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Cosmic-ray effects of propagating disturbances: Including the heliosheath

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Abstract. It has been known for a long time that the effects of the heliosphere on cosmic rays extends beyond the termination shock and into the heliosheath. The inclusion of the region beyond the termination shock into models of modulation is still not universal, although the effects of the heliosheath may be considerable in the outer heliosphere. Previously published 2- and 3-D model results including a termination shock have all been for stationary systems. We have modified our two-dimensional heliosperic cosmic-ray simulation code to be time dependent and to include a propagating disturbance which propagates out from the Sun and into the Heliosheath. The code follows the time variation of the intensity of both galactic and anomalous cosmic rays as the shock propagates past the point of observation and beyond. The results show encouraging similarities with recent observations on outer-heliosphere spacecraft which show differences in the recovery of anomalous and galactic cosmic rays. A new consequence of this picture is predicted.

1 Introduction and Background

The effects of the heliosphere on cosmic rays in the heliosphere have been studied for decades. The heliosphere consists of a number of different regions such as the inner heliosphere, the outer heliosphere, the termination shock and the heliosheath, each of which affects the observed intensities.

Figure 1 illustrates a current view of the heliosphere. The solar wind blows radially outward from the Sun at the center, carrying with it the solar magnetic field, producing an Archimedean spiral magnetic field. At a radius of about 100 AU, because of the resistance of the interstellar gas, the wind undergoes a shock transition to subsonic flow (illustrated by the inner circular boundary). Beyond this termination shock, the dark line labeled heliopause marks the contact surface which separates the ionized interstellar gas from the solar wind gas. A possible second, outer shock in the interstellar plasma may also exist, but is not shown in the diagram.

This whole system is bathed by an isotropic, uniform distribution of galactic cosmic rays. These cosmic rays have greater or lesser difficulty in traveling into the inner solar system, resulting in a depressed intensity there. In addition, anomalous cosmic rays are accelerated at the termination shock to energies in excess of 1.5 GeV and also propagate through the system, much like galactic cosmic rays. In the following I will denote galactic cosmic rays by GCR and anomalous cosmic rays by ACR. Basically, the GCR and ACR intensities are "modulated" by the solar wind and its magnetic field. In addition, of course, the ACR are accelerated at the termination shock, which is part of the model. The intensities reach a maximum at the Earth during periods of sunspot minimum and are a minimum when the sun spots are at a maximum. This reflects a general, heliospheric depression of the intensity of cosmic rays.

The outer portions of this model, beyond the termination shock are not understood in detail. It seems that the general properties of $\approx$ 100 MeV- 1GeV particles in the inner heliosphere are not very sensitive to these uncertainties, although there are certainly effects.

Also shown in Figure 1 is the progress of a transient disturbance which propagates past an observer out beyond the termination shock. This disturbance will have effects on the cosmic-ray flux which is discussed below.

2 The Region Beyond the Termination Shock

Traditionally, models of GCR in the heliosphere neglected the poorly-known region beyond the termination shock and placed the outer boundary of the region of interest at the termination shock. At this point, the GCR intensity was taken to be the undistorted galactic intensity of galactic cosmic rays, as a function of energy. This is perhaps not unreasonable for the study of GCR phenomena in the inner heliosphere, as the effects of the outer regions are less there. In fact, such models are still used with effect (e.g., Burger, et al, 2000). Nonethe-

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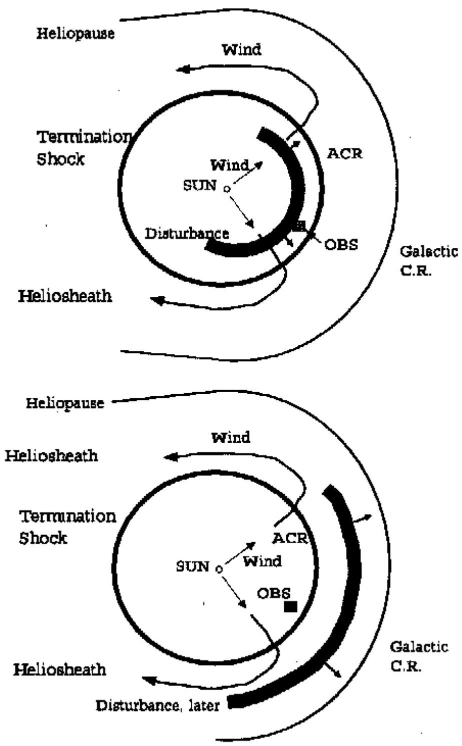

