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Advances in Space Research 49 (2012) 1660–1669

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Modelling of galactic Carbon in an asymmetrical heliosphere: Effects of asymmetrical modulation conditions

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Received 31 October 2011; received in revised form 23 February 2012; accepted 28 February 2012
Available online 6 March 2012

Abstract

Observations of galactic cosmic rays (GCRs) from the two Voyager spacecraft inside the heliosheath indicate significant differences between them, suggesting that in addition to a possible global asymmetry in the north–south dimensions (meridional plane) of the heliosphere, it is also possible that different modulation (turbulence) conditions could exist between the two hemispheres of the heliosphere. We focus on illustrating the effects on GCR Carbon of asymmetrical modulation conditions combined with a heliosheath thickness that has a significant dependence on heliolatitude. To reflect different modulation conditions between the two heliospheric hemispheres in our numerical model, the enhancement of both polar and radial perpendicular diffusion off the ecliptic plane is assumed to *differ* from heliographic pole to pole. The computed radial GCR intensities at polar angles of 55° (approximating the Voyager 1 direction) and 125° (approximating the Voyager 2 direction) are compared at different energies and for both particle drift cycles. This is done in the context of illustrating how different values of the enhancement of both polar and radial perpendicular diffusion between the two hemispheres contribute to causing differences in radial intensities during solar minimum and moderate maximum conditions. We find that in the $A > 0$ cycle these differences between 55° and 125° change both quantitatively and qualitatively for the assumed asymmetrical modulation condition as reflected by polar diffusion, while in the $A < 0$ cycle, minute quantitative differences are obtained. However, when both polar and radial perpendicular diffusion have significant latitude dependences, major differences in radial intensities between the two polar angles are obtained in both polarity cycles. Furthermore, significant differences in radial intensity gradients obtained in the heliosheath at lower energies may suggest that the solar wind turbulence at and beyond the solar wind termination shock must have a larger latitudinal dependence.

Keywords: Cosmic rays; Modulation; Heliosphere; Heliosheath; Solar activity

1. Introduction

The cause(s) of the asymmetrical heliospheric modulation of galactic cosmic rays (GCRs) as observed by Voyager 1 (V1) and Voyager 2 (V2) in the heliosheath (e.g., Webber et al., 2009; Caballero-Lopez et al., 2010; Manuel et al. 2011) is not well established or understood. It is, however, established that GCRs are modulated in anti-phase with solar activity and that this strong anti-correlation seems to exist well into the heliosheath (Webber et al., 2011), the region between the solar wind termination shock (TS) and the heliopause (HP).

The numerical modeling of GCR modulation in the heliosphere depends on assumptions about the elements of the diffusion tensor, the local interstellar spectra (LIS) and heliospheric geometry in addition to the solar wind and heliospheric magnetic field (HMF). The diffusion coefficients are basically determined by the turbulence properties of the expanding solar wind and the imbedded HMF. Up to now, particularly in numerical modeling, it has simply been assumed that the turbulence and the consequent

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0273-1177/$36.00
doi:10.1016/j.asr.2012.02.036

modulation conditions are symmetrical away from the heliospheric equatorial plane. However, this is not necessarily the case, especially not in the heliosheath.

MHD modeling points to the existence of an asymmetry in the magnetic structure between the northern and the southern hemispheres of the heliosheath, with the northern part found to be a region with more magnetic islands or holes. As a result diffusion could be different in the two hemispheres. The geometrical alignment of the HMF and the interstellar magnetic field at the HP only on one side of the heliosphere could easily enhance this asymmetry (e.g., Opher et al., 2011).

Changing solar activity, as the important driver of the heliospheric modulation of GCRs, exhibits a north–south asymmetry (e.g., Li et al., 2009). It is therefore possible that quite different levels of turbulence may occur between the northern and southern heliospheric hemispheres (e.g., Efimov et al. 2008) thus causing what is referred to in this work as inherent asymmetric modulation, in addition to the modulation effects of an asymmetrically structured heliosphere. The existence of inherent asymmetrical modulation conditions can also be related to the global structuring of the HMF. Ulysses observations of the HMF in the polar regions of the inner heliosphere indicated that it was stronger in the southern hemisphere than in the northern hemisphere (Forsyth et al., 1996; Smith et al., 2000; Erdos and Balogh, 2010). This north–south asymmetry was also clearly evident from cosmic ray observations by Ulysses (Heber and Potgieter, 2006; see also the discussion of this effect by Potgieter, 2011). Since the HMF affects both particle drift and diffusion, one is inclined to conclude that different modulation conditions of GCRs should exist between the two hemispheres.

