3D heliospheric simulations of cosmic rays in the light of Ulysses (*)

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Summary. — Recent Ulysses observations in the polar regions of the heliosphere have provided fundamental new insights into the modes of cosmic-ray transport in the heliosphere. Ulysses discovered variations in the magnetic field which are large enough to produce significant cosmic-ray effects, and which are consistent with a previous prediction. In addition to impeding the inward, radial diffusive and drift access of cosmic rays over the poles as discussed previously, the magnetic fluctuations imply a significantly larger latitudinal diffusion. These effects directly lead to both a much reduced latitudinal gradient and significant 27-day time variations near the pole. We conclude that the general picture of cosmic-ray transport and modulation developed over the past decade, with reasonable parameters, can account for most of the observed global, large-scale phenomena.

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1. – Introduction

The polar passages of the Ulysses spacecraft have offered the first opportunity to measure directly the solar-wind parameters and cosmic-ray intensity at high heliographic latitudes. This offers an opportunity and a challenge to our ideas regarding the modulation and transport of cosmic rays in the heliosphere. In this paper we summarize new magnetic-field data and their interpretation in terms of a three-dimensional model of the heliosphere. It appears that the large-scale observations, obtained near sunspot minimum, can be explained in terms of a simple, well-ordered, co-rotating heliosphere with reasonable values for the parameters and transport coefficients.

The interplanetary magnetic field is generally considered to be an Archimedean spiral [1] upon which irregular fluctuations are superimposed. Observations near the

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ecliptic plane have verified the general correctness of this prediction (see, *e.g.*, Smith *et al.* [2]). But until Ulysses [3], no measurements were available at mid or high heliographic latitudes.

Jokipii and Kóta [4] (hereinafter denoted JK) suggested the existence of large-scale, transverse magnetic-field fluctuations in the heliographic polar regions. This prediction was based on the dynamics of the solar wind and magnetic field in the polar regions of the Sun, and a consideration of cosmic-ray observations in the ecliptic. They pointed out that the fluctuating field should be more apparent near the heliospheric poles and at large heliocentric radii, but that Ulysses might be able to observe them. Subsequent analyses were published by Hollweg and Lee [5], Roberts [6], and Lou [7]. A recent analysis of the Ulysses data by Jokipii *et al.* [8] presents arguments that these are consistent with the original idea of JK. We summarize this analysis below and go on to discuss effects on cosmic rays.

2. – Transverse heliospheric magnetic fluctuations

JK pointed out that the Parker spiral magnetic field near the heliospheric pole is primarily radial and falls off as $1/r^2$, whereas any large-scale transverse fluctuations which may be present fall off as $1/r$ (quasi-static) or $1/r^{3/2}$ (WKB), (*e.g.*, Heinemann and Olbert [9]). In the linear approximation, the transition between quasi-static and WKB behavior occurs at a time scale T_c, which may be written in terms of the radial component of the Alfvén speed V_{ar} and the wind speed V_w as [6, 9]

$$\frac{4\pi r V_{ar}}{T_c V_w^2} = 1\,, \tag{1}$$

which yields $T_c \approx 1.4$ days at 1 AU. Referring to earlier work of Jokipii and Parker [10], JK suggested that one source of magnetic fluctuations was the super-granulation in the solar photosphere.

The supergranulation is a random transverse motion with a characteristic time scale of 20–48 h and mean velocities of 300–600 m/s [11, 12]. Hence, variations produced by supergranulation can have periods longer than T_c.

These effects on the magnetic field should be most observable near the heliospheric poles where the average magnetic field is smaller, and the complicating effects of solar rotation and solar activity are less.

From the previous section, it is clear that the amplitude of transverse fluctuations should vary as r^{-1} at time scales greater than about a day, and as $r^{-3/2}$ at shorter scales. Figure 1 shows the radial variation of the variances in the transverse magnetic field for two different averaging intervals, one corresponding to large temporal scales, and one corresponding to smaller scales. These are special cases of the data set discussed by Balogh *et al.* [13]. For the data indicated by +'s, the magnetic-field data were first averaged over 4.3 minutes, from which hourly variances of the transverse components are computed. The data were finally binned in one-degree latitude bins. The points indicated by diamonds were computed in the same manner except that the magnetic-field data are first averaged over 24 hours (to eliminate the high-frequency fluctuations) and the variances are taken over twenty days. The variance of the *radial* magnetic-field component is much smaller at all scales [13]. The data, covering a wide range in latitude, are consistent

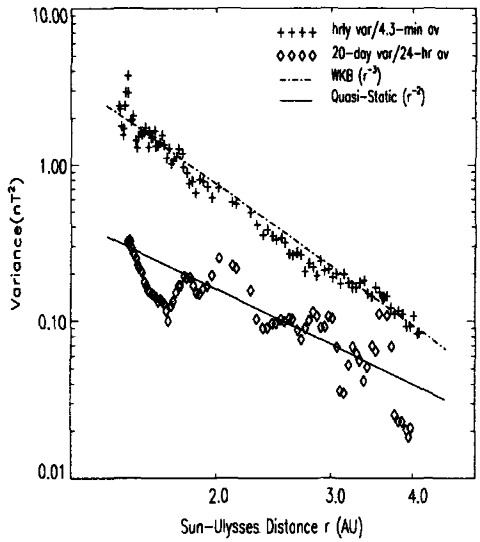

Fig. 1. – Comparison of observed variances of the transverse magnetic field and model predictions [13, 8]. The dash-dotted curve is the unnormalized WKB prediction and the solid line is the quasi-static prediction, with the normalization set by the nominal supergranulation parameters as in the text. + + + hourly variation/4.3 min average, ◊◊◊ 20-day variation/24 h average.

with one curve of radial variation, suggesting little latitudinal variation. This is consistent with the observation that supergranulation has no significant latitude dependence.

