THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 90:595–597, 1994 February

ON THE ASYMMETRY OF THE DISTRIBUTION OF THE ANOMALOUS COSMIC-RAY COMPONENT IN THE HELIOSPHERE

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Received 1993 February 2; accepted 1993 June 4

ABSTRACT

An analysis based on a fluid type equation for the spatial diffusion of the anomalous component of cosmic rays in the solar wind is presented. The source distributions of the high-energy particles are related to the pick-up ion flux intensities at the position of the heliospheric shock. Due to the strong asymmetric distributions of the different species of pick-up ions in the heliosphere and a possible aspherical termination shock of the solar wind, the source distributions are expected to exhibit element specific upwind-downwind asymmetries. An analytical treatment of the problem, using boundary conditions derived from observations by the *Pioneer* and *Voyager* satellites, leads to an estimate of the asymmetries of the anomalous component in the heliosphere. The investigation is performed in two stages: the problem is solved for an axially symmetric heliosphere in the first instance, and a latitudinal variation of the solar wind velocity as well as in the hydrodynamic diffusion coefficient is incorporated to model the effects of a heliospheric magnetic field in the second.

Subject headings: acceleration of particles — cosmic rays — shock waves — solar wind

1. INTRODUCTION

After thirty years of satellite-based observations of the heliosphere, the region around the Sun dominated by the solar wind plasma, there appear to be some fundamental questions still either unanswered or only partially answered. Amongst these are (1) the actual shape and structure of the heliospheric shock, i.e., the termination shock of the supersonic solar wind; (2) the geometry of the distant flow in the supersonic regime of the wind; and (3) the geometry and structure of the subsonic flow in the heliosheath, the region between the shock and the heliopause.

It appears that the answers to all of these questions involve the so-called anomalous component of cosmic rays (hereafter ACR), their acceleration at the heliospheric shock, and subsequent diffusion in the heliosphere. This is because the pressure in the heliosheath is possibly mainly controlled by the ACR and this pressure in turn influences also the dynamics of the solar wind in the outer heliosphere (Fahr, Fichtner, & Grzedzielski 1992) and the structure of the shock. A rigorous study of the latter phenomenon requires the construction of a self-consistent model that is capable of treating the back-reaction of the acceleration process of the ACR on the shock structure. Such a back-reaction could decrease the shock compression ratio from 4 to a lower value for which there appears to be evidence from different observations (e.g., Potgieter & Moraal 1987).

In view of the many consequences of the ACR, a particularly important information concerns their distribution within the heliosphere. As suggested elsewhere (Fahr & Fichtner 1991; Fahr et al. 1992; Grzedzielski, Fahr, & Fichtner 1991) a main characteristic of the ACR intensity or pressure distribution is most probably an overall upwind-downwind asymmetry resulting from the two basic properties of the heliosphere, namely: (1) that the heliospheric shock is not spherically symmetric but has a clearly developed upwind-downwind asymmetry which is dynamically enforced (Dessler 1967; Matsuda et al. 1989), and (2) the seed population of the ACR, the so-called pick-up ions, arising from ionization of the neutral particles from the local interstellar medium (hereafter LISM), which flow into the heliosphere also has a strongly pronounced upwind-downwind asymmetry (Moebius et al. 1988; Rucinski & Fahr 1989; Fahr 1990). Both these properties are directly caused by the motion of the Sun relative to the surrounding LISM, which is responsible for all the upwind-downwind asymmetries of the heliosphere (for a recent review see Fahr & Fichtner 1991). In this brief presentation, we address the problem of determination of the actual asymmetry of the ACR pressure distribution by first decoupling the two properties of the heliosphere mentioned earlier. We assume a spherically symmetric heliospheric shock to examine exclusively the influence of the specific asymmetry in the seed population. We derive a source-distribution for the ACR at the location of the heliospheric shock and investigate the spatial diffusion of these particles in the heliosphere. We return to the full coupled problem elsewhere.