Fig. 1. Schematic diagram of the structure of the heliosphere, showing the propagation of a disturbance past an observer in the heliosphere to beyond the termination shock and into the heliosheath. In the top panel the disturbance is just reaching the observer, and in the bottom panel the disturbance is beyond the termination shock in the heliosheath.

less, as emphasized by Jokipii, et al (1993), it is necessary to incorporate the region to describe accurately phenomena in the outer heliosphere. They presented a series of model calculations showing the large effects of the region beyond the termination shock on the gradients of cosmic rays near the termination shock, both inside and outside of the shock.

Of course, it is, *in principle* impossible to model ACR without including the region beyond the termination shock, because the particles must spend time on both sides of the shock. Hence, models of the ACR incorporated the heliosheath region right from the beginning (Jokipii, 1986). Shortly thereafter, the Arizona models all incorporated the region beyond the shock as a matter of course, although this was not specifically emphasized until the 1993 paper discussed above. Of course, predictions for the outer heliosphere must be treated with caution, even if they incorporate the heliosheath. This is because the region is poorly understood, and the structure must be considerably simplified.

2.1 Recent Observations of Transient Effects

As pointed out in the introduction, although effects of the regions beyond the terminations shock have been recognized for a long time, and have been incorporated into our multidimensional models since 1986, there have been no observations which pointed directly toward heliosheath effects. This was changed recently in an observational paper by McDonald, et al (2000), which reported *transient* effects which seemed to be best explained by effects occurring beyond the termination shock. Attempts to model the observed effects are reported below.

3 Modeling Cosmic Rays in the Heliosphere

3.1 The Transport Equation

We consider the problem of cosmic-ray transport in a magnetic field which is a function of position and time, and which is frozen into the outward- moving plasma. The cosmic-ray particles are subjected to four distinct transport effects. There are: a random walk or spatial diffusion, convection with the fluid flow, curvature and gradient drifts and energy changes. They were combined first by Parker (1965), to obtain the transport equation for the distribution function $f(\mathbf{r}, p, t)$ of cosmic rays of momentum p at position $\mathbf{r}$ and time t.

$$
\begin{aligned}
\frac{\partial f}{\partial t} = & \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] && (\mathit{diffusion}) \\
& - U_i\frac{\partial f}{\partial x_i} && (\mathit{convection}) \\
& - V_{di}\frac{\partial f}{\partial x_i} && (\mathit{guiding-center\ drift}) \\
& + \frac{1}{3}\frac{\partial U_i}{\partial x_i}\left[\frac{\partial f}{\partial \ell np}\right] && (\mathit{energy\ change}) \\
& + Q(x_i, t, p) && (\mathit{source}) \qquad (1)
\end{aligned}
$$

The guiding-center drift velocity is given in terms of the local magnetic field $\mathbf{B}$ and the particle charge q and for weak scattering by $\mathbf{V}_d = (pcw/3q)\nabla\times(\mathbf{B}/B^2)$. This transport equation is remarkably general, and is a good approximation if there is enough scattering by the magnetic irregularities to keep the distribution nearly isotropic. It also requires that the particles have random speeds substantially larger than the fluid convection speed. The velocity need not be a continuous function of position and shocks can be included.

3.2 The Model

We must first specify the magnetic field. The large-scale structure of the magnetic field in the heliosphere, at least in the several years around sunspot minimum, is now well known. The field is generally organized into two hemispheres separated by a thin current sheet across which the field reverses direction. In each hemisphere the field is generally assumed to be a classical Parker Archimedean spiral, with the sense of the field being outward in one hemisphere and inward in the other. At solar sunspot minimum, the current sheet is nearly equatorial. The field direction alternates with each 11-year sunspot cycle, so that during the 1995 sunspot minimum, the northern field was directed outward from the sun, but in 1985 the northern field pointed inward. Observations indicate that the inclination of the current sheet increases as a function of time away from sunspot minimum. The structure for the years near sunspot maximum is not simple. It will be generally assumed here that the overall magnetic structure is given by this model.

The structure beyond the solar-wind termination shock is uncertain. Here we simply assume, in each case, 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 the cosmic-ray distribution function takes on the specified "interstellar" value. The magnetic field is readily determined in this flow pattern.

