ON THE ANOMALOUS COMPONENT

M. S. Potgieter, L. A. Fisk and M. A. Lee
Space Science Center, University of New Hampshire
Durham, NH 03824, USA

1. Introduction. The so-called anomalous cosmic ray component, which occurs at energies of about 10 MeV/nucleon and consists only of He, N, O, and Ne, has been a subject of interest for more than a decade. The origin of this component is generally considered to be interstellar neutral gas that is ionized and accelerated in the solar wind, as was proposed by Fisk et al. (1974). The mechanism and the location for the acceleration, however, remains an unsolved problem.

In this paper, we use a model which includes the effects of gradient and curvature drifts and consider the implications of observed spatial gradients of the anomalous component for the location of the acceleration region. We conclude that if drifts are important the acceleration region cannot lie at the solar poles. We also conclude that there is no single region for the acceleration which can account for both the observed intensities and gradients in models which include drift effects.

2. Results and Discussion. Pesses et al. (1981) proposed a mechanism for the acceleration of the anomalous component based on the acceleration of particles at the solar wind termination shock over the poles. They argue that once the particles are accelerated, gradient and curvature drifts will bring the particles downward from the heliospheric polar regions onto the equatorial plane. After a polarity reversal of the solar magnetic field, the oppositely directed drifts will restrict the passage of particles onto the equatorial plane. They therefore predict a dramatic change in the intensity of the anomalous component from cycle to cycle.

A complicating factor for drift models, however, is the small radial gradients these models predict for periods when the interplanetary magnetic field (IMF) is directed outwards in the northern heliosphere, as in 1970-80 (Potgieter, 1985). During this period the downward drifts of particles from the polar regions onto the equatorial plane tend to make the radial gradients in the equatorial plane small. The gradients also prove to be rather insensitive to changes in modulation parameters, for instance, the parallel diffusion coefficient. The question therefore arises whether a polar source for the anomalous component and strong drift effects can be compatible with the observed radial gradients of 10%-15%/AU for the anomalous component (Webber et al., 1981, 1985).

In this preliminary study we assumed a source spectrum for the anomalous oxygen which yields approximately the observed 1976-77 energy spectrum at Earth using a drift model for the modulation of cosmic rays (Potgieter and Moraal, 1985). To obtain a source which can be placed at various Θ-(polar angle) values at a radial distance of 50 AU, we used Gaussian spectra of the form

$$j_T^* = j_T \exp\{-0.028(\Theta - \Theta_o)^2\} \quad ,$$

with a half-width of 10° about Θ_o and j_T the assumed Θ-independent anomalous oxygen spectrum. We then solved the cosmic-ray transport equation,