2. THE MODEL

The analysis of the spatial diffusion of the ACR is based on a basic fluid-type transport equation for the energy density of cosmic rays (e.g., Parker 1965; Drury & Völk 1981; Zank 1989):

$$\nabla\left[\frac{\gamma_{acr}}{\gamma_{acr}-1}\,p_{acr}\boldsymbol{v}_{sw}-\kappa\nabla\left(\frac{p_{acr}}{\gamma_{acr}-1}\right)\right]=\boldsymbol{v}_{sw}\cdot\nabla p_{acr}\,, \qquad (1)$$

with p_{acr} being the pressure of the ACR to which we attribute a

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polytropic index $\frac{4}{3} < \gamma_{\rm acr} < \frac{5}{3}$. The second term on the left-hand side describes the diffusion of the ACR particles with a scalar diffusion coefficient within the expanding solar wind plasma with given velocity:

$$\boldsymbol{v}_{\rm sw} = \boldsymbol{v}_{\rm sw}(r, \theta) = \begin{cases} u_E \boldsymbol{e}_r & ; \quad \theta \geq \theta_c \\ u_E U(\theta) \boldsymbol{e}_r ; & \theta < \theta_c \end{cases}$$

$$\kappa = \kappa(r, \theta) = \begin{cases} \kappa_E\left(\frac{r}{r_E}\right) & ; \quad \theta \geq \theta_c \\ \kappa_E\left(\frac{r}{r_E}\right) K(\theta) ; & \theta < \theta_c , \end{cases} \qquad (2)$$

which means that we assume in generalization of Fahr et al. (1992), a region of constant velocity and diffusion coefficient between the heliomagnetic co-latitude $\theta = \pi$ and $\theta = \theta_c < \pi$, i.e., close to the plane of the heliomagnetic equator, but a latitudinal dependence for $\theta < \theta_c$. The quantities u_E and κ_E are the solar wind velocity and the diffusion coefficient, respectively, in the plane of the heliomagnetic equator at a distance of 1 AU, and $0 \leq U(\theta), K(\theta) \leq 1$ are dimensionless functions describing a latitudinal variation. The chosen r-dependence of the diffusion coefficient is in agreement with suggestions of several authors (see Jokipii 1971; Cummings, Mewaldt, & Stone 1987).

An analytical solution of equation (1) can be obtained with a separation *Ansatz*. We discuss two different scenarios. First, by neglecting the heliospheric magnetic field, one finds for an axisymmetric heliosphere [$U(\theta) = K(\theta) = 1$] the ACR pressure distribution:

$$p_{\rm acr}(r, \delta) = \sum_{\nu} (c_{\nu 1} r^{p_{\nu 1}} + c_{\nu 2} r^{p_{\nu 2}}) P_\nu(\cos \delta) , \qquad (3)$$

where the P_ν's are Legendre-Polynomials. The $c_{\nu i}$'s are determined by fitting the pick-up ion intensities at the location of the heliospheric shock which represents the source surface of the ACR particles (see below), and the $p_{\nu i}$'s are constants depending on κ_E and γ_c (see Fahr et al. 1992). The quantity δ denotes the angle between the direction of the Sun's motion (upwind direction) and the direction to a heliospheric point at a distance r from the Sun.

Second, for the general case of a three-dimensional heliosphere, magnetic field effects are incorporated with the choice $U(\theta) = K(\theta) = \cos \theta$, and the solution can be expressed in spherical coordinates as

$$p_{\rm acr}(r, \theta, \phi) = \sum_{\nu=0, \mu \leq \nu} (c_{\nu 1} r^{p_{\nu 1}} + c_{\nu 2} r^{p_{\nu 2}}) P_{\nu\mu}(\sin \theta) \cos(\mu\phi) \qquad (4)$$

$$P_{\nu\mu}(\sin \theta) = \begin{cases} P_\nu(\sin \theta) & ; \quad \mu = 0 \\ \sum_{l=0}^{\infty} k_l \cdot (\sin \theta)^{(2l+\eta)} ; & \mu \neq 0 . \end{cases} \qquad (5)$$

