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A comparison of turbulence-reduced drift coefficients of importance for the modulation of galactic cosmic-ray protons in the supersonic solar wind

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Abstract

The study of the modulation of cosmic rays in the heliosphere relies heavily on a thorough understanding of the transport of these charged particles in the turbulent solar wind. Drift effects due to gradients and the curvature of the background magnetic field have long been known to be reduced in the presence of turbulence, and as such, several forms for the drift coefficient that include the effect of turbulence have been proposed. The present study aims to investigate the qualitative effects of various turbulence-reduced drift coefficients on cosmic ray intensities computed using an *ab initio* 3D steady-state cosmic-ray modulation code. Results from a two-component turbulence transport models are used as inputs for the basic turbulence quantities. Furthermore, an expression for the perpendicular mean free path is derived here from a modification of the non-linear guiding center theory of Matthaeus et al. (2003) assuming a 2D turbulence power spectrum with a k^{-1} energy range wavenumber dependence, and is used in conjunction with the various proposed turbulence-reduced drift coefficients. Cosmic-ray intensities computed using different drift coefficients but assuming the same turbulence conditions are found to differ widely. This study emphasises the need to gain a better understanding of the effect of turbulence on drifts in the heliosphere.

Keywords: Cosmic-rays; Diffusion; Turbulence

1. Introduction

Many studies have shown that drifts due to gradients and curvatures in the heliospheric magnetic field (HMF), as well as along the wavy current sheet, are important processes in the transport of the various species of galactic cosmic rays (CRs) and have a significant effect on cosmic-ray modulation (see, e.g., Jokipii and Levy, 1977; Jokipii et al., 1977; Isenberg and Jokipii, 1978; Jokipii and Kopriva, 1979; Jokipii and Thomas, 1981; Potgieter and Moraal, 1985; Zhang, 1997; Lockwood and Webber, 2005), accounting for the observed 22-year cycle in cosmic-ray intensities (Jokipii and Thomas, 1981). Drift effects, however, have been shown both theoretically and by means of numerical simulations to be reduced in the presence of turbulence (see, e.g.,Jokipii, 1993; Giacalone et al., 1999; Candia and Roulet, 2004; Minnie et al., 2007; Tautz and Shalchi, 2012). Given the importance of drift in any study of cosmic-ray modulation, this reduction needs to be carefully modelled throughout the heliosphere. This endeavour suffers from a relative paucity of numerical studies of the drift coefficient in the presence of turbulence, as opposed to those done to investigate diffusion parallel and perpendicular to the mean HMF. A self-consistent theoretical

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approach to the problem of drift reduction due to turbulence appears to be rather complicated, and relatively few attempts to do so have been made (see, e.g., Bieber and Matthaeus, 1997; Stawicki, 2005; le Roux and Webb, 2007; Weinhorst et al., 2008; Tautz and Shalchi, 2012). The purpose of this study is to investigate the effects of the turbulence-reduced drift coefficients proposed by Bieber and Matthaeus (1997), Burger and Visser (2010) and Tautz and Shalchi (2012), as well as those of an *ad hoc* reduced drift coefficient used in previous numerical studies of cosmic-ray modulation, on galactic cosmic ray proton intensities computed using an *ab initio*, *3D steady state modulation code*.

Perpendicular diffusion also plays an integral part in the transport of the various species of galactic cosmic rays (see, e.g., Langner and Potgieter, 2004; Burger et al., 2008; Della Torre et al., 2012; Bobik et al., 2013; Engelbrecht and Burger, 2013b), electrons of Jovian origin (see, e.g., Ferreira et al., 2001; Zhang et al., 2007; Strauss et al., 2011) and solar energetic particles (see, e.g., Zhang et al., 2009; Dröge et al., 2010; Kelly et al., 2012; Marsh et al., 2013; Dalla et al., 2013). Since the publication of the NLGC theory by Matthaeus et al. (2003), much work has been done on this phenomenon, both theoretical (see, e.g., Shalchi, 2006, 2009, 2010, 2013, 2014; Shalchi and Dosch, 2008; Ruffolo et al., 2012; Qin and Zhang, 2014), and by means of numerical simulations (see, e.g., Giacalone and Jokipii, 1999; Qin et al., 2002a,b; Candia and Roulet, 2004; Minnie et al., 2007). A key input of perpendicular scattering theories is the 2D modal turbulence power spectrum, and the perpendicular mean free paths (MFPs) derived from it are particularly sensitive to assumptions made as to the form of this spectrum in the low-wavenumber, energy-containing range (Shalchi et al., 2010, 2013). We derive a nonlinear expression for the perpendicular MFP from the extended NLGC theory of Shalchi (2006) (ENLGC) for a 2D turbulence power spectrum which displays the k^{-1} wavenumber dependence in the energy-containing range seen in spacecraft observations (see, e.g., Bieber et al., 1993; Goldstein and Roberts, 1999). The basic turbulence quantities this expression and some of the forms of turbulence-reduced drift coefficient considered here are functions of, are modelled using the two-component turbulence transport model (TTM) proposed by Oughton et al. (2011) and employed by Engelbrecht and Burger (2013a,b). This MFP and the drift coefficients are then characterised throughout the heliosphere. These coefficients are then employed in the three-dimensional steady state modulation code of Engelbrecht and Burger (2013a) so as to qualitatively demonstrate the effects of the various turbulence-reduced drift coefficients on computed galactic cosmic-ray proton intensities.

