

Transient heliosheath modulation

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ABSTRACT

Voyager 1 has explored the solar wind–interstellar medium interaction region between the terminal shock and heliopause, following the intensity distribution of Galactic cosmic ray protons above 200 MeV energy. Before this component reached the expected galactic flux level at 121.7 au from the Sun, four episodes of rapid intensity change occurred with a behaviour similar to that found in Forbush Decreases in the inner Solar system, rather than that expected from a mechanism related to models for the long-term modulation found closer to the Sun. Because the mean solar wind flow is both expected and observed to be perpendicular to the radial direction close to the heliopause, an explanation is suggested in terms of transient radial flows related to possible heliopause boundary flapping. It is necessary that the radial flows are of the order either of the sound speed found for conditions downstream of the terminal shock or of the fluctuations found near the boundary by the *Voyager 1* Low Energy Charged Particle detector and that the relevant cosmic ray diffusion perpendicular to the mean field is controlled by ‘slab’ fluctuations accounting for about 20 per cent of the total power in the field variance. However, additional radial drift motion related to possible north to south gradients in the magnetic field may allow the inclusion of some diffusion according to the predictions of a theory based upon the presence of 2D turbulence. The required field gradients may arise due to field variation in the field carried by solar plasma flow deflected away from the solar equatorial plane. Modulation amounting to a total 30 per cent drop in galactic intensity requires explanation by a combination of transient effects.

Key words: diffusion – Sun: heliosphere – solar wind – cosmic rays – ISM: magnetic fields.

1 INTRODUCTION

Since the provision of early models of heliosheath modulation (Potgieter & Le Roux 1989; Quenby, Lockwood & Webber 1990), it has been assumed that this region between the terminal shock and the heliopause is a location where a substantial fraction of the solar modulation of the galactic cosmic ray (GCR) intensity occurs (see review by Potgieter 2008). A very recent description of heliosheath modulation in a spherically symmetric approximation is due to Webber, Higbie & McDonald (2013) while Potgieter (2013) provides a recent general review. The heliopause represents the boundary beyond which the interstellar cosmic ray intensity would be encountered. Strauss et al. (2013) have recently questioned this assumption and mentioned various possibilities of increased particle scattering beyond the heliopause as the interstellar field wraps around the heliopause. Models and observations related to the interaction of the interstellar medium (ISM) with the heliosphere allow a solar wind terminal shock and a heliosheath lying between this shock and the

heliopause. These models suggest that the heliosheath comprises a low-latitude region where the magnetic structure is determined by reconnection of the sector structure fields and a high-latitude region where field lines connect back to the solar wind (Opher et al. 2012). The field is carried by the solar wind as it is diverted to high latitudes and back downwind of the interstellar flow. While no interstellar bow shock was expected, based upon some estimates of the Alfvén speed (McComas et al. 2012), inclusion of the probable He density suggests such a shock to exist (Scherer & Fichtner 2014). Since the flow inside such a shock is still mainly towards the Sun, little extra modulation is expected beyond the heliopause. However, the external field pressure causes asymmetry in the terminal shock (Opher, Stone & Liewer 2006) and may also explain intermittent observation of shock accelerated cosmic rays (Jokipii, Giacalone & Kota 2004; Stone et al. 2005) prior to the termination shock crossing.

The dramatic *Voyager 1* observation of two sudden increases of the greater than 200 MeV proton GCR component near the heliopause reached at 121.7 au (Stone et al. 2005; Webber & McDonald 2013) presents a challenge to current ideas of modulation within the heliosheath. It is the purpose of this paper to provide a simple class of models for these sudden increases in terms analogous to the

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cause of Forbush Decreases in the inner Solar system. There should exist transient, enhanced radial plasma flows which may or may not be accompanied by changes in magnetic field gradients suitable to yield enhanced particle drift speeds. A companion paper (Webber & Quenby 2015) discusses the observations of the two extraordinary increases in GCR intensity in relation to magnetic field data.

