Longitudinal Gradients in the Spectra of Anomalous CRs

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Abstract

We employ a steady-state transport model of the Anomalous component of Cosmic Rays to investigate further the longitudinal structure of their spatial as well as spectral distribution. The spectra are computed for kinetic energies ranging from 2 keV to the exponential cutoff at a few GeV for anomalous hydrogen, helium and oxygen.

1 Introduction

We have recently investigated the potential of detecting the variation of the spectra of anomalous cosmic rays (ACRs) with ecliptic longitude on the basis of forthcoming observations to be made with the two Voyager spacecraft (Fichtner and Sreenivasan 1999). Such longitudinal gradients, so far unobserved in the outer-heliospheric ACR distributions, should exist for several reasons.

First, the particle population from which ACRs originate, i.e. the pick-up ions (PUIs), have longitudinal flux variations asymmetric with respect to ecliptic longitude (see e.g. Mall et al. 1998, Chalov, Fahr and Izmodenov 1997). Second, the injection efficiency of PUIs in the process of diffusive shock acceleration at the heliospheric shock is probably a function of ecliptic longitude, also. This is because the local shock environment, characterized e.g. by the shock structure (precursor, foot, ramp; see le Roux, Fichtner and Zank (1999)) and the orientation of the heliospheric magnetic field (HMF) relative to the shock surface, probably changes from upwind to downwind within the ecliptic. Third, according to recent models of the global structure of the heliosphere (e.g. Linde et al. 1998, Pauls and Zank 1997, Ratkiewicz et al. 1998, Kausch 1998), the heliocentric distance to the heliospheric shock is systematically increasing from the upwind to the downwind direction. This contributes to the other two effects purely on geometrical grounds.

We improve here our earlier modelling of three-dimensional ACR phase space distributions (Fichtner, deBruijn and Sreenivasan 1996,1997, Fichtner and Sreenivasan 1999) by including the drift of particles in the HMF in the Parker equation. We then compare and discuss the results for anomalous hydrogen, helium and oxygen.

2 The Model

The basis for our model is the time-independent Parker equation

$$\nabla_{\vec r} \cdot \left(\overset{\leftrightarrow}{\kappa} \, \nabla_{\vec r} f \right) - (\vec v_{sw} + \vec v_{dr}) \cdot \nabla_{\vec r} f + \frac{1}{3} \left(\nabla_{\vec r} \cdot \vec v_{sw} \right) \frac{\partial f}{\partial ln p} = 0 \tag{1}$$

where, in standard notation, $f = f(\vec r, p)$ denotes the distribution function in the four-dimensional phase space defined by heliocentric position $\vec r$ and momentum p. The ACRs diffuse anisotropically in space according to the tensor $\overset{\leftrightarrow}{\kappa}(\vec r, p)$, convect with the solar wind velocity $\vec v_{sw}$ and drift in the HMF with the velocity $\vec v_{dr}$. The tensor of spatial diffusion $\overset{\leftrightarrow}{\kappa}(\vec r, p)$ is that used by Fichtner, Sreenivasan and Fahr (1996), but here without applying any averaging procedure.

At the inner boundary $r = r_\odot$ a vanishing gradient of f is assumed, i.e. $(\partial f/\partial r)_{r_\odot} = 0$, and for the outer boundary in upwind direction we assume shock spectra of ACRs resulting from the acceleration study performed by le Roux, Potgieter and Ptuskin (1996). To this end, we employ an analytical representation of the source spectra suggested by Steenberg (1998):

$$j_{source,upwind}(E_{kin}) = p^2 f(p) = j(1\,keV)\;\frac{x^{(1-q/2)}\;exp\,(-bx^a)}{x_0^{(1-q/2)}\;exp\,(-bx_0^a)} \tag{2}$$