2. Diffusion coefficients

Assuming magnetostatic, axisymmetric turbulence that is anisotropic, the standard NLGC perpendicular diffusion coefficient can be calculated from (Matthaeus et al., 2003):

$$\kappa_\perp = \frac{a^2 v^2}{3B_0^2} \int d^3k \frac{S^T(\mathbf{k})}{v/\lambda_\parallel + k_\perp^2 \kappa_\perp + k_\parallel^2 \kappa_\parallel}, \tag{1}$$

where v is the particle speed, B_o the uniform background magnetic field, $S^T(\mathbf{k}) = S^{2D}(k_\perp)\delta(k_\parallel) + S^{slab}(k_\parallel)\delta(k_\perp)$, and a^2 is a constant (see, e.g., Shalchi and Dosch, 2008; Ruffolo et al., 2012, for more detail), set here to a value of 1/3 following Matthaeus et al. (2003). Expressions for the perpendicular MFP derived from this theory were presented by Shalchi et al. (2004), and employed in cosmic-ray modulation studies by Burger et al. (2008) and Engelbrecht and Burger (2010).

Since the publication of the NLGC theory, several refinements have been proposed. Shalchi (2006) argues on the basis of test particle simulations preformed by Qin et al. (2002a,b) that the slab contribution to perpendicular transport always behaves in a subdiffusive manner, proposes an extended NLGC (ENLGC) theory, such that the perpendicular diffusion coefficient, assuming again magnetostatic axisymmetric turbulent fluctuations, can be calculated from

$$\kappa_\perp = \frac{a^2 v^2}{3B_0^2} \int dk_\perp \frac{S^{2D}(k_\perp)}{v/\lambda_\parallel + k_\perp^2 \kappa_\perp}, \tag{2}$$

thus taking into account only the 2D turbulent fluctuations. Shalchi (2010) proposes a unified nonlinear theory (UNLT), derived under more general assumptions than the NLGC theory, from which previous theories can be derived as special limits. However, the perpendicular MFP calculated using this theory does not differ much from that calculated using the ENLGC for a given form for the 2D turbulence power spectrum, and is therefore not considered here.

All of the abovementioned theories require expressions for the 2D modal turbulence power spectrum as basic inputs, and are particularly sensitive to its behaviour in the low-wavenumber, energy-containing range, so much so that the inertial range behaviour of the spectrum is not expected to have much effect on the perpendicular MFPs derived using one of the NLGC theories (Shalchi, 2013). Spacecraft observations taken in the solar ecliptic plane of the low-wavenumber behaviour of turbulence power spectra reveal either a flat wavenumber dependence (Hedgecock, 1975), or a $\sim k^{-1}$ wavenumber dependence (Bieber et al., 1993; Goldstein and Roberts, 1999), with a possible solar-cycle dependence (Bieber et al., 1993, 1996). In the heliospheric polar regions, Horbury et al. (1996) and Goldstein et al. (1995) find a k^{-1} wavenumber dependence, while Smith et al. (1995) report that the spectrum flattens in the energy range. Motivated by these findings a 2D spectrum with an energy-containing range that scales as $k_\perp^{-1}$ is employed, as opposed to spectral form employed by Engelbrecht and Burger (2013a), who assumed that the energy-containing range was wavenumber-independent.