2 VOYAGER DATA

The starting point of this work lies in data obtained by Webber & McDonald (2013) from the *Voyager 1* CRS instrument (Stone et al. 1977). We concentrate on the period of the final increase in the >200 MeV proton intensity to attain the expected galactic flux value, witnessed by the steady intensity distribution beyond 121.7 au. The increase around 2012 day 240 is represented by a change of scaled count rate from 4.08 to 4.58 in 3.7 d (see fig. 1 of Webber & McDonald 2013). It is seen that these data correspond to the final step like GCR intensity increase before a galactic value is reached and that it is preceded by two fluctuations of similar magnitude over the previous month. These two preceding fluctuations do not reach the galactic GCR value. They could be regarded as two Forbush Decreases exhibiting rapid recovery of the flux to pre-decrease levels or above. If this structure in the GCR intensity is convected past *Voyager 1* with velocity V_{100} in units of 100 km s^{-1} , the spatial gradient is typically $0.56/V_{100}$ per au. Since the spacecraft is moving at only 0.07 au per week, it is very unlikely that the intensity structure is stationary in time. The regions of observed high spatial gradient extend back to about 120.5 au to include the second region of high spatial gradient discussed by Webber & McDonald (2013) and Burlaga & Ness (2014). The modulation of 200 MeV protons and of 10 MeV galactic electrons may be compared. Both species exhibit the step intensity increases but the relative modulation is higher by about a factor 2 for the electron channel.

In order to estimate the likely mean solar wind velocity close to the heliopause, we refer to the models provided by Opher et al. (2012) who provide alternatives, based upon whether or not reconnection in the sector region is included. Some verification is provided by using the Low Energy Charged Particle (LECP) *Voyager 1* results to deduce the radial and tangential flow components in the absence of a working plasma probe. Unfortunately, the numerical results need scaling from a modelled heliopause at 162 au. The Opher et al. (2012) flow vectors are given, both at 120 au which is within 2 au of the heliopause and at 110 au for the radial, tangential and normal components in Table 1 for alternative models, either ignoring the low-latitude sector structure or taking into account reconnection associated with the sector structure.

The LECP keV data are given at 110 au for two components. It appears that the experiment seems to agree better with the sector model for V_R and the non-sector model for V_T . However, the data

Table 1. Opher et al. (2012) models and *Voyager 1* flow data in the heliosheath in km s^{-1} .

Source	$V_R(120)$	$V_T(120)$	$V_N(120)$
No-Sector	44	−30	68
Sector	4	−5	30
Data			
	$V_R(110)$	$V_T(110)$	$V_N(110)$
No-Sector	52	−71	50
Sector	12	−5	15
Data	22	−36	(29)

Table 2. *Voyager 1* field magnitude and standard deviation, sd.

Period	DOY 150–171	DOY 176–202	DOY 204–238
B , nT	0.182	0.339	0.225
sd, nT	0.0690	0.0596	0.0735

exhibit very large fluctuations of up to $\pm 30 \text{ km s}^{-1}$ throughout the heliosheath. Negligible LEPC data are available for the normal, V_N component which clearly becomes the dominant steady flow at these distances. We estimate the measured $V_N(110)$ as the mean of the other two components. Extrapolation of the experimental results suggests that $V_R(120)$, $V_T(120) \leq \pm 20 \text{ km s}^{-1}$.

Magnetometer data obtained by Burlaga, Ness & Stone (2013) during the heliopause crossing enable us to estimate the power in the fluctuations of the magnitude of B . These authors observe a period of outward pointing polarity in 2012 from DOY 150 to DOY 171, inward polarity from DOY 176 to DOY 202 and outward polarity from DOY 204 DOY 238, the last period including two intervals where post-heliopause conditions are apparently encountered. Using data from fig. 2 of Burlaga et al. (2013), we give in Table 2 the mean and standard deviations of the fields in these three periods, neglecting the post-heliopause data. The quoted experimental errors are ± 0.01 nT, so are not expected to greatly distort the estimates of the standard deviation.