The constants $c_{\nu i}$ are the same as in the axisymmetric case, $\eta = \eta(\mu)$ and $k_l = k_l(l, \nu, \mu)$. The simple θ-dependence of $v_{\rm sw}$ and κ is a compromise between a correct description of the observed increase of both quantities with increasing magnetic latitude and the desire to maintain separability of variables in equation (1). Furthermore, this choice yields the same radial variation of the pressure distribution. Particle drifts are neglected. In equation (4), the presence of the magnetic field manifests itself through the functions $P_{\nu\mu}(\sin \theta)$, which describe the latitudinal variations of the pressure distribution which are different from the azimuthal (ϕ) ones.

To demonstrate the two principal element dependent shapes of the ACR pressure distribution and to determine the asymmetry explicitly for the elements H and He, we have to determine the constants $c_{\nu i}$. Assuming that the intensities of the ACR species at the heliospheric shock are proportional to the corresponding pick-up ion intensities (for them see, e.g., Rucinski & Fahr 1989) we can derive the required values (Rucinski, Fahr, & Grzedzielski 1993) and calculate the pressure distributions shown in Figure 1.

3. RESULTS AND DISCUSSION

The main differences in both the distributions (Fig. 1), besides the absolute intensity values (which are expected to be higher for hydrogen due to its higher cosmic abundance) are obvious: as a consequence of the reversed upwind-downwind asymmetries of the corresponding pick-up ion distributions of

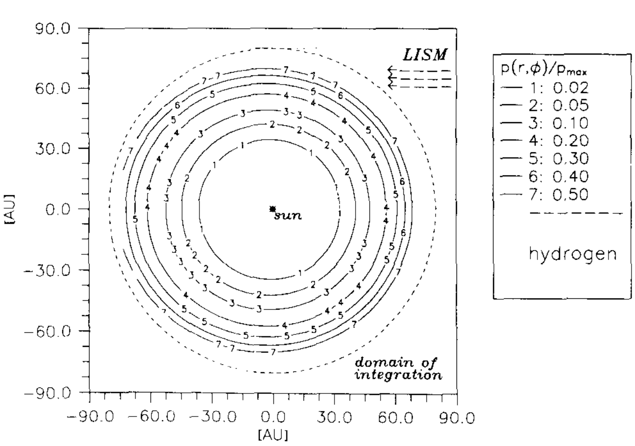

FIG. 1*a*

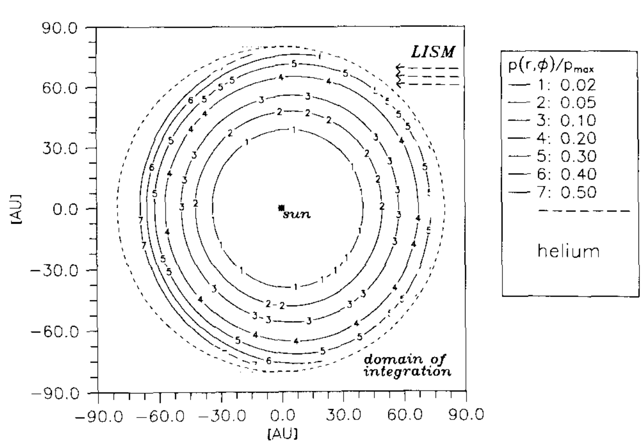

FIG. 1*b*

FIG. 1.—Normalized pressure distributions for (*a*) hydrogen and (*b*) helium in the plane $\theta = 0$. The upwind side is on the right as indicated by the arrows showing the flow direction of the LISM in the rest frame of the Sun.

the two elements (Rucinski & Fahr 1989; Rucinski et al. 1993), the maximum of the H-distribution is located at the position of the shock in the upwind direction, whereas the He-distribution peaks at the opposite direction on the downwind side.

