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Advances in Space Research 53 (2014) 1634–1646

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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A study of the global heliospheric modulation of galactic Carbon

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Received 12 November 2013; received in revised form 27 January 2014; accepted 3 March 2014
Available online 12 March 2014

Abstract

Observations of galactic Carbon in the heliosphere provide a useful tool with which a comprehensive description of the global modulation of cosmic rays both inside and outside off the solar wind termination shock (TS) can be made. This is, in part, because galactic Carbon is not contaminated by anomalous cosmic rays as is the case for oxygen, helium and hydrogen. However, this kind of study requires that there should be reasonable compatibility of model solutions to spacecraft and earthbound observations. In this study, the well-established two-dimensional model that contains a TS, a heliosheath, as well as shock re-acceleration of galactic cosmic rays and particle drifts, is used first to study modulation from solar minimum to moderate maximum activity at Earth. This model can handle any global heliospheric geometry of both the TS and heliopause (HP) positions. Second, the model is applied to study the contribution of drifts and the enhancement of polar perpendicular diffusion in the heliosheath to the total modulation in the heliosphere as a function of energy for both polarity cycles of the magnetic field during solar minimum conditions. This modeling is done with a new heliopause spectrum (HPS, usually referred to as the local interstellar spectrum) at kinetic energy $E < \sim 200$ MeV/nuc. This HPS is derived from observations made by the Voyager 1 spacecraft of galactic Carbon at a radial distance of ~122 AU from the Sun. We find that: (1) The model gives realistic modulation for both magnetic polarity cycles of the Sun, from Earth to beyond the TS, and that the level of modulation at Earth between the recent solar minimum and the previous moderate maximum condition exceed that between the HP and Earth in the recent solar minimum. (2) Neglecting drifts in the heliosheath along the Voyager heliolatitude is a reasonable assumption, but in the equatorial plane of the heliosphere drifts are important for heliosheath modulation in the $A < 0$ polarity cycle, especially when galactic particles are re-accelerated at the TS. (3) The contribution of the enhancement of the polar perpendicular diffusion in the heliosheath to the total modulation seems insignificant. (4) The new HPS as observed by Voyager 1 at $E < \sim 200$ MeV/nuc is found to be significantly higher than previous estimates, for example, at $E = 100$ MeV/nuc by a factor of ~2. We find that the total modulation between the HP and Earth at 10 MeV/nuc causes the intensity at Earth to be only ~4.5% of the HPS, whereas for 100 MeV/nuc it is ~17.5%. Respectively, this means that the global radial gradient for galactic Carbon for this period was ~2.5%/AU and ~1.4%/AU, if the heliopause is taken at 122 AU.

Keywords: Cosmic rays; Heliosphere; Solar modulation; Galactic Carbon

1. Introduction

Galactic cosmic rays (GCRs) enter the heliosphere from all directions and then propagate toward the Sun. Once inside the heliosphere they interact with the convective solar wind and its embedded turbulent magnetic field. The understanding of this global interaction is currently based on four major modulation processes: convection,

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http://dx.doi.org/10.1016/j.asr.2014.03.004
0273-1177/

diffusion, adiabatic energy changes, and gradient, curvature and current sheet drifts. Combined, these interplaying processes cause the intensity of GCRs to decrease toward the Sun and to change significantly over its 11-year solar activity cycle, exhibiting also a clear 22-year solar magnetic cycle.

In numerical models of the global solar modulation of GCRs, the location of the heliospheric boundary, usually assumed to be the heliopause (HP) is most relevant (see e.g. Langner and Potgieter, 2005a; Nkosi et al., 2011; Manuel et al., 2011). In modeling this boundary is where modulation is assumed to commence, more specifically where the input spectra usually referred to as the local interstellar spectra (LIS) of the various GCR species, are specified. From a solar modulation point of view, these input spectra should rather be called heliopause spectra (HPS) because they are specified at the boundary of the heliosphere. It is to be determined if they truly are identical to LIS (see e.g. Strauss et al., 2013). These HPS are modulated throughout the heliosphere as a function of position, energy and time; the process known as the heliospheric and solar modulation of GCRs.