The purpose of this work is to investigate the mentioned inherent asymmetrical modulation conditions using a numerical model with different enhancements for radial and perpendicular diffusion between the two hemispheres. It will be illustrated how differently these assumptions as implemented in the model effect the modulation of GCR Carbon between polar angles of $\theta = 55°$ (approximating the V1 direction) and $\theta = 125°$ (approximating the V2 direction). This is done with a simulated heliosphere that already contains a north–south (meridional) asymmetrical geometry as described by Ngobeni and Potgieter (2011). The modeling presented here is done for the two HMF polarity cycles (A < 0 and A > 0), and assuming solar activity increasing from solar minimum conditions, with a heliospheric current sheet (HCS) tilt angle of $\alpha = 10°$, to large solar activity represented by a tilt angle of $\alpha = 50°$. This paper is an extension of the work done by Ngobeni and Potgieter (2011).

2. Numerical model for asymmetrical modulation

The model is based on the numerical solution of the time-dependent transport equation (TPE) derived by Parker (1965):

$$\frac{\partial f}{\partial t} = -(\mathbf{V} + \langle \mathbf{v}_D \rangle).\nabla f + \nabla.(\mathbf{K}_s.\nabla f) + \frac{1}{3}(\nabla.\mathbf{V})\frac{\partial f}{\partial lnp} + J_{source}, \quad (1)$$

where f $(\boldsymbol{r}, p, t)$ is the omnidirectional GCR distribution function, p is particle momentum, $\boldsymbol{r}$ is the heliocentric position vector, and t is time, with $\mathbf{V}(r,\theta) = V(r,\theta)\ \boldsymbol{e}_r$ the solar wind velocity. The terms on the right-hand side represent convection, gradient and curvature drifts, diffusion, adiabatic energy changes and a particle source, respectively. The function J_{source} could represent any local source inside the heliosphere e.g., the Jovian magnetosphere as source of low-energy electrons (e.g. Ferreira et al., 2001) or the pick-up ion source for the anomalous component (e.g. Strauss et al., 2010), but for this study $J_{source} = 0$ (e.g. Strauss et al., 2011). The diffusion tensor $\boldsymbol{K}_S$ consists of a diffusion coefficient $K_{||}$, that is parallel to the average HMF, a radial perpendicular diffusion coefficient $K_{\perp r}$ and a polar perpendicular diffusion coefficient $K_{\perp\theta}$ (e.g. Potgieter, 1996, 2000). For a Parker-type geometry for the HMF, the effective radial (K_{rr}) and polar ($K_{\theta\theta}$) diffusion coefficients are

$$K_{rr} = K_{||}\cos^2\psi + K_{\perp r}\sin^2\psi \quad \text{and} \quad K_{\theta\theta} = K_{\perp\theta}, \quad (2)$$

where ψ is the angle between the radial and averaged HMF direction. It is easily noted from Eq. (2) that K_{rr} becomes dominated by $K_{\perp r}$ in the equatorial plane towards the outer heliosphere.

The averaged guiding centre drift velocity for a near isotropic cosmic ray distribution is given by $\langle v_D \rangle = \nabla \times (K_T e_B)$, with $e_B = B/B_m$, where B_m is the magnitude of the modified background HMF assumed to have a basic Parkerian geometry in the equatorial plane but modified in the polar regions similar to the approach of Jokipii and Kota (1989). Here K_T is the coefficient specified by the off-diagonal elements of the generalized tensor $\boldsymbol{K}_S$, that describes gradient and curvature drifts in the large scale HMF. The spatial and rigidity dependence of $K_{||}$ is taken from Burger et al. (2008), while $K_{\perp r}$, $K_{\perp\theta}$ and K_T are based on a steady-state model derived by Burger et al. (2000). This set of diffusion coefficients is compatible to galactic C observations during solar minimum conditions (see Ngobeni and Potgieter, 2011). For increasing solar activity an adjustment is made to $K_{||}$, with respect to the assumed solar minimum value ($\alpha = 10°$), similar to Ferreira and Potgieter (2004), for both polarity cycles given by

$$\left(\frac{10^{\circ}}{\alpha}\right)^{\frac{1}{\eta}} K_{||}, \quad (3)$$

where α is the HCS tilt angle in degrees and $\eta = 3.25$. For $\alpha = 50°$ this adjustment changes $K_{||}$ by a factor of ~0.6 as compared to its value when $\alpha = 10°$. Furthermore, to represent modulation during increasing solar activity $K_{\perp r}$ and $K_{\perp\theta}$ are increased by a factor of ~1.5 from their assumed solar minimum values. These adjustments are considered optimal and in accordance with the time