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The charge-sign dependent effect in the solar modulation of cosmic rays

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Abstract

The centennial anniversary of the discovery of cosmic rays was in 2012. Since this discovery considerable progress has been made on several aspects related to galactic cosmic rays in the heliosphere. It is known that they encounter a turbulent solar wind with an imbedded heliospheric magnetic field when entering the Sun's domain. This leads to significant global and temporal changes in their intensity inside the heliosphere, a process known as the solar modulation of cosmic rays. The prediction of a charge-sign dependent effect in solar modulation in the late 1970s and the confirmatory observational discoveries can also be considered as a milestone. A short review is given of these predictions based on theoretical and numerical modelling work, the observational confirmation and related issues.

Keywords: Cosmic rays; Heliosphere; Solar modulation; Particle drifts

1. Introduction

Galactic cosmic rays (GCRs) encounter a turbulent solar wind with an imbedded heliospheric magnetic field (HMF) when entering the heliosphere. This leads to significant global and temporal changes in their intensity, a process known as the solar modulation of GCRs. Once inside the heliosphere, surely on the upwind side of the solar wind termination shock (TS), GCRs quickly sense the gradients and curvatures of the HMF and subsequently undergo gradient and curvature drifts, one of four major solar modulation mechanisms. These charged particles consequently exhibit charge-sign dependent modulation with very interesting features. The HMF also has a wavy current sheet, separating inward directed magnetic field lines in one hemisphere from the outward directed ones in the opposite hemisphere. This current sheet changes its waviness according to variations in solar activity and forms therefore an important part of particle drifts with an explicit modulation effect.

Every ~11 years the polarity of the HMF reverses during periods of extreme solar activity so that GCRs from then on gradually begin to drift in opposite directions. This means that while protons and positrons will drift towards the inner heliosphere primarily through the polar regions of the heliosphere and then mainly outwards along the wavy current sheet, anti-protons and electrons will drift inwards mainly along the current sheet and outwards through the polar regions. In the process, they sample different modulation conditions during the same solar cycle before reaching Earth. Global particle drifts, together with current sheet drifts, yield a distinct 22-year modulation cycle.

This short review covers the topic of charge-sign dependence in the solar modulation of GCRs since its prediction in the late 1970s, the observational evidence and the impact it has had on modulation theory and modelling over the years until the precise measurements of cosmic particles and their anti-particles at Earth over the recent years. The review is not meant as a historical record and does not attempt to discuss all the research that has been published on this particular topic so that citations are given only as examples of the basic issues. The focus is on GCRs with energies below 10 GeV.

2. Prediction of charge-sign dependent modulation

It was not until around 1976–78 that particle drifts were considered seriously as a competitive modulation mecha-

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nism, on top of the conventional convective, diffusive and adiabatic energy loss mechanisms. It was experienced as controversial when introduced and it took 10 years to become widely accepted. Even today the full extent of its relevance and importance over a complete solar activity cycle is debated. See as an example the critical review by Cliver et al. (2011). The early stages of this theoretical development, and the status of the research round that time, were comprehensively reviewed by Quenby (1984). The realization also came that the only way to understand the full scope of particle drifts on GCR modulation was with numerical modelling. Therefore, since the early 1980s increasingly more sophisticated numerical models had been introduced that kept on improving, lately based on the approach using stochastic differential equations (e.g. Bobik et al., 2012; Strauss et al., 2011, 2012a) that was first introduced in solar modulation modelling by Zhang (1999).

Convincing theoretical arguments for the importance of particle drifts were presented by Jokipii et al. (1977) and later followed by persuasive numerical modelling (e.g. Jokipii and Thomas, 1981; Kóta and Jokipii, 1983; Potgieter and Moraal, 1985) which illustrated that gradient and curvature drifts could cause charge-sign dependent modulation and a dazzling 22-year cycle. The main reason for this to occur is that the solar magnetic field reverses polarity every ~11 years so that GCRs of opposite charge will reach Earth from different heliospheric directions. This also makes the wavy heliospheric current sheet (HCS) of the HMF a very important modulation feature with its tilt angle (Hoeksema, 1992) being a very useful modulation parameter. When protons drift inwards mainly through the equatorial regions of the heliosphere (called $A < 0$ polarity cycles) they encounter the dynamic HCS and get progressively reduced by its increasing waviness as solar activity surges. This produces the sharp peaks in the GCR intensity-time profiles whereas during the $A > 0$ cycles the profiles are flatter (see e.g. Potgieter, 2011; Krymsky et al., 2012). The effect reverses for negatively charged GCRs. See also the reviews by Heber and Potgieter (2006, 2008) and Kóta (2012).