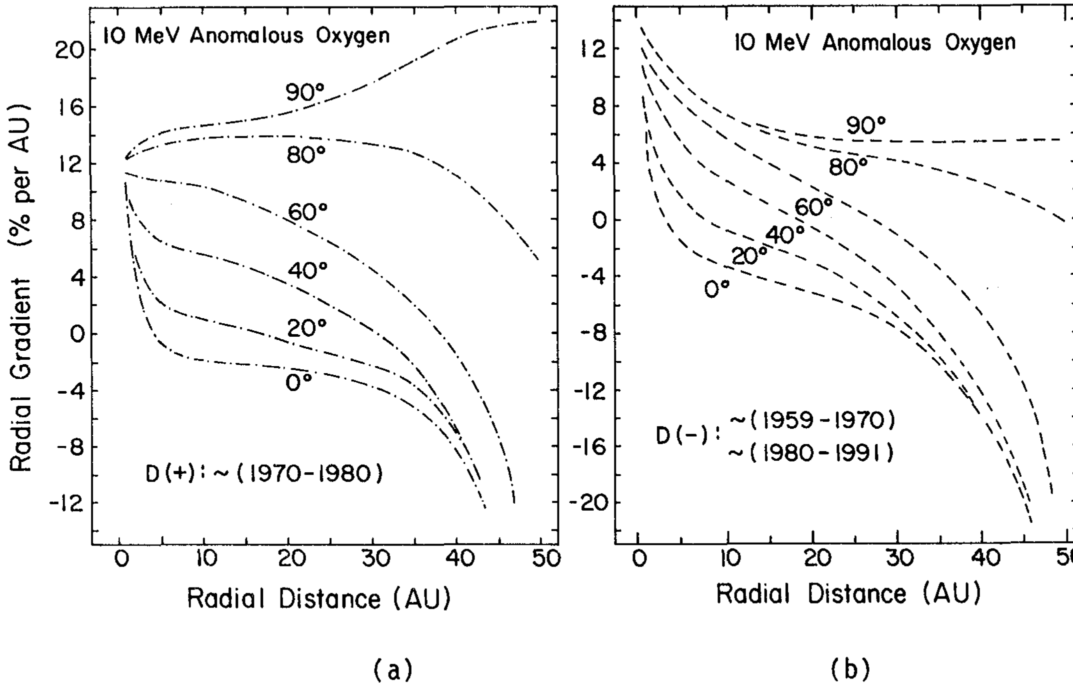

Fig. 1: Calculated radial gradients in the equatorial plane as a function of radial distance with a source at 50 AU and various polar angles; (a) for a D(+) cycle with drifts downward onto the equatorial plane at Θ = 90°, and (b) for a D(-) cycle that is with the polarity of the IMF reversed.

assuming a steady-state and azimuthal symmetry, shifted the source in 10° intervals from the pole to the equator at Θ=90°, and calculated the radial gradients in the equatorial plane for each location of the source. We repeated the calculations with the IMF polarity reversed, but otherwise unchanged modulation parameters. The diffusion coefficients used correspond to solar-minimum conditions (Potgieter and Moraal, 1985).

To distinguish between the two configurations of the IMF, we use the notation D(+) for ∿1970-80 and D(-) for the 11 years before and after this period. Starting with a D(+) period, that is with drifts directed downward onto the equatorial plane, we show in Fig. 1a the radial gradients in the equatorial plane for 10 MeV anomalous oxygen as a function of radial distance with the source at 50 AU and various polar angles. The striking feature of this figure is the dramatic decrease of the radial gradient with increasing radial distance, from ∿10%/AU at Earth to a negative gradient, with the source placed at 50 AU over the pole. With the source at the equatorial plane, the radial gradient steadily increases from 12%/AU at Earth to about 22%/AU at 50 AU. Fig. 1b shows the situation with the polarity of the IMF reversed, that is with drifts directed from the equatorial plane toward the polar regions. The radial gradients, with the source at the pole, again rapidly decrease with increasing radial distance. With the source at the equator, the radial gradients compared to Fig. 1a are smaller for most of the heliosphere out to 50 AU.

The results of Fig. 1 indicate the following. The radial gradients in the equatorial plane, with a source at the pole, are inconsistent with the observed radial gradients for the anomalous component, independent of the polarity of the solar magnetic field. By moving the source towards the equatorial regions, the calculated radial gradients become comparable to those observed. The calculated values, however, are significantly smaller, except in the inner heliosphere, for the present cycle as compared to the previous cycle, whereas the observed values seem to remain constant before and after the polarity change in 1980 (Webber et al., 1985).

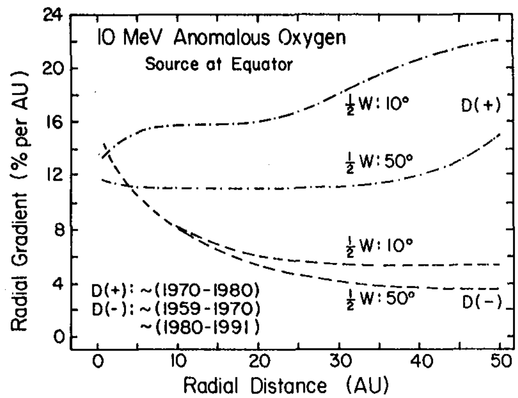

Fig. 2: The effect of increasing the half-width (W) of the source spectrum, from 10° to 50°, on the radial gradients in the equatorial plane with a source at the equator at 50 AU.

