Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 56 (2015) 1525–1537

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Modelling the effects of scattering parameters on particle-drift in the solar modulation of galactic cosmic rays

M.D. Ngobeni [a],*, M.S. Potgieter [b]

[a] Dept. of Physics and NDT, Vaal University of Technology, 1900 Vanderbijlpark, South Africa
[b] Centre for Space Research, North-West University, 2520 Potchefstroom, South Africa

Received 24 March 2015; received in revised form 23 June 2015; accepted 25 June 2015
Available online 3 July 2015

Abstract

It is well known that particle drift motions are suppressed by diffusive scattering as established by direct numerical simulations. The effect of constant scattering on the drift velocities of charged particles has always been included in numerical modulation models provided that the weak scattering drift velocity is scaled down in magnitude, although in an empirical manner as comparison between drift models and observations required. What has not yet been established is the spatial dependence of the scattering parameter ($\omega\tau$), with ω the gyro-frequency and τ a time scale defined by diffusive scattering. In this work, current knowledge about the spatial and rigidity dependence of $\omega\tau$ is used to illustrate and discuss its effect on the drift coefficient in the modulation of cosmic ray Carbon in the heliosphere. This is done with a well-established numerical model which includes all four major modulation processes, also the solar wind termination shock (TS) and the heliosheath. We estimate that a reasonable range in the value of $\omega\tau$ is $0 \leqslant \omega\tau \leqslant 5$, applicable to modulation studies inside and outside the TS. Furthermore, it is found that the considered different scenarios for $\omega\tau$ cause significant modifications to the weak scattering drift coefficient and as such on the subsequent computed differential intensities in both solar magnetic polarity cycles. For example, it is found that when $\omega\tau$ decreases rapidly over the heliospheric polar regions, the resulting drift coefficient at 1 AU becomes smaller at the poles compared to its value in the equatorial plane. This is contrary to the generally assumed spatial dependence of the maximal weak scattering drift coefficient. The consequent effect is that in the equatorial plane the $A < 0$ spectra are higher than the $A > 0$ spectra at all energies primarily because of drifts; which is unexpected from a classical drift modelling point of view. This feature persists for the equatorial plane modulation even when the explicit enhancement of perpendicular polar diffusion is neglected. Thus, scenarios of $\omega\tau$ with strong decreases over the heliospheric polar regions seem unlikely for the modulation of galactic cosmic rays in the upstream region of the TS.

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

1. Introduction

The understanding of the global interaction between the convective solar wind and galactic cosmic rays (CRs) in the heliosphere is currently based on four major modulation processes: convection, diffusion, adiabatic energy changes, and gradients, curvature and current sheet drifts. Of the four processes, particle drifts were neglected in earlier modulation studies until Jokipii et al. (1977) pointed out that they could alter the modulation of charged particles in the heliosphere. Particle drifts are an important aspect of the heliospheric modulation of CRs, since they are sensitive to the polarity of the heliospheric magnetic field (HMF), leading to charge-sign dependent modulation and a 22-year modulation cycle (for elaborate discussions, see

---

* Corresponding author. Tel.: +27 169509814; fax: +27 169509779.
E-mail addresses: donaldng@vut.ac.za (M.D. Ngobeni), Marius.Potgieter@nwu.ac.za (M.S. Potgieter).

http://dx.doi.org/10.1016/j.asr.2015.06.034
0273-1177/

Ferreira and Potgieter, 2004; Potgieter et al., 2013; Potgieter, 2013).