Another indication of the role of particle drifts came in the form of a 22-year variation in the direction of the daily anisotropy vector in the GCR intensity as measured by neutron monitors from one polarity cycle to another (Levy, 1976; Potgieter and Moraal, 1985). Potgieter et al. (1980) also discovered a 22-year cycle in the differential response function of neutron monitors used for geomagnetic latitude surveys at sea-level in 1965 and 1976 (see also Moraal et al., 1989).

The theory behind these observed phenomena is briefly discussed next, followed by a list of the major predictions from numerical drift models.

2.1. Theory and modeling

The basics of the global modulation of GCRs in most parts of the heliosphere are theoretically contained in Parker's (1965) transport equation:

$$\frac{\partial f}{\partial t} = -(\mathbf{V} + \langle \mathbf{v}_D \rangle) \cdot \nabla f + \nabla \cdot (\boldsymbol{K}_s \cdot \nabla f) + \frac{1}{3}(\nabla \cdot \mathbf{V}) \times \frac{\partial f}{\partial \ln R} + f_{source}, \quad (1)$$

where $f(\boldsymbol{r}, R, t)$ is the cosmic ray distribution function, R is rigidity, $\mathbf{r}$ is position, $\mathbf{V}$ is the solar wind velocity and t is time. Terms on the right-hand side represent respectively convection, gradient and curvature drifts, diffusion, adiabatic energy changes, and a source function e.g. for Jovian electrons. The details of particle motion and scattering in the irregular HMF are contained in the diffusion coefficients as elements of the tensor $\boldsymbol{K}_s$ which consists of a parallel diffusion coefficient ($K_\|$) and two perpendicular diffusion coefficients, one in the radial direction ($K_{\perp r}$) and one in the polar direction ($K_{\perp\theta}$). The pitch angle averaged guiding center drift velocity for a near isotropic cosmic ray distribution is given by $\langle \mathbf{v}_D \rangle = \nabla \times (K_A \mathbf{e}_B)$, with $\mathbf{e}_B = \mathbf{B}/B_m$ and B_m the magnitude of the background HMF, with K_A the off-diagonal element of the full tensor. For a Parker type HMF, the effective radial diffusion coefficient is given by $K_{rr} = K_\| \cos^2\psi + K_{\perp r} \sin^2\psi$, with ψ the angle between the radial and the averaged HMF direction. The geometry of the HMF is thus contained in the expressions of the elements of the diffusion tensor. For this case, $\psi \to 90°$ when $r > \sim 10$ AU and with the polar angle $\theta \to 90°$; $\psi \to 0°$ when $\theta \to 0°$, which means that $K_\|$ dominates K_{rr} in the inner heliosphere, and in the polar regions, with $K_{\perp r}$ dominating in the middle to outer regions of the heliosphere. These differences are important for the modulation of GCRs in the inner heliosphere. The expressions for these diffusion coefficients become significantly complicated when more complex geometries are used for the HMF. The important role of perpendicular diffusion (radial and polar) in the inner heliosphere has become increasingly better understood over the past decade since it was realized that it should be anisotropic, with reasonable consensus that $K_{\perp\theta} > K_{\perp r}$ away from the equatorial regions.

Evidently, the geometry of the HMF largely determines how much gradient and curvature drifts will occur. Under idealistic conditions the effects of particle drifts on solar modulation can easily be overestimated as was done with first generation numerical models (e.g. Jokipii and Kopriva, 1979; Potgieter et al., 1989). The spatial and rigidity dependence of the element of the diffusion tensor in Eq. (1) that describes drifts (K_A) is almost entirely based on the assumption of weak-scattering, except for an empirical reduction at low rigidities ($R < 1$ GV). This reduction is in line with what Potgieter et al. (1989), Ferreira and Potgieter (2004), Potgieter and Langner (2004a,b) and Strauss et al. (2010), to mention only a few, found when describing computed modulation in terms of gradient and curvature drifts with a HCS tilt angle dependence in models. A fundamentally sound theoretical description of all possible manners of particle drifts in the heliosphere is still due. Numerical simulations (e.g. Giacalone, 2003) have been presented requiring the reduction of drifts in particular with increas-