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Abstract.

A model of the anomalous component of the quiet-time cosmic ray flux is presented in which ex-interstellar neutral particles are accelerated continuously in the polar regions of the solar-wind termination shock, and then drift into the equatorial regions of the inner heliosphere. The observed solar-cycle variations, radial gradient, and apparent latitude gradient of the anomalous component are a natural consequence of this model.

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1. Introduction

The anomalous component in quiet-time cosmic rays has been the subject of considerable discussion and speculation. As summarized recently by Gloeckler (1979), beginning in 1972 as the polarity of the solar magnetic field was changing, anomalies appeared in <70 MeV/nucleon cosmic rays. In this anomalous component He, N, O, Ne and possibly Fe are enhanced relative to other "galactic" cosmic rays. Observations show that this component is not of solar origin and appears to originate more than 20 AU. from the sun and above 10^{0} in heliographic latitude (McKibben, et al. 1979, Webber 1980).

There was no evidence for anomalous He above 20 MeV/nucleon during 1965 (Gloeckler and Jokipii 1967). In 1971, just before the solar dipole field changed sign, it was not seen on the IMP-5 spacecraft, which detected it later in 1972 (M. Garcia-Munoz, private communication). This suggests that the intensity of the anomalous component was quite low during the 1965 solar minimum, arguing for a 22-year solar magnetic cycle dependence. There is evidence that the anomalous component again disappeared in 1979 at 1 AU., when the magnetic polarity changed (Hovestadt et al. 1979), lending further support to this picture. McKibben et al. (1979) used the above facts and the large latitudinal gradient they observed to infer a dependence of the anomalous component on the sign of the sun's dipole magnetic field.

Previous attempts at modelling the anomalous component have been published by Fisk, Koslovsky and Ramaty (1974), Fisk (1976 a,b) and Klecker (1977). These models have attractive features, but they do not include particle drifts nor do they predict the temporal history.

It has recently been realized that gradient and curvature drifts in the interplanetary magnetic field can have a profound effect on cosmic ray modulation, and give rise naturally to 22-year solar-cycle-dependent effects (eg. Levy 1976, Jokipii et al. 1977, Jokipii and Kopriva 1979, Jokipii and Thomas 1981, Jokipii and Davila 1981).

In this paper we combine drifts with inferences from models of particle acceleration by shock waves, to suggest a model for the anomalous component in which it is accelerated continuously in the polar regions of the solar wind termination shock.

2. Drift Considerations

The effects of particle drifts on cosmic rays depend on the large-scale structure of the interplanetary magnetic field. For a period of several years around the last solar minimum, the heliospheric magnetic field was well approximated by oppositely directed Parker Archimedean spiral fields above and below an approximately equatorial current sheet (Smith, Tsurutani and Rosenberg 1979). During the 1975 solar minimum the northern field was directed outward and the southern field was directed inward toward the sun. In successive 11-year sunspot cycles the fields reverse sign.

The particle drifts in such a field were computed by Jokipii, Levy and Hubbard (1977), and typical drift streamlines are shown in Figure 1. During the period around the 1975 solar minimum <u>all</u> drift streamlines which reach the solar equatorial plane originated in a small region of latitude near the poles. In the preceding sunspot cycle, the magnetic field was such that positive particles entered at the equator.

Including a large enough diffusion coefficient will make the drifts less important. However, numerical calculations based on the full transport equation, have been reported by Jokipii and Kopriva (1979), and Jokipii and Davila (1981). They show that even for substantial values of the diffusion coefficients, the origin of the particles is as discussed above. These calculations show more than a factor of ten change in the number of particles originating at the poles during alternate solar cycles.

Although a definite assessment of the drift effects awaits observations at high heliographic latitudes, we suggest that positively charged particles observed near the ecliptic during the 1975 solar minimum would have come in preferentially from the heliographic polar regions. During the previous solar cycle they came in preferentially from the equatorial regions.

If these considerations are applied to the anomalous component, its strong correlation with the sign of the solar dipolar magnetic field could be natually explained even with a time independent source, if the source were substantially stronger at the heliographic poles than at the heliographic equator.

Such a model predicts a specific shape for the radial intensity gradient in the solar equatorial plane. Calculations show that the gradient would be positive in the inner solar system (as observed) and changes smoothly at some 15 to 30 AU to a negative gradient. The radius where the negative gradient appears depends on the parameters and may be adjusted over a wide range.