The time interval for this study was chosen so that Ulysses was entirely in the high-speed solar wind.

The lines superposed on the curves are theoretical predictions based on the previous discussion. The upper line represents the WKB radial variation (since the variance corresponds to δB^2), with a normalization chosen to fit the data. Clearly, the WKB approximation is consistent with the higher-frequency data. The lower line corresponds to the quasi-static prediction of $1/r^2$. Again, the curve is consistent with the data. The normalization here, which is clearly consistent with the observed values, is obtained by putting nominal supergranulation values in JK. The transition from WKB to quasi-static behavior occurs for scales of the order of a day or less, close to the value of T_c derived above. Goldstein *et al.* [14] analyzed the cross-helicity of the solar wind observed on Ulysses, and showed that the fluctuations at frequencies higher than $\approx 10^{-5}$ Hz have a higher value, consistent with the above picture, although they found indications that the WKB scaling down to time scales of 1 day, so the interpretation is still not completely clear.

3. – Cosmic-ray transport and modulation

As mentioned by JK, the magnetic fluctuations discussed above will impede the access of cosmic rays from the polar regions, particularly during positive magnetic cycles (*e.g.*, the 1975 and 1995 sunspot minima).

An important aspect to the transverse magnetic-field fluctuations discussed above,

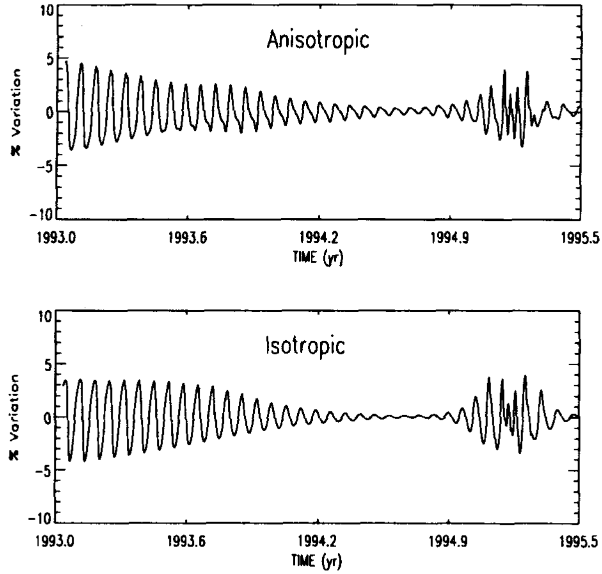

Fig. 2. – The computed co-rotating variation of cosmic rays at Ulysses, showing the effect of varying $\kappa_{\perp}$.

which was emphasized by Jokipii and Parker [10], but not discussed by JK, is the implied mixing, or random walk of the magnetic-field lines relative to the average magnetic field. Because cosmic rays tend to follows field lines, this field-line mixing contributes to the diffusion of cosmic rays normal to the average magnetic field [10, 15].

The general problem was considered by Jokipii [16] who showed that the diffusion coefficient is different in the θ (latitudinal) direction than in the direction normal to the magnetic field, but in the r, ϕ direction. Denoting these by $\kappa_{\perp 2}$ and $\kappa_{\perp 1}$, respectively, one obtains $\kappa_{\perp 1} \propto r^{-1}$ and $\kappa_{\perp 2} \propto r$, for $r\Omega \sin(\theta)/V_{\mathrm{w}} \gg 1$, whereas for small r ($r\Omega \sin(\theta)/V_{\mathrm{w}} \ll 1$) they both vary as r^2. From this it is clear that the diffusion of cosmic rays may be much more rapid in the latitudinal (θ) direction than in the radial direction in the outer heliosphere, where $\kappa_{rr} \approx \kappa_{\perp 1} \propto r^{-1}$ and $\kappa_{\theta\theta} \approx \kappa_{\perp 2} \propto r$.

As mentioned above, JK realized that the expected transverse magnetic fields in the polar regions would impede the rapid inward, radial access of cosmic rays over the poles. They constructed models in which this was approximated by reducing both the diffusion and drift by fixed amounts in the polar regions (see also Potgieter and le Roux [17]). Kóta and Jokipii [18] recently discussed the persistence of co-rotating cosmic-ray variations to high heliographic latitudes and the interpretation of Ulysses cosmic-ray variations to the heliographic polar regions. This is illustrated in fig. 2 for isotropic and anisotropic $\kappa_{\perp}$.