One estimate of the correlation length of the field magnitude fluctuations may be obtained from the power spectrum provided by Burlaga & Ness (2010) where a break at 1.8×10^{-7} Hz is found in the *Voyager 1* data at 110 au. If the field is convected past the spacecraft at a relative speed of 46 km s^{-1} , as suggested by the data, the correlation length is 1.7 au, taking into account the *Voyager 1* velocity. However, we shall provide a second estimate after discussing the manner in which it appears in models of perpendicular diffusion.

Webber & Quenby (2015) and Burlaga & Ness (2014) show large changes in the magnetic field well correlated with the large fluctuations in GCR intensity during the period day 208 to day 240. This observation provides indirect evidence of significant change in plasma velocity. Quenby & Webber (2013) have suggested that transient radial plasma flow velocities near the boundary, triggered by large changes in plasma pressure, could reach the sound speed obtained by Borovikov et al. (2011) in simulations of post terminal shock conditions. Their value is 228 km s^{-1} . The attainment of this speed out to near the heliopause depends on the plasma temperature not decaying significantly. If the Alfvén speed becomes the dominant fast mode speed, a simple estimate can be made based on the continuity of mass flow, $nVr^2 = \text{constant}$, where n is plasma number density at radial distance r . Using the observed field and the post-shock and non-sector velocities of previously mentioned models, we find an Alfvén speed of 31 km s^{-1} at 120 au.

3 DIFFUSION MEAN FREE PATHS

To carry out our calculation, we need to estimate possible values of the diffusion coefficients parallel and perpendicular to the mean field. In principle, it would seem best to employ the results of numerical trajectory integration in a field model directly related to actual spacecraft, *in situ* measurements (Valdes-Galicia, Quenby & Moussas 1992, and references therein). 3D wave and discontinuity structural effects are included. Due to the lack of suitable data,

we will use a theoretical simplification which has achieved reasonable agreement with experimental results in the inner heliosphere. This simplification, adopted in most recent literature, represents the field using the measured total power in the fluctuations, the parallel and perpendicular correlation lengths, an estimate of the percentage power in ‘slab’-like fluctuations and an assumed power law for the spectrum of waves. This paper will employ measured field data obtained far out in the heliosheath to obtain both the total fluctuation power and an average correlation length. The waves in the field model are Alfvénic and are composed 80 percent of a two-dimensional component with fluctuation vectors perpendicular to both the mean field and wave propagation direction and 20 percent of a slab component with fluctuations perpendicular to the mean field but with wave propagation along the mean field. As derived by Le Roux, Zank & Ptuskin (1999), this composite field model yields a parallel diffusion mean free path where the dependence on the ratio r_g/λ_{sl} is specified

$$\lambda_{||} = 2.433 \frac{B^2}{b_{x,sl}^2} \left(\frac{P}{cB} \right)^{1/3} \lambda_{sl}^{2/3} \left[0.0972 \left(\frac{r_g}{\lambda_{sl}} \right)^{5/3} + 1 \right], \quad (1)$$

where P is particle rigidity, B is the mean field, $b_{x,sl}$ is the x -component of the slab field fluctuations, λ_{sl} is the correlation length of the fluctuations, which are assumed to be valid for all components and r_g is the particle gyroradius. Pei et al. (2010) employ a very similar result to model the parallel diffusion coefficient throughout the heliosphere.

For the perpendicular diffusion coefficient, we follow the Le Roux et al. (1999) non-perturbative approach where

$$D_{sl} = \frac{1}{2} \lambda_{sl} A_{sl}^2; \quad D_{2D} = \lambda_{2D} A_{2D}. \quad (2)$$

Here, D_{sl} describes the magnetic field wandering due to slab turbulence with the x -component $A_{sl} = b_{x,sl}/B$ and with a corresponding correlation length λ_{sl} . D_{2D} denotes the magnetic field line wandering for 2D fluctuations. A_{2D} is the amplitude for this turbulence and λ_{2D} is the corresponding correlation length perpendicular to background field.

If the contribution of the 2D fluctuations is ignored, the perpendicular diffusion coefficient becomes the expression given in Jokipii (1971) as written by Le Roux et al. (1999)

$$K_{\perp} = \frac{v}{4} \lambda_{sl} A_{sl}^2, \quad (3)$$

where v is particle velocity. Le Roux et al. (1999) also propose a modified quasi-linear model with A_{sl} in the above equation replaced by the total amplitude of the turbulence. If however, 2D turbulence dominates, we find from Le Roux et al. (1999) the modified value

$$K_{\perp,2D} = \frac{1}{2} v \lambda_{2D} A_{2D}. \quad (4)$$

Le Roux et al. (1999) also consider the model of Chuvilgin & Ptuskin (1993) for a set of relatively weak, isotropic linear waves taking into account resonant and non-resonant interactions. Compound diffusion which is the result of the divergence of initially close random, static lines is included. Le Roux et al. (1999) use

$$K_{\perp} = 0.5 A^2 K_{||}, \quad (5)$$

where A is the total fractional deviation in the field. In fact the expression applies to the magnetosonic mode but we will neglect a relatively unimportant adjustment by a factor 0.54 applying to the Alfvén mode and wave amplitudes assumed here.

In the following section, it will become apparent that the simple, Jokipii (1971) expression is more likely to satisfy the proposed

Table 3. Parallel and perpendicular diffusion coefficients and mean free paths derived from Table 2 data for 200 MeV protons with $\lambda_{sl} = 1.7$ au.

Period	DOY 150–171	DOY 176–202	DOY 204–238
$K_{ }$ au ² s ^{−1}	7.42×10^{-3}	1.3×10^{-2}	8.01×10^{-3}
$\lambda_{ }$ au	19.6	34.3	21.2
$K_{\perp}$ au ² s ^{−1}	3.66×10^{-5}	1.7×10^{-5}	3.17×10^{-5}
$\lambda_{\perp}$ au	9.7×10^{-2}	4.49×10^{-2}	8.4×10^{-2}

modulation model. In Table 3, values of parallel diffusion coefficients and mean free paths are calculated from the data of Table 2, using the Le Roux et al. (1999) expression, equation (1), while perpendicular diffusion coefficients and mean free paths are obtained from the same data using the Jokipii (1971) expression (3). To estimate the power in the slab component, i.e. that due to wave propagation along the mean field direction, it is assumed that the dominant fluctuation power is transverse. To first order, for field standard deviation sd,

$$\frac{sd}{B} = \frac{1}{2} \frac{\delta B_{\perp}^2}{B^2}, \quad (6)$$

and if only 20 percent of the standard deviation results from the slab-like fluctuations, then as applied in equation (3)

$$A_{sl} = 0.2 \frac{\delta B_{\perp}^2}{B^2}. \quad (7)$$

A second estimate of the relevant value of the correlation length arises if we note that theoretical estimates of the perpendicular diffusion length arise under the assumption that the particle guiding centre follows field lines so that the general non-linear theory involves an integral over time involving the field correlation function of the form $\int_{-\infty}^{\infty} R_{xx}(y, t') P(y|t') dt'$ where $P(y|t')$ is a probability density for particle displacement (Matthaeus et al. 2003). The correlation function in turn is represented by a power spectrum whose amplitude is fixed by the power at frequencies below the reciprocal of $\lambda_{sl,2D}$. Expressions (3), (4) and (5) represent approximations to the general diffusion tensor considered by Pei et al. (2010). The domain of application of this perturbative approach is clearly limited by the sector structure since field lines are mainly confined by these large-scale neutral sheets. It is therefore not valid to include the contribution to the power spectrum from the sector structure at larger scales. Typically, the sector structure is 34 d wide at 120 au, so that depending on the wind speed which is variously estimated between 35 and 79 km s^{−1}, the sectors appear 0.65–1.95 au apart. The latter estimate is similar to that derived from the Burlaga & Ness (2010) power spectrum. Since the standard deviations of the field values given in Table 2 were derived for intervals of less than 35 d and subject to selection according to the sign of the sector field, they already exclude the contribution from the large-scale polarity changes. In view of the lack of data points, a simple estimate of the correlation