3. Acceleration of Ions at the Solar Wind Termination Shock

Jokipii (1968) first suggested that the solar wind termination shock (SWTS) could accelerate cosmic rays. Spacecraft observations have shown that solar-flare-induced magnetosonic fast mode shock waves propagating through the interplanetary medium accelerate ions to energies >45 MeV/nucleon (Bryant et al. 1962, Rao et al. 1967, Sarris et al. 1976) and on occasion to energies >1 GeV/nucleon (Pomerantz and Duggal 1974). In terms of mach number, compression ratio and size, the SWTS resembles the strongest flare-induced shocks more than either corotating interplanetary shocks or the Earth's bow shock.

Nonthermal charged particles can be accelerated in fast-mode shock waves by two distinct processes: the shock drift acceleration mechanism (also called the $\underset{\sim}{V}\times\underset{\sim}{B}$ mechanism) (Chen and Armstrong 1975, Armstrong et al. 1977, Pesses 1979a,b,c,1981a,b) and the compression mechanism (Jokipii 1966, Fisk 1971, Krymsky 1977, Axford et al. 1977, Bell 1978, Blandford and Ostriker 1978, 1980, Eichler 1979, 1981a,b, Fisk and Lee 1980, Pesses 1981a, b). In the presence of strong pitch angle scattering the distinction between these mechanisms can become blurred.

If the source of the anomalous component is injected into the termination shock at approximately solar wind energies $\sim$1 KeV/nucleon, then according to all shock models many (at least five) shock encounters are required to accelerate the ions. The minimum speeds for a downstream particle to overtake a shock, or for an upstream particle to be directly reflected by the shock, decrease as Ψ_1, the acute angle between the SWTS normal vector and upstream $\underset{\sim}{B}$, decreases (Pesses 1979b, 1981a, Eichler 1981a,b). We take the lower of these speeds to be the injection threshold.

Observations of the terrestrial bow shock (Greenstadt and Fredericks 1979) show that the amplitude of downstream variations in $\underset{\sim}{B}$ increases steadily with decreasing values of Ψ_1 in agreement with the above conjecture.

The combination of the decrease in minimum particle velocity for overtaking the shock or for being reflected by it, and the increase in downstream backscattering probability with decreasing values of Ψ_1, makes quasi-parallel shock geometries much more effective than quasi-perpendicular geometries in picking up low energy particles (Eichler 1981a,b, Pesses 1981 b).

Pioneer 11 observations (Pesses et al. 1979, 1981 a) show that the magnetosonic fast-mode shock waves bounding solar wind corotating interaction regions (Smith and Wolfe 1977) accelerate protons to $\sim$1 MeV energies most efficiently when Ψ_1 oscillates between $\sim 30^{\circ}$ and $\sim 90^{\circ}$ with a period of $\sim$20 minutes. When Ψ_1 remains at 90° for a prolonged period only small intensity enhancements are observed. Pesses et al. (1981) interpret this as a two-step acceleration process where solar wind protons are accelerated when Ψ_1 is small to superthermal energies and then the superthermal protons are accelerated to $\sim$1 MeV when $\Psi_1 \sim 90^\circ$. This is consistent with the injection efficiency for ions of solar wind energy being a maximum at small Ψ_1 as argued above.

The solar wind is expected to undergo a shock transition to subsonic flow at $\sim$50 AU. from the sun (Axford 1972). The solar wind termination shock should be a reverse, magnetosonic fast-mode shock with a compression ratio $\sim$4 (Brandt 1970, Axford et al. 1972). The Ψ_1 angle for the termination shock will have the same value as the "garden hose" angle between the interplanetary magnetic field vector and the radius vector from the sun. Assuming that Parker's (1963) model is valid at $\sim$50 AU. we have

$$\tan \Psi_1 = (2\pi/(V_w P)) \cos(\theta) \quad (1)$$

where θ is the heliographic latitude , r is the heliocentric radial distance, P is the solar rotation period and V_w is the solar wind bulk speed in the sun's rest frame. Howard and Harvey (1970) find that

$$P = 26.0\ (1-0.125 \sin^2(\theta) - 0.168 \sin^4(\theta))^{-1} \text{ days} \quad (2)$$

Equation (2) gives P = 26.0 days at the heliographic equator and P = 36.7 days at the geographic poles.