We consider protons and use parameter sets which we have used in the past and which are physically reasonable. . The values of the diffusion coefficients used here are those used in previous calculations (see, e.g., Jokipii et al, 1993). We take

$$\begin{aligned} \kappa_{\parallel} &= \kappa_0 P^{1/2}\beta\frac{B_E}{B} \\ \kappa_{\perp} &= \eta\kappa_{\parallel} \end{aligned} \quad (2)$$

where B is the magnetic field, B_E is its value at 1 A.U.,η is usually set equal to .01 − .05 and, if the rigidity P is expressed in GV, $\kappa_0 \approx 1.5 \times 10^{22} cm^2 sec^{-1}$. These are typical values used in our previous calculations. The numerical model used is time-dependent in two spatial dimensions, radius and polar angle. Hence the current sheet is flat. A propagating disturbance is then introduced.

4 Effects of the Heliosheath

4.1 Steady State

The effects of the termination shock in a steady state were reported by Jokipii, et al, (1993) we summarize the results briefly here. The computed variations of intensity with heliocentric radius are quite complex. They found that at low energies, the shock acts to depress the counting rate at the shock and thus cause a larger radial gradient beyond the shock. However, the reverse occurs at higher energies. Hence, application to the observations of Webber and Lockwood (1987), which are *integral* gradients above 60 MeV depends on the relative contribution of low and high energy particles. Jokipii et al (1993) therefore concluded that without much more accurate modeling it was possible only to conclude that effect of the heliosheath on the integral flux could be equivalent to the region of enhanced modulation suggested by Webber and Lockwood (1987). It was further suggested that the effects explained by invoking a modulation barrier at large radii might be naturally explained in terms of the effects of modulation beyond the termination shock.

4.2 Propagating Disturbances

McDonald, et al (2000) reported an analysis of the recovery of both ACR and GCR from a Forbush decrease caused by the passage of a disturbance (GMIR) at some 46 AU in the distant heliosphere, as observed by the Voyager I spacecraft. The particles studied were 150-380 MeV/nucleon He+ for GCR and 9-18 Mev/nucleon O^+ and 30-56 Mev/nucleon He^+ for ACR. See figure 1 for a diagram of such a propagating disturbance initially inside of the termination shock in the top panel, and subsequently in the heliosheath in the lower panel. The disturbance was a propagating extended region of disturbed solar wind with a large magnetic field and, presumably it impeded cosmic-ray transport. As it passed the point of observation, it caused a sudden simultaneous decrease in the counting rates of both ACR and GCR, followed by a slow recovery as it propagated further out to larger heliocentric distances. The data analysis was complicated by the fact that the disturbance and recovery were superposed on the large-scale solar-cycle related recovery of the counting rates.

In simplest terms, McDonald et al (2000) concluded that the GCR recovery after the initial decrease took considerably longer than the recovery of the ACR. They interpreted this as due to the fact that, once the disturbance which caused the decrease passed the termination shock, it could no longer could impede the access of ACR to the point of observation. Once the disturbance was past the termination shock, the ACR accelerated there would begin to populate the region behind it relatively unimpeded. Conversely, the GCR would not yet have fully recovered since they are required to come from the heliopause, which is far out beyond the termination shock, and would still be impeded by the disturbance.

4.3 Modeling a Propagating Disturbance

We have carried out a full two-dimensional simulation using our two-dimensional modulation code modified to include a region of small diffusion coefficient having a given radial extent, which moves with the solar wind. Thus our originally time-independent code was made time-dependent, which considerably increased its running time. Hence only a few sample simulations are available. We present the results for 120 Mev protons for both ACR and GCR to represent the behavior of typical ACR and GCR. The parameters used in these runs, in addition to the transport parameters defined above, we took the propagating disturbance to be a region of decreased diffusion coefficient, moving with the solar wind, which was a Gaussian in shape with a minimum κ of .1 of the non disturbance value and which had a half width of 3 AU in radius and extending essentially over all latitudes. The simulation proceeded by computing the steady state and then introducing the propagating disturbance which was followed until it passed the outer boundary of the heliosheath. The simulated intensities as a function of time, for ACR and GCR, at three different points in the heliosphere, for the current solar magnetic phase (A positive,