with $x = E_{kin}/E_c$ and $x_0 = (1\,keV)/E_c$. The element-independent parameters $a(\gamma) = 0.689\gamma + 1.340$, $b(\gamma) = 0.083\gamma + 0.272$ and $q = 3s/(s-1)$ with s denoting the shock compression ratio (Steenberg 1998) are used with $\gamma = 1$ and $s = 3.4$, respectively. The element-dependent parameters are obtained from fits to the spectra computed by le Roux, Potgieter and Ptuskin (1996) and taken as $j(1\;keV, H) = 6.3\cdot 10^6 part./m^2/s/sr/(MeV)$, $j(1\;keV, He) = 3.0\cdot 10^6 part./m^2/s/sr/(MeV/nucleon)$, $j(1\;keV, O) = 3.0\cdot 10^5 part./m^2/s/sr/(MeV/nucleon)$, $E_{c,H} = 380\,MeV$, $E_{c,He} = 120\,MeV/nucleon$ and $E_{c,O} = 30\,MeV/nucleon$.

These source spectra $j_{source,upwind}(E_{kin})$ are multiplied by functions $V(\vartheta, \phi)$ depending on helio-latitude ϑ and -longitude ϕ:

$$j_{source}(E_{kin}) = j_{source,upwind}(E_{kin}) \cdot V(\vartheta, \phi) \tag{3}$$

The element-dependent functions V are taken as

$$\begin{aligned} V_H(\vartheta,\phi) &= (v_1 + v_2\,cos\,\vartheta) \times (0.6 + 0.20\,[1 + cos\,\phi]) \\ V_{He}(\vartheta,\phi) &= (v_1 + v_2\,cos\,\vartheta) \times (1.0 + 1.00\,[1 - cos\,\phi]) \\ V_O(\vartheta,\phi) &= (v_1 + v_2\,cos\,\vartheta) \times (1.0 + 0.15\,[1 - cos\,\phi]) \end{aligned} \tag{4}$$

with $v_1 = v_2 = 0.5$ for $A > 0$ and $v_1 = 1.0, v_2 = -0.5$ for $A < 0$, with $sign(A)$ indicating as usual the orientation of the HMF during solar activity minima. Assuming that during activity maxima the drifts are suppressed as a consequence of an irregular HMF structure, we consider the non-drift case together with $v_1 = 1$ and $v_2 = 0$ to approximate maximum conditions.

The latitudinal variations are assumed in accordance with the results of standard transport theory (see e.g. Jokipii and Giacalone 1998). The longitudinal variations correspond to the available, relatively crude estimates of variations in the fluxes (Rucinski, Fahr and Grzedzielski 1993) and injection efficiencies of PUIs (Chalov 1993, Chalov, Fahr and Izmodenov 1997). A downwind extension of the heliospheric shock is still neglected here.

As in Fichtner and Sreenivasan (1999), the Parker equation (1) was solved with a vectorizable adaptive grid solver for partial differential equations in three dimensions (Blom and Verwer 1996).

3 The longitudinal structure of the ACR distributions

As a test of our model, Figure 1 shows the spectra of anomalous H, He, and O for various heliocentric distances in the upwind (solid lines) and downwind (dashed lines) directions.

A comparison of the upwind spectra with the results obtained by le Roux, Potgieter and Ptuskin (1996) demonstrates good performance of the code. In constrast to ACR H, the flux levels of ACR He and O are higher in the downwind than in upwind direction. This reflects the well-known difference in the ionisation of the corresponding neutral species and the related PUI fluxes (see e.g. Rucinski, Fahr and Grzedzielski 1993), formulated here with boundary conditions given by the relations (4).

The variation of the H and O spectra with ecliptic longitude is shown in Figures 2 and 3 for the latitudes $|\pm\vartheta| = 30^o$ to which Voyager 1 and 2 are approaching.

The Figures give the distribution of ACR H at 31 MeV and O at 11.5 $MeV/nucleon$ for the no-drift case (activity maxima) and the two drift cases $A > 0$ and $A < 0$ (activity minima).