The upwind-downwind asymmetry in each distribution is obvious from Figure 1. Explicit values are listed in Table 1 for the upwind/downwind direction as well as the actual trajectories (King & Parthasarathy 1991) of *Voyager 2* (flying approximately upwind) and *Pioneer 10* (flying downwind). From these values we may conclude that the upwind-downwind asymmetries $A = p_{acr,up}/p_{acr,do}$ are of the order of $A_H = 1.6$ for hydrogen and $A_{He} = 0.5$ for helium, and that the magnetic field tends to reduce the asymmetries at higher heliomagnetic latitudes.

The actual measurement of the postulated asymmetries by the deep space probes *Pioneer 10, 11* and *Voyager 1, 2* faces several problems: First, the satellites are not located exactly in the upwind or downwind direction, and, as a consequence, the measurements of $A_{H,He}$ at the spacecraft trajectories are expected to yield values slightly *closer to 1* than the actual upwind-downwind values (Table 1). Second, the data have to be corrected for solar activity, i.e., the cosmic-ray modulation, because the spacecrafts reached the same distances, with a delay of years. Third, one has to realize that the employed instruments are not identical and, consequently, the measurements are therefore not directly comparable. For instance, in a recent analysis of the modulation of the Galactic cosmic rays (GCR) by Burlaga, Perko, & Pirraglia (1992), the *Pioneer 10* (downwind) data were multiplied by a (conversion) factor of 1.62 in order to relate them to *Voyager 2* (upwind) measurements.

Of course, we do not claim that this difference could be solely related to the expected ACR asymmetry, but we wish to point out that in view of this uncertainty (which is of the same order as the asymmetry) it might be complicated, if not impossible, to extract reliable information concerning upwind-downwind asymmetries from these data. In order to provide a proper observational basis, a pair of identical satellites, with one spacecraft flying in the upwind and the other in the downwind direction, but located at the same time at the same distance, would be required. Also, for an investigation of the actual asymmetry of the heliospheric shock such a twin mission would be ideal.

From the above it is apparent that use of the ACR as a main and valuable diagnostic of the structure of the heliosphere requires a detailed and self-consistent model of the acceleration process of the ACR with two important requirements: (1) it should link the asymmetric seed population, providing an asymmetric injection into the shock region, with a non-spherically symmetric heliospheric shock and (2) it should take into account the influence of the accelerating particles on the microscopic structure of the shock. The resulting ACR source distributions incorporated in the diffusion models would then lead to the desired heliospheric ACR distributions, which will not only provide information about the structure of the heliosphere, but also serve as a valuable test of self-consistent models of the diffusive shock acceleration.

TABLE 1

NORMALIZED PRESSURE VALUES FOR ANOMALOUS HYDROGEN AND HELIUM FOR DIFFERENT LOCATIONS IN THE HELIOSPHERE: VALUES ALONG THE UPWIND-DOWNWIND AXIS AND FOR THE TRAJECTORIES OF *VOYAGER 2* AND *PIONEER 10*

Species	40 AU	50 AU	60 AU	70 AU	Direction
hydrogen	0.0460	0.1234	0.2776	0.5516	Upwind
	0.0288	0.0773	0.1740	0.3456	Downwind
	1.60	1.60	1.60	1.60	Asymmetry
hydrogen	0.0460	0.1215	0.2681	0.5281	*Voyager 2*
	0.0296	0.0785	0.1767	0.3511	*Pioneer 10*
	1.55	1.55	1.52	1.50	Asymmetry
helium	0.0209	0.0551	0.1235	0.2452	Upwind
	0.0469	0.1238	0.2779	0.5517	Downwind
	0.45	0.45	0.44	0.44	Asymmetry
helium	0.0208	0.0612	0.1341	0.2720	*Voyager 2*
	0.0456	0.1219	0.2734	0.5430	*Pioneer 10*
	0.46	0.50	0.49	0.50	Asymmetry

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https://doi.org/10.1017/S0252921100077861 Published online by Cambridge University Press