Since the earlier work of Jokipii et al. (1977), it has become apparent that drift models often describe observations of CRs better when drifts are reduced (see Potgieter et al., 1989; Potgieter and Burger, 1990; Webber et al., 1990; Burger et al., 2000; Ferreira and Potgieter, 2004; Ndiitwani et al., 2005). This has indicated that when weak scattering drifts are applied, they result in excessive drift-modulation effects. Examples of such effects can be seen in the numerical modelling of e.g. Jokipii and Kopriva (1979), Potgieter and Moraal (1985), Potgieter et al. (1989). Furthermore, the possibility that particle drift motions are suppressed by diffusive scattering as confirmed by theoretical work and numerical simulations (Giacalone et al., 1999; Stawicki, 2005; Minnie et al., 2007; Tautz and Shalchi, 2012), in particular its rigidity dependence, has been widely accepted. What has not yet been established is the effects of changing the spatial dependence of the scattering parameter ($\omega\tau$), with ω the gyro-frequency of a CR particle and τ a time scale defined by its scattering (here τ relates to the treatment of scattering effects based on turbulent magnetic field fluctuations), on the drift coefficient in the modulation of galactic CRs in the heliosphere. It is puzzling that close to four decades after particle drifts were emphasised, only relatively few studies have been done on the spatial dependence of $\omega\tau$ as applicable to the global modulation of CRs in the heliosphere. This is probably owing to the lack of proper knowledge about how the HMF turbulence develops throughout the heliosphere in all directions. However, the interest in the effects of turbulent magnetic fields on weak scattering drifts has increased, but it is clearly a work in progress (see e.g. Burger and Visser, 2010; Tautz and Shalchi, 2012; Engelbrecht and Burger, 2015). Particularly relevant to the work reported here are the studies originally done by Bieber and Matthaeus (1997) and later followed by Burger and Visser (2010), which provide some new insights and interesting departure points for the study of the spatial dependence of $\omega\tau$. Recently, considerations concerning the effects of turbulence in reducing the drift coefficient were presented by Engelbrecht and Burger (2015), which is further investigated in this study. They stated that the understanding of the effects of turbulence on CR drifts is far from complete. For a comprehensive overview of diffusion theory, see Shalchi (2009).

In an effort to improve the understanding of the reduction of particle drifts on the modulation of galactic CRs in the heliosphere, this work utilises current knowledge about the spatial and rigidity dependence of $\omega\tau$ to illustrate, evaluate and discuss its effects on the drift coefficient. It follows from published work, that there is a pressing need to study how different scenarios of $\omega\tau$ cause modifications to the weak scattering drift coefficient, both qualitatively and quantitatively. This is the focus of the current work as applied to the solar modulation of galactic Carbon.

2. The heliospheric drift coefficient

In general, the average drift velocity caused by the gradients and curvature in the HMF is given by

$$\langle \mathbf{v}_d \rangle = \nabla \times K_T \frac{\boldsymbol{B}}{B}, \tag{1}$$

with K_T the generalised drift coefficient (in some reports indicated as K_A), and $\boldsymbol{B}$ the HMF vector with magnitude B. The simplified drift coefficient based on assuming weak scattering, that is with $\omega\tau \gg 1.0$, is then given as

$$K_T = \frac{\beta P}{3B} f_s, \tag{2}$$

where f_s is the drift reduction factor due to diffusive scattering, with P the CR particle's rigidity and β the ratio of this particle's speed to the speed of light.

In many studies on the solar modulation of CRs and in the context of reducing drifts, B in Eq. (2) was replaced by B_m, which is called the modified Parker HMF magnitude, in particular, modified only over the polar regions of the heliosphere (as applied by e.g. Ferreira et al., 2003; Ngobeni and Potgieter, 2014). This was introduced to modulation models after the Ulysses space mission observed very small latitudinal CR gradients in contrary to drift model predictions before this mission (see the review by Heber and Potgieter (2006)). Weak scattering drifts, together with an unmodified Parker HMF, give drift-modulation effects much larger than observed, as was pointed out originally by Potgieter et al. (1989).

It follows from Eq. (2) that when $f_s = 0$, the drift coefficient and the particle drift velocity in Eq. (1) become zero; when $f_s = 1$ drifts become maximal. Bieber and Matthaeus (1997) gave an expression for f_s as

$$f_s = \frac{(\omega\tau)^2}{1 + (\omega\tau)^2}. \tag{3}$$

The functional form of the drift coefficient in Eq. (2) taken together with Eq. (3) is also found in Gleeson (1969) but using a hard-sphere scattering approach (see also the discussion by Bieber and Matthaeus (1997)). As a result Eq. (1) can be re-written as

$$\langle \mathbf{v}_d \rangle = \frac{\beta P}{3} \left[f_s \nabla \times \frac{\boldsymbol{B}}{B_m^2} + \nabla f_s \times \frac{\boldsymbol{B}}{B_m^2} \right]. \tag{4}$$

Here, now with the modified B_{m}. It follows from this equation that when f_s is assumed a constant, meaning no spatial dependence in $\omega\tau$, the term $\nabla f_s = 0$. As a result, the effect of particle scattering on the drift velocity is to reduce its magnitude by a constant factor f_s (see also Jokipii, 1993). However, when $\omega\tau$ has a spatial dependence $\nabla f_s \neq 0$ and the second term on the right hand side of Eq. (4) can have significant effects on the drift coefficient.

In a general context, a modification of weak scattering drifts can be accomplished through changing $\omega\tau$: First, assuming it is a constant throughout the heliosphere, but