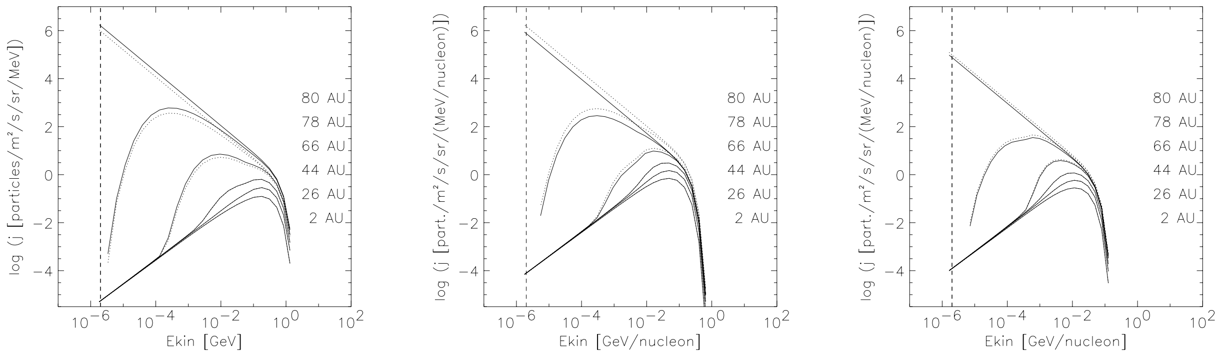

Figure 1: *The spectra of ACR H (left), He (middle) and O (right) in the upwind (solid line) and downwind (dashed line) directions for a solar activity minimum with* $A > 0$ *occuring around 1977/78 and 1996/97. The vertical dashed line indicates* $E_{kin} = 2\,keV$.

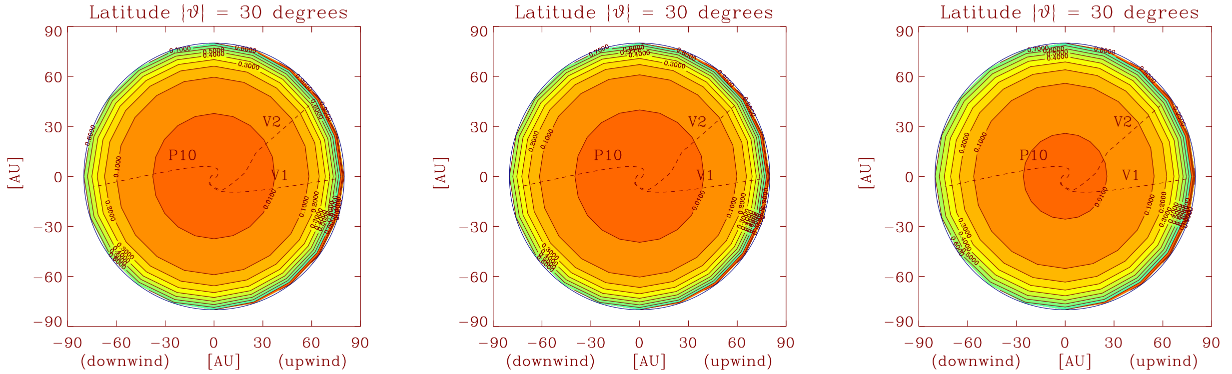

Figure 2: *The distribution of ACR H with a kinetic energy of* $31\ MeV$ *at heliographic latutides* $|\vartheta| = 30^o$ *for the no-drift case (left) and the two drift cases with* $A > 0$ *(middle) and* $A < 0$ *(right). The dashed lines are projections of the spacecraft trajectories onto this latitude.*