Here we present the results from models incorporating an increased $\kappa_{\theta\theta}$ resulting from the transverse magnetic variations, and compare the resulting solutions with the same model without the enhanced value of $\kappa_{\theta\theta}$.

The model calculations reported here are for a model heliosphere which is the same as that used previously (*e.g.*, [19]). The magnetic field is taken to correspond to the classical Parker spiral, except that its magnitude is larger at the poles, which has the effect of reducing the inward drift and diffusion. The standard diffusion coefficients are $\kappa_{\parallel} = \kappa_0 P^{1/2} \beta B_E / B$ and $\kappa_{\perp} = \eta \kappa_{\parallel}$, where B is the magnetic field, B_E is its value at 1 AU, η is

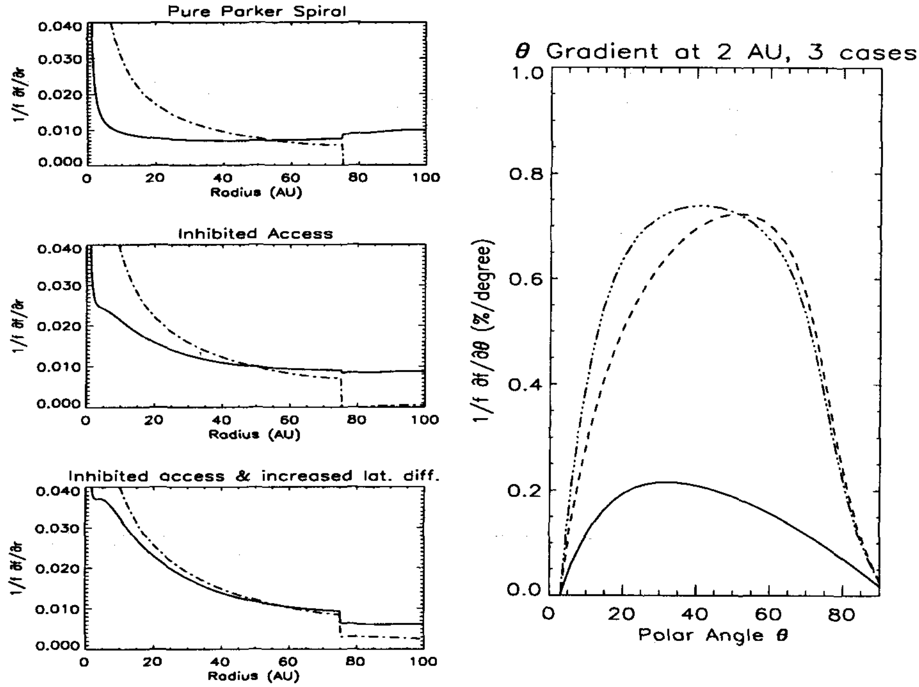

Fig. 3. – Illustration of the effect of the enhanced polar variances on the computed radial (left) and latitudinal (right) gradients of 200 MeV cosmic-ray protons. On the left, the solid line and dashed lines are for northern solar magnetic field outward and inward, respectively. The curves on the right are only for the case northern field outward. The dot-dashed, dashed, and solid lines correspond to the top, middle and bottom panels on the left, respectively.

usually set equal to 0.01–0.05 and, if the rigidity P is expressed in GV, $\kappa_0 \approx 1.5 \cdot 10^{22}$ cm^2. The effect of the enhanced latitudinal diffusion can be included by increasing the value of $\kappa_{\theta\theta}$, while keeping κ_{rr} the same. In addition, the standard drift velocity for the case of weak scattering is used, $V_\mathrm{d} = (pcw/3q)\nabla \times (\boldsymbol{B}/B^2)$.

Figure 3 illustrates one of the major effects of this increase in $\kappa_{\theta\theta}$. Shown in each panel on the left are the radial gradients of 500 MeV cosmic-ray protons, near the heliospheric equator, for the two alternating phases of the solar magnetic cycle, corresponding to northern magnetic field directed outward and inward. The top panel presents the gradients for a standard Archimedean spiral magnetic field, clearly illustrating the significant difference between the two phases. The middle panel shows the gradient for decreased radial diffusion and drift in the polar regions resulting from the non-Archimedean field, and the lower panel illustrates the effects of using both a decreased diffusion and drift at the pole and an enhanced latitudinal diffusion (as discussed above). In the last case, it is apparent that the radial gradients are considerably closer for the two magnetic phases, bringing theory into even closer agreement with observations than did previous models (see, *e.g.*, Chen and Bieber [20]). The right panel in fig. 3 illustrates the effects of the three situations illustrated on the left on the latitudinal gradients.

4. – Summary and conclusions

The observed large-scale magnetic variances of the magnetic-field components normal to the radial direction, observed on Ulysses [13] appear to be consistent with a rather simple theoretical picture put forth previously (JK). Variances with time scales of the order of a day or longer decrease with heliocentric radius as $1/r^2$, more slowly than the shorter-scale variances, and are expected to dominate in the outer heliosphere. These variances have significant effects on the modulation of galactic cosmic rays, and calculations suggest that they can bring modulation models into even better agreement with observations.

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