Interplanetary scintillations (Kakinoma 1977, and references therein) have shown that V_w increases about 100 kms^{-1} per 30° of heliographic latitude. For simplicity we assume that

$$V_w = 400 + 3.33\theta \text{ km/sec} \quad (3)$$

where θ is in degrees. Combining equations (1), (2) and (3) shows that the termination shock is nearly perpendicular (Ψ_1 = 80) outside of 15° of the poles and is quasi-parallel (Ψ_1 <45^o) only within 3^o of the poles. Note that the value of Ψ_1 should fluctuate over many time scales as does the "garden hose" angle at 1 A. U.

The above arguments imply that the polar regions of the termination shock will be more efficient than other regions for accelerating solar wind particles to higher energies.

Fisk, Koslovsky and Ramaty (1974) have noted that the composition of the anomalous component, dominated by high first-ionization-potential elements, suggests that its source is interstellar neutral atoms which are singly ionized in the heliosphere. Note that the rate of production of these singly-ionized particles, per unit increment in heliocentric radius, is approximately independent of radius.

Such atoms that are ionized inside the heliosphere will have a speed in the solar wind rest frame equal to the bulk speed of the solar wind (400-700 kms $^{-1}$), as compared to ion thermal speeds ~30-60 kms^{-1}. Thus, interstellar neutral particles meet the shock injection criterion far more readily than the other solar wind ions. It is readily shown that for a nominal Parker spiral angle at 50 AU., the shock threshhold is satisfied within 4^o of the pole for ex-interstellar neutrals and only 1.5^o for solar-wind ions.

Particles of these energies will have average inward radial drift velocities ~ 10^8 cm/sec 5^o from the pole, and will be able to bounce back and forth many times before drifting away. Also the expected strong turbulence near the shock would impede drift to enable acceleration.

Particles, in drifting from the polar regions of the termination shock to the solar equatorial plane, lose ~240 MeV/charge (Jokipii and Kopriva 1979 , Jokipii and Davila 1981). The energy per nucleon a particle must attain at the termination shock (T_s) in order to be observed in the solar equatorial plane with energy per nucleon T_o is then given approximately by

$$T_s = (240\ QA^{-1} + T_o)\ \mathrm{MeV/nucleon} \qquad (4)$$

where Q(A) is the particle net charge(mass). Equation (4) shows that the required energy gain is much less if Q = 1 than if the atom is fully stripped for elements other than hydrogen. For example, if T_o = 10 MeV/nucleon then T_s for $^4He^+$ is 70 MeV/nucleon whereas it is 130 MeV/nucleon for $^4He^{++}$. The difference is considerably greater for heavier nuclei.

It is clear from Equation (4) that particles with the largest mass to charge ratios (A/Q) require the smallest energy gain from the SWTS to be observed in the solar equatorial plane. Alternatively, the drift speed at any given energy per nucleon increases as A/Q increases, facilitating the particles' drift to the solar equatorial plane. Ex-interstellar neutrals, then, would be strongly enhanced in the anomalous component, both because they are picked up more readily by the acceleration mechanisms, due to their greater speed, and because they propagate most readily back into the inner heliosphere, due to their being only singly ionized.

4. Conclusions

We have shown that if acceleration occurs preferentially in the outer polar regions of the heliosphere, many observed features of the anomalous component can be explained in terms of drift effects on the transport of the particles. In particular, the strong decrease in intensity of the anomalous component in alternate solar cycles is expected, even if the source were time-independent, and the apparent positive gradient away from the solar equatorial plane is naturally explained.

Arguments and observations were presented which suggest that shock wave acceleration at low energies is most efficient for quasi-parallel shocks.

Hence, a model in which particles are accelerated at the SWTS, which on the average is quasi-parallel only near the heliospheric poles, possesses the desired features. Furthermore, we find that singly ionized ex-interstellar particles are favored for acceleration by the polar SWTS over more highly ionized ex-interstellar particle and chemical solar wind ions. These singly-ionized particles will also drift more rapidly in the spiral magnetic field.

Therefore, we suggest that a model of $\sim$ continuous acceleration by the quasi-parallel terminal solar-wind shock, near the heliospheric poles, with subsequent drift-related transport to the heliospheric equatorial regions, can explain most of the observed temporal and spatial behavior of the anomalous component. A future paper will consider the acceleration in more detail and explore possible energy spectra.