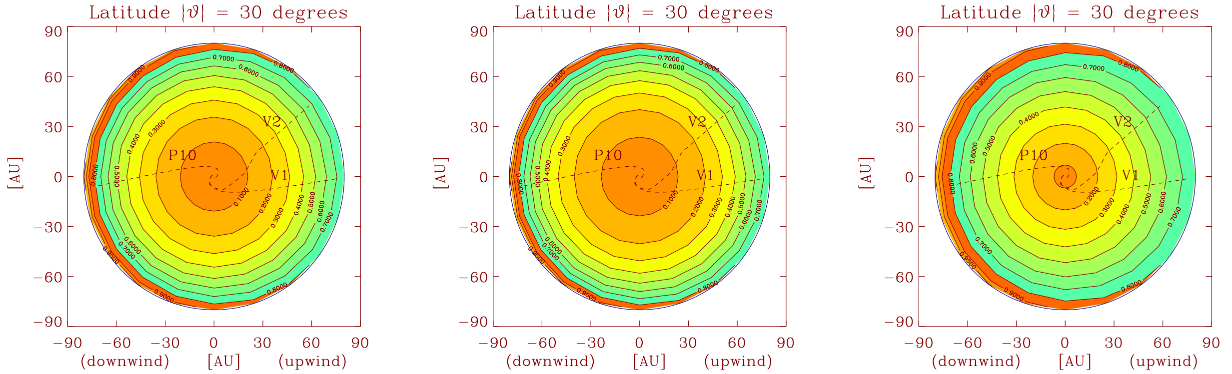

Figure 3: *Same as Figure 2, but for ACR O with a kinetic energy of* $11.5\ MeV/nucleon$.

For both species the difference between the no-drift case and the drift case $A > 0$ is almost neglible at the chosen latitudes of $|\vartheta| = 30^o$. However, there is a clear difference to the drift case $A < 0$: the radial gradient is somewhat smaller in the latter case. This result does not contradict observations at lower latitudes, where the radial gradient for $A > 0$ is smaller than that for $A < 0$ (e.g. Cummings et al. 1995), because this relation reverses towards higher latitudes (see e.g. Fig. 2 in Jokipii and Giacalone 1998). The solar activity minimum following the next maximum around 2001 is of type $A < 0$, and since the Voyagers will then be close to $|\vartheta| = 30^o$, this change in the ordering of the gradients might show up in the data.

The (non-local) longitudinal gradient of the distribution of ACR H at the chosen energy of $31\,MeV$ is about $5\%/37^o \approx 0.14\%/deg$ in the outer heliosphere (37^o is the longitudinal separation of the Voyagers). Thus, it is half the value found by Fichtner and Sreenivasan (1999) for ACR H with $11\,MeV$. This gradient is practically independent of the drift behaviour of the particles. Consequently, in contrast to the latitudinal and radial gradient, it is not a function of solar activity.

Considering the well-observed oxygen as an example for such ACR species having higher flux levels in the downwind heliosphere, we can address the question of whether the Voyagers would be able to detect (the reversed) longitudinal gradients for such species as well. From Figure 3 one can easily extract the expected answer: the separation of two spacecraft in ecliptic longitude is far too small to detect any longitudinal gradient for ACR species with a flux maximum in the downwind heliosphere.

4 Conclusions

We have confirmed our earlier findings about the existence and the order of magnitude of longitudinal gradients in the phase space distributions of ACRs. At a kinetic energy of $31\,MeV$, there is, in the outer heliosphere, a small longitudinal gradient of about $0.14\%/deg$ (counted positive towards the upwind direction) in the distribution of ACR H. This gradient increases somewhat towards lower energies. The gradients of all other main ACR species are opposite in sign, but far too small between the trajectories of the two Voyager spacecraft to be detectable. The inclusion of the drift motions have practically no influence on the longitudinal structure of the ACR distributions, i.e. the latter is, in contrast to the radial and latitudinal structure, independent of solar activity.

In view of the above it is clear that, as long as the spacecraft are only in the outer upwind heliosphere, only the observations of anomalous hydrogen might provide a potential diagnostic to extract information about the large-scale structure of the heliosphere.

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