Anomalous Cosmic Rays at a Termination-Shock Crossing

J. R. Jokipii,[1] and J. Giacalone [1]
(1) Dept. of Planetary Sciences, Univ. of Arizona, Tucson, AZ 85721, USA

Abstract

We consider the response of anomalous cosmic rays to transient radial incursions of the solar-wind termination shock. We find that the anomalous-cosmic-ray spectrum and anisotropy has a temporal variation which depends on the time and spatial scale of the radial incursion, its speed, and the energetic-particle transport coefficients. For reasonable parameters, the energy spectrum of the very-low-energy particles shows the largest effect, and the spectrum of the higher-energy particles the least. For an observer enveloped by an inward incursion of finite lateral extent, we find, depending on the extent of the incursion, that the energy spectrum of high-energy particles, including the turnover caused by upstream modulation, can remain much the same as before. Simultaneously, however, the energy spectrum at the lowest energies is the characteristic downstream, post-shock spectrum with no turnover at low energies.

1. Introduction

One of the most important goals of heliospheric exploration has been to observe the heliospheric termination shock, where the supersonic solar wind undergoes a sudden transition to subsonic flow, in response to the local interstellar medium. Anomalous cosmic rays (hereinafter ACRs) are freshly-ionized interstellar neutrals [3] accelerated at the termination shock by the mechanism of diffusive shock acceleration [4,7]. ACRs have long been regarded as an early-warning indicator of the termination shock.

It has been noted that the termination shock is expected to be turbulent and the location of the termination shock is expected to vary with time over a variety of time scales [1,8,9]. As emphasized by Suess [8], the variations of the termination shock radius will likely involve non-spherical, irregular incursions which have a variety of spatial scales in directions along the surface of the shock, as illustrated schematically in figure 1 (left). It is likely that the first encounter of a spacecraft with the termination shock will be at such an incursion, because it can move much faster than the spacecraft.

Clearly, the ACR spectrum will fluctuate in time at any given location as the termination shock moves in and out. Here we discuss the nature of the tem-

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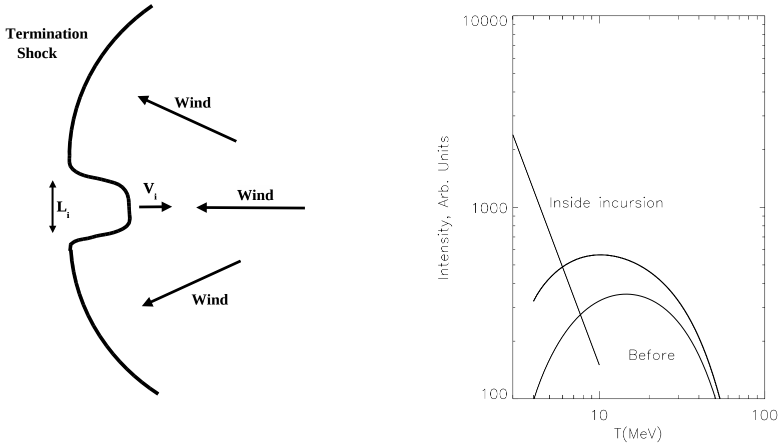

Fig. 1. *Left*: Cartoon drawing of a spatially limited incursion which is moving inward at a speed V_i through the wind. *Right*: Schematic illustration of the spectra observed before (lower) and after (top two) the shock incursion.

poral variations in ACRs which might be observed at a spacecraft as an inward-moving incursion crosses it.

2. Diffusive Shock Acceleration of Anomalous Cosmic Rays

The Parker transport equation [6] for the phase-space density $f(\mathbf{r}, p)$ as a function of position $\mathbf{r}$ and momentum magnitude p, may be written in terms of the diffusion tensor κij, the fluid flow velocity $\mathbf{U}$ and any source Q as:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] - U_i\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial \ell n(p)} + Q. \tag{1}$$

We solve this for a model system which includes a shock or a discontinuity in the fluid velocity $\mathbf{U}$. Note that, in this form, the drift velocity $\mathbf{V_d}$ is incorporated in the antisymmetric part of κ_{ij}. In general, the diffusion coefficient increases with increasing momentum as some power of the momentum.