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Figure captions

1. The lines with arrows indicated the drift streamlines (neglecting the radial solar wind convection at 400 km/sec) in a meridional plane, of 70 MeV/Nuc He^+ in an Archimedean spiral magnetic field which has a nominal magnitude of 5×10^{-5}G at r = 1 AU. The heavy solid line denotes the wavy current sheet which separates the northern hemisphere, where the magnetic field is outward, from the southern hemisphere, where the field is inward toward the sun. The radius of the boundary is 25 AU. The configuration shown is for the period around the 1975 solar minimum. Alternate sunspot cycles will have fields with the opposite sign, and the sense of the arrows will be reversed.

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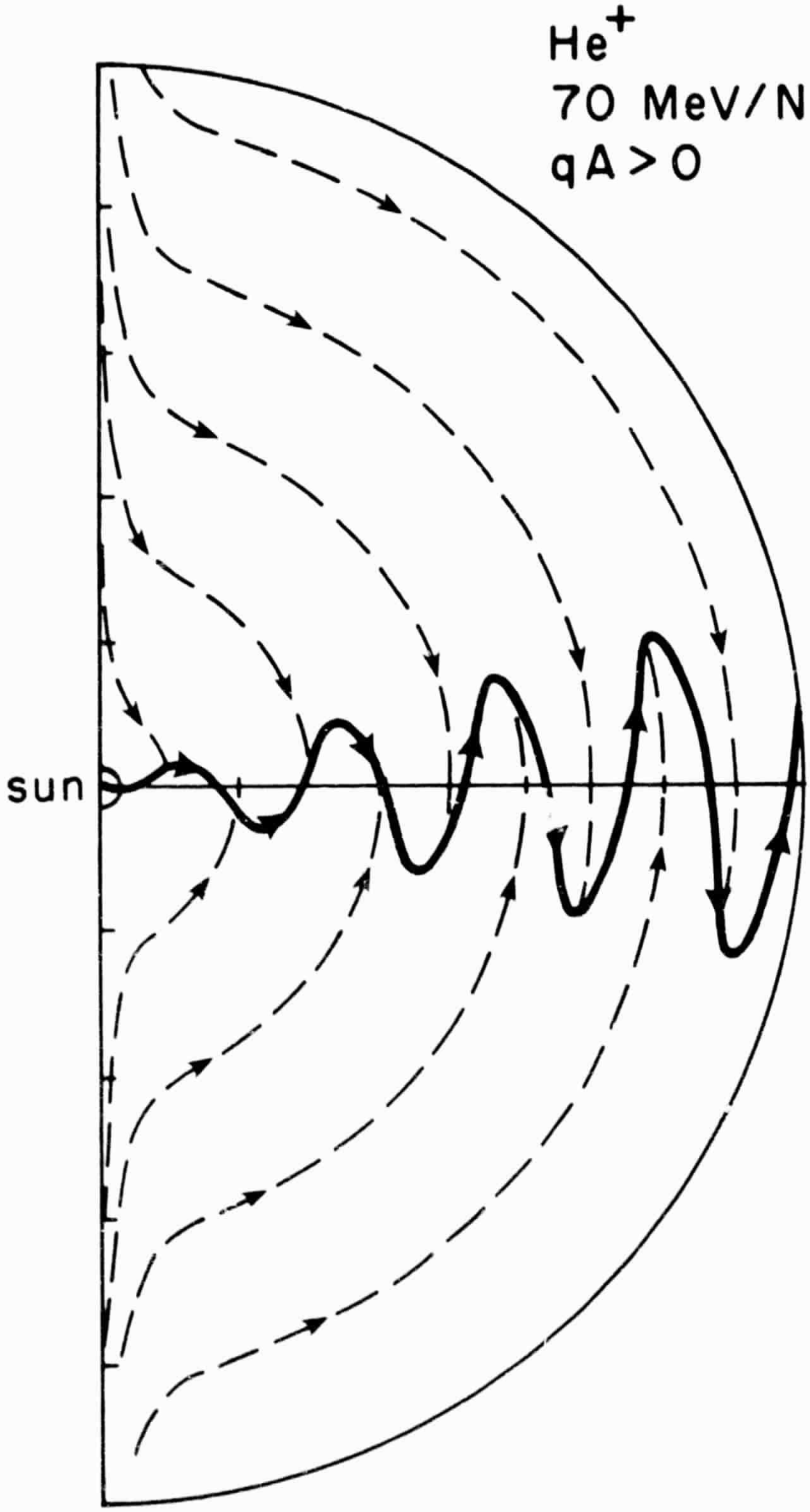

He^{+}
70 MeV/N
qA > 0
sun