified field near the poles to in part reveal the effects of such fluctuations. This reduces both the radial diffusion and drift. Further, the possibility of enhanced latitudinal transport by anisotropic field-line random walk is considered.

We first consider the modulation of galactic cosmic rays having energies near 1 GeV. An external boundary condition re-

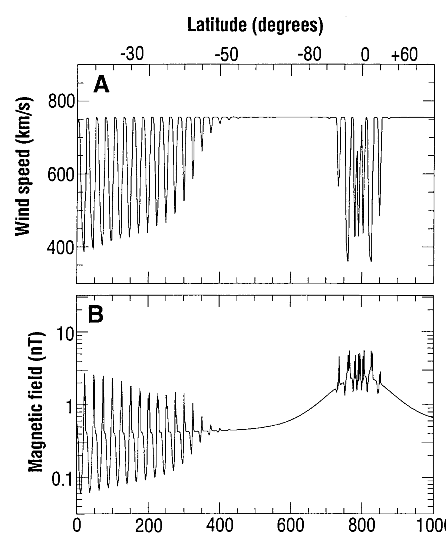

Fig. 1. The variation of the (**A**) solar wind speed and (**B**) large-scale magnetic field along the trajectory of Ulysses as predicted from our tilted dipole model heliosphere.

flecting the bath of galactic cosmic rays is imposed. Our conclusions are not sensitive to the precise form of this spectrum, which is taken to be a power law in total energy with an exponent of -2.65.

In comparison to a scenario of axial symmetry and a flat current sheet, a wavy current sheet and CIRs affect the transport of cosmic rays in several ways (*9*). Particle drifts will be less uniform in this more complex field. Regions of stronger magnetic field in the compression regions have smaller diffusion coefficients. Charged particles are accelerated at the shocks. This last effect is also included, but the effect of acceleration for cosmic rays with energies $\gtrsim 100$ MeV is relatively unimportant. For local variations and short-term variations such as the 26-day and 13-day intensity waves, the small diffusion coefficient associated with the strong magnetic fields in CIRs is most important (*9*). Previous numerical simulations (*9*) indicated that the flux of galactic cosmic rays decreases whenever a region of strong field passes, which is in agreement with the observations (*15*).

Ulysses approached the south pole when the heliospheric magnetic field pointed away from the sun above the current sheet and toward the sun below the sheet. In this configuration, positively charged particles enter the heliosphere at the heliospheric poles and drift toward the current sheet. Thus, at high latitudes, the intensity is insensitive to the structure of the current sheet. Of course, this simplified picture is modified by diffusion.

Figure 1 shows the simulated variation of solar wind speed and magnetic field strength as Ulysses moves along its trajectory from January 1993 to late 1995. We used the form of the wind given by Eq. 2, so that there is almost no variation in the wind or magnetic field at high latitudes [in contrast to our previous work (*10*)]. Figure 2 displays the corresponding variation of the intensity of 1-GeV galactic cosmic rays. The tilt angle α was set at 30° for the whole period because a slowly changing angle would not significantly alter the character of the predicted 26-day variations.

The predicted 26-day variations are largest when the latitude of the spacecraft is comparable to the latitudinal excursion of the current sheet and decreases dramatically in the unipolar region below the current sheet (Fig. 2). Depending on the perpendicular diffusion, these 26-day cosmic ray variations can still be present at latitudes as high as $-80°$, where there are no associated magnetic field or wind variations. We conclude that these variations must be connected with particle diffusion across the field lines, which transports the local effects of the CIRs to high latitudes without removing the global effects of the drifts.

The cosmic ray intensity increase from equator to pole is quite moderate in these simulations. The variation in Fig. 2, for a range of parameters, is consistent with the observed ~50% variation between the equator and $-80°$ reported by Simpson *et al.* (*3*). The effect of varying the magnitude of the perpendicular diffusion coefficient is seen in Fig. 2.

We have also simulated 4-MeV protons, for which the most likely source is acceleration at CIRs. This acceleration involves very small spatial scales and cannot be accurately modeled in our global simulation. Hence, to illustrate the transport of these particles after acceleration, we have simply put a corotating source of these accelerated particles at shocks and put compression regions at low heliographic latitudes.

Again, the simulated corotating, 26-day variation persists to high latitudes (Fig. 3), even though the source of variation is at much lower latitudes. We suggest that the absence of detectable variations beyond about $-70°$ latitude (*4*, *5*) is a consequence of two facts: The current sheet has a smaller α corresponding to lower solar activity, and Ulysses has moved to a smaller heliospheric radius so that the CIRs have not yet accelerated enough particles. This interpretation is supported by the fact that, when Ulysses returned from its highest latitudes, moving back toward the equator, the corotating variations did not return until $-45°$ latitude (*4*).

It is generally thought that particles of low rigidity have a small coefficient of latitudinal diffusion, primarily because they cannot readily cross field lines. However, latitudinal diffusion can also result from the mixing or random walk of field lines normal to the average magnetic field direction (*16*). The expected variation of the magnetic fluctuations with heliographic latitude and heliocentric radius (*17*) indicates that the perpendicular diffusion coefficient may itself be anisotropic and may increase more rapidly with radius in the latitudinal direction than in the radial and azimuthal directions. This would result in even more corotating variations at high latitudes and, further, would reduce the latitudinal gradient considerably.

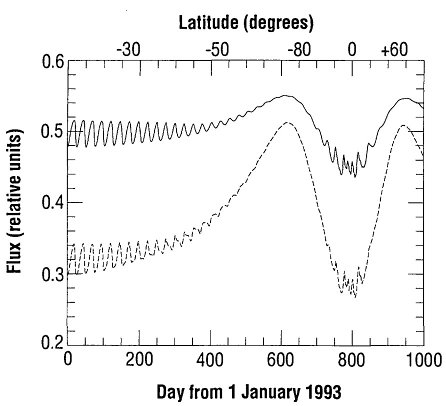

Fig. 2. Computed variation of the flux of 1-GeV cosmic ray protons along the trajectory of Ulysses for the heliospheric model in Fig. 1. Calculations were carried out for larger ($\kappa_{\|}/\kappa_{\perp} = 0.05$, solid line) and lower ($\kappa_{\|}/\kappa_{\perp} = 0.02$, dashed line) values of the perpendicular diffusion coefficient.

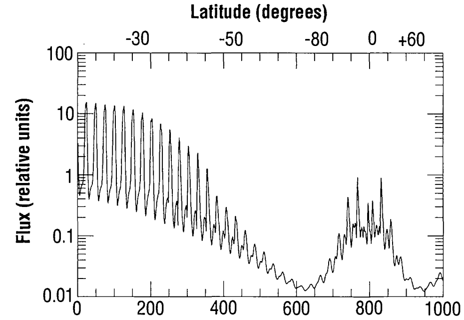

Fig. 3. Predicted variation of the flux of low-energy (4-MeV) protons, with sources placed at shocks and compression regions associated with CIRs at lower latitudes. Here $\kappa_{\|}/\kappa_{\perp} = 0.02$.

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18. This work was supported by the National Aeronautics and Space Administration (NASA) through the Jet Propulsion Laboratory (JPL) as part of an Interdisciplinary Investigation on the Ulysses mission; JPL contract 959376 (J.R.J.). The research was also supported, in part, by the National Science Foundation grant ATM-9307046 and NASA grants NAGW 5-2251, NAGW 1931 (J.R.J.), and NAGW-2549 (J.K.).

8 February 1995; accepted 20 April 1995