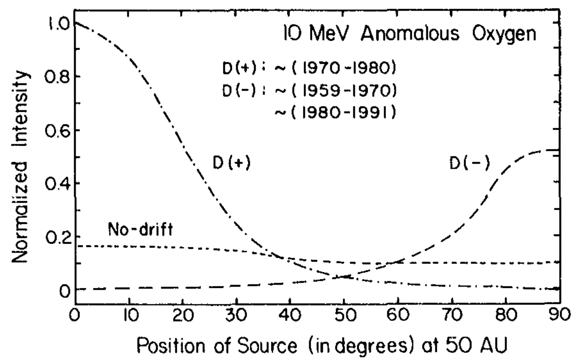

Fig. 3: The normalized intensity at Earth of 10 MeV anomalous oxygen as a function of various polar angle positions of the source at 50 AU for periods before and after a polarity reversal.

We also investigated the effect of increasing the half-width of the source spectra from 10°, in steps of 10°, to 50° to simulate an extended, less localized source. For both the D(+) and D(-) cycle of the magnetic field the radial gradients in the equatorial plane change insignificantly with the extended source over the polar regions. The effect of an extended source placed at the equator is shown in Fig. 2. For the D(+) period the radial gradients now seem compatible with those observed.

The intensity for the anomalous oxygen at Earth with a source at various latitudes should also be taken into consideration. The intensity of the 10 MeV anomalous oxygen at Earth, normalized to the intensity during a D(+) period with a source at the pole, is given in Fig. 3 as a function of the position of the source at 50 AU at various polar angles. For the D(+) period (downward drifts) the intensity at Earth decreases rapidly as the source is shifted from the pole to the equator. Comparing the intensity for the two periods, with the source at the pole, the D(-) intensity is substantially lower (a factor of 200) as was suggested by Pesses et al. (1981). For the D(-) cycle the intensity increases as the source is shifted toward the equator. It is interesting to compare this behavior, dependent on the polarity of the IMF, to the no-drift case shown in Fig. 3.

Our calculations show that, although the intensity of the anomalous oxygen, with a source at the pole, dramatically decreases after a change in the IMF polarity, the radial gradients in the equatorial plane are inconsistent to those observed. Furthermore, although the radial gradients for a D(-) cycle (the present cycle) with a source at 50 AU at the equator seem comparable to observations, the calculated intensity during this cycle exceeds the intensity during a D(+) cycle (the previous cycle), which is again contrary to what is observed.

3. Concluding Remarks. It should be noted that no attempt has been made in this preliminary study to include acceleration at the termination shock in a self-consistent manner. As has been pointed out recently by Jokipii (1985), drifts along the shock front and in the IMF can affect the spectrum and the spatial distribution of particles at the termination shock. When drifts are downward from the poles, they are poleward along the shock front. Both effects tend to limit the shock acceleration of particles that are injected near the poles. Conversely, when the drifts are towards the poles in the IMF, as they are in the current cycle, the drifts are downward from the poles along the shock front. These effects will increase the number of times particles interact with the shock, thereby increasing the energy they can gain, and will spread particles injected over the poles towards the equatorial region.

The complication of an accelerated spectrum which evolves with changing field polarity does not affect our conclusion that the injection and acceleration cannot occur primarily over the solar poles in models in which drift effects are important. During the last cycle, when drifts were downward from the poles, drifts along the termination shock front would concentrate the acceleration at the poles. However, as we demonstrated above, in this case the radial gradient seen in the equatorial plane is inconsistent with observations. An evolving spectrum at the termination shock could, however, affect the intensity seen at Earth.

In conclusion, we argued in this paper that the source for the acceleration of the anomalous component cannot lie at the solar poles in models that include gradient and curvature drifts. Such models will not yield the observed spatial gradients in the equatorial plane. We argued also that a source near the equatorial plane can yield the correct gradients, but in drift models will not yield the observed behavior in the intensity from cycle to cycle.

It would appear, therefore, that drift models may have significant difficulty in accounting for the observed features of the anomalous component.

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