Of interest here is the variation of the ACR spectrum as the observer moves from upstream of the shock to downstream. The behavior expected in a static picture is as follows: upstream, the turnover of the spectrum as one goes from high to lower energies caused by the transport of the lower-energy particles being slower. They cannot as easily diffuse or drift upstream, so their intensity must be lower than at higher energies. As one approaches the shock, this turnover moves to lower and lower energies and vanishes at the shock. The radial gradient may become quite steep at low energies. This behavior, combined with observations, has been used to estimate the distance to the termination shock [2]. Clearly if the shock moves inward to cross the observer, this behavior will be changed.

3. Effects of a Termination-Shock Incursion on the Spectrum

Clearly, if the shock moves slowly, on a large scale comparable to the heliospheric scale, we have essentially an inward spherical motion. This results in the relatively simple situation where the standard, static, spectra are not much changed, with the associated radial changes in the spectrum simply moving inward with the shock.

However, if the shock is turbulent, the incursion likely has a finite lateral extent and the energy spectra change in a more interesting manner. Consider the situation sketched in figure 1(left), where the incursion has a scale Δ_i and it moves radially inward at a speed V_i. We expect that the changes of the spectrum at high and low energies are different. In this case, the finite extent of the shock in the lateral direction restricts the maximum energy of the particles which can be accelerated by the shock to a smaller value than for a spherical shock. The accelerated particles simply escape over the sides of the shock before they gain more energy. This has been discussed by Jokipii [5] for the case of a quasi-perpendicular shock where drifts cause particles to drift off of the shock.

Suppose the incursion is at a distance of some 90 AU, with a transverse scale $\Delta_i = 10$ AU. A characteristic acceleration energy for a particle having charge q accelerated at an incursion moving inward at about 100 km/sec in a 400 km/sec wind can be obtained from the expression

$$\tau_c = q\frac{(V_w + U_i)}{c} B_\phi \Delta_i \approx 30MeV \tag{2}$$

This is $\approx$ 2 Mev/nuc for oxygen, to be compared with the $\approx 15MeV$ Mev/nuc characteristic energy for the steady termination shock. The resulting spectra are illustrated in figure 1(right).

We conclude that an observer at point which is enveloped by the incursion as it moves upstream, will observe two distinct spectal regimes. First, there will be new low-energy particles which have been accelerated by the shock incursion as it moved upstream. These will exhibit no low-energy turnover, and will extend to a characteristic maximum energy determined by equation (2), which would be lower than the maximum prior to the shock motion. In contrast, the higher energy particles will not have been accelerated, so the ones previously upstream will remain, retaining the original turnover.

4. Spatial Gradients and Anisotropies

The spatial gradient in the region downstream of the shock is also changed by the motion of the shock past the observer. In particular, at low energies, the gradient should be quite small. The associated pitch-angle anisotropy is simply the Compton-Getting anisotropy corresponding to the (slow) downstream flow of the solar wind.

5. Discussion and Conclusions

The simple model of a radial incursion of the heliospheric termination shock proposed here has significant consequences for observations of anomalous cosmic rays. If the inward incursion has a scale significantly smaller than the heliosphere, it cannot accelerate high-energy ACR. Observations from a spacecraft which has been engulfed by the inward incursion are predicted from the model calculations to be: A) There will be a power-law energy spectrum of the lowest-energy ACR right down to the injection energy, as these particles can be quickly accelerated by the shock as it moves past. This is the classic downstream spectrum. B) The ACR energy spectrum at high energies, including the turnover caused by upstream propagation from the initial position of the shock (modulation) will be little changed and will still be present. C) The transition from the low-energy power-law spectrum to the high-energy spectrum should exhibit a cutoff of the low energies at the highest energy which can be locally accelerated during the shock movement. D) The downstream anisotropy should exhibit the standard Compton-Getting anisotropy corresponding to the convection in the post-shock flow except for occasional bursts. E) There may occur intensity bursts in the low-energy, locally accelerated particles if regions of enhanced scattering or magnetic field are encountered by the moving shock.

It is important to note that we can have simultaneously present a high-energy ACR energy spectrum which exhibits the characteristic turnover associated with upstream propagation or modulation *and* a low-energy spectrum at energies of the order of 1-10 MeV which shows the downstream characteristics of a power law energy spectrum with no turnover and a Compton-Getting anisotropy corresponding to the post-shock flow.

This work was supported, in part, by NASA under grants NAG5-6620, NAG5-7793 and by the NSF under grant ATM9616547. We acknowledge helpful discussions with R. Decker, T. Krimigis and F.B. McDonald. .

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