Before the recent Voyager 1 (V1) observations (Stone et al., 2013; Krimigis et al., 2013), the HPS at lower energies (kinetic energy $E < 500$ MeV/nuc) were simply estimated, or at best based on the computed results of galactic propagation models (e.g. Moskalenko et al., 2002; Webber and Higbie, 2009). The location of the heliopause (HP) has been based on hydrodynamic and magnetohydrodynamic model predictions (e.g. Scherer and Ferreira, 2005). Generally it was placed around ~140 AU in the nose region of the heliosphere, the direction in which the heliosphere is moving. This is important in global modeling because it determines the size of the total modulation volume. As a result two interrelated problems existed, namely: (1) Inadequate knowledge about the form of various GCR input spectra (or HPS) at lower energies, for both the intensity level and spectral shape. (2) The lack of accurate information about the location of the HP, and with that the total effect of the heliosheath especially on low energy GCRs. This has resulted in uncertainties in the modeling of the modulation of GCRs because the total amount of modulation, including the heliosheath, depends on the assumed value of the relevant HPS. For example, if the location of the HP and termination shock (TS) is fixed, that is the width of the heliosheath prescribed, a higher input spectrum for a given low energy will result in more modulation and larger spatial gradients at a certain position in the heliosphere based on a given set of modulation parameters (e.g. Potgieter and Ferreira, 2002; Langner et al., 2003; Ngobeni and Potgieter, 2010; Nkosi et al., 2011). As long as these HPS were uncertain at low energies, the actual total modulation between the HP and Earth, for example, could not be determined, even with the most sophisticated global heliospheric models. However, with the HP location fairly well-known and also the relevant HPS, progress can be made to establish all transport coefficients on a global scale. This has become possible because the recent V1 observations (Stone et al., 2013; Krimigis et al., 2013) indicate that it has encountered regions associated with what may be called a layered HP (Swisdak et al., 2013) and probably crossed it into the very local interstellar medium at a radial distance of ~122 AU already in August 2012 (Gurnett et al., 2013). This observation of the Voyager mission is indeed a milestone and a giant step towards understanding the very local interstellar space, providing both the intensity and spectral shape down to few MeV. If this is indeed the case, V1 may now be measuring HPS that can trustworthy be considered the lowest possible very LIS for GCRs, also for galactic Carbon (C) on which this work is focused.

The availability of Carbon observations measured by ACE at Earth between 1997 and 2010 (http://srl.caltech.edu/ACE/ASC/level2; Webber, 2006; Lave et al., 2013; Webber et al., 2012) combined with the new HPS below ~200 MeV based on V1 *in situ* observations, provide an opportunity to study modulation from solar minimum to moderate maximum activity. This is done using the shock re-acceleration modulation model as described previously by Ngobeni and Potgieter (2010, 2011, 2012), which can handle any global heliospheric geometry for the TS and HP e.g. a nose tail asymmetry (Langner and Potgieter, 2005b) and/or a north–south asymmetry (Ngobeni and Potgieter, 2011, 2012). Essentially, a modulation modeling investigation can be made as to what adjustments should be made to the elements of the diffusion and drift tensors during increasing solar activity relative to their values during solar minimum conditions by establishing compatibility with Carbon observations at Earth. These observations are from ACE for 1997–2010, representing different heliospheric modulation conditions. Galactic Carbon is not contaminated by anomalous cosmic rays as is the case for oxygen, helium and hydrogen.

Furthermore, it has been established from numerical modeling that the amount of modulation taking place in the heliosheath depends on energy as well as on solar activity with more than ~80% of the total modulation at lower energies occurring in the heliosheath (Potgieter, 2008). This prediction is indeed confirmed by V1 observations (Webber et al., 2013). However, it is not yet established as to what extent the various known modulation processes contribute to the total modulation in the heliosheath as a function of energy. The model is also applied to study modulation in the outer heliosphere, in particular to investigate the relative importance of the role of drifts and the enhancement of polar perpendicular diffusion inside the heliosheath. The modeling solutions are shown for both solar magnetic polarity cycles (two drift cycles) and during solar minimum and moderate solar maximum modulation conditions.

2. Numerical model

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