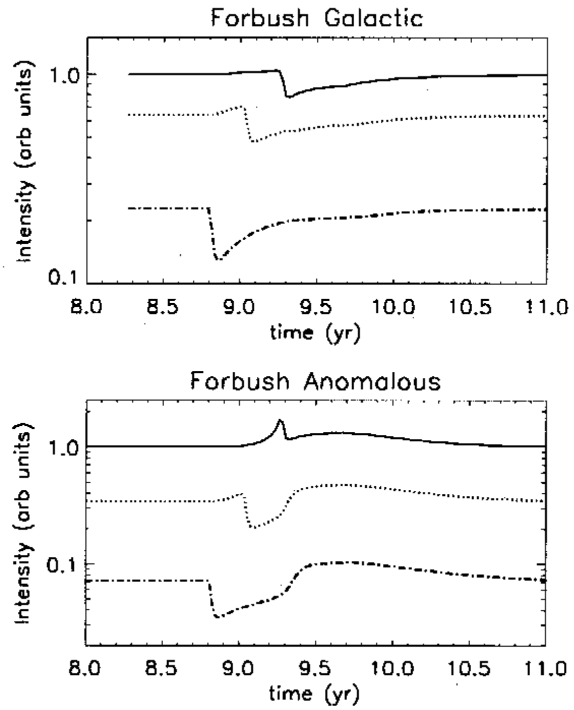

Fig. 2. Results of time-dependent simulations of the effects of a propagating disturbance on the intensity of GCR (top panel) and ACR (bottom panel). In each panel are plotted the intensity as a function of time at three locations in the heliosphere, all near the equator. The bottom curve in each is the intensity at the innermost point, 50 AU and is the lowest because of the radial gradient. The second and third curves in each case represent the intensity at 70 AU and at the shock, which is at 90 AU.

northern magnetic field directed outward) are shown in Figure 2. There is a small snowplow effect as the disturbance approaches the point of observation. It is also apparent that the major conclusion of McDonald, et al (2000), that the ACR recover more quickly than the GCR is born out. Also, comparison with Figure 4 of McDonald, et al, suggests that the time scales for recovery are about right.

However, the simulations show another significant structure in the time dependence which was not discussed by McDonald, et al (2000). Most apparent in all three curves is a moderate *increase* in the intensity *after* the recovery, which lasts for approximately as long as the recovery of the GCR. This effect was not expected but, in retrospect, should have been. As a region of impeded cosmic-ray transport approaches the shock and then engulfs it, the rate of acceleration of the ACR increases directly in proportion to the decrease in the diffusion coefficient (the acceleration rate is proportional to $1/\kappa_{rr}$). This increased acceleration rate of the ACR increases their intensity. This is also probably the cause of the spike seen in the point of observation at the shock (top curve in the ACR plot). This increased intensity then begins to decay after the disturbance passes beyond the termination shock and the ACR acceleration rate returns to normal. This decay would be expected to occur on the same scale as the recovery of the GCR. If this interpretation of the simulation results is correct, it should be very robust and not sensitive to the parameters.

The post-recovery increase in the ACR counting rate is not obvious in the data, but it could be masked by the overall solar-cycle-related recovery of the background ACR intensity. We conclude that the model simulations are in satisfactory agreement with observations. It would be interesting to see if the predicted post-recovery enhancement can be unambiguously established in the data.

We have carried out similar calculations for the opposite phase of the solar magnetic cycle (A negative, northern magnetic field directed inward), and the resulting time-intensity plots are similar. Modeling with drifts turned off also show qualitatively similar effects. This implies that the effects do not depend directly on the gradient and curvature driftsThese results support the robustness of the post-recovery increase of the ACR.

5 Conclusions

We have discussed time-dependent, two-dimensional simulations of the effects of a propagating disturbance on the intensity of both galactic and anomalous cosmic rays, including the effects of the region beyond the termination shock. Our results are broadly consistent with the observations of McDonald et al (2000) and support their suggestion that the propagation of the disturbance beyond the termination shock is the explanation for the different recovery of the anomalous and galactic cosmic rays. In addition, a robust new consequence of this picture was discovered. the intensity of the ACR should show a post-decrease intensity enhancement, above the original level, caused by the more rapid acceleration as the disturbance propagates past the termination shock. This consequence is not obviously present in the data, but could be masked by other variations. Future investigations should lood for this effect. Its absence would cast some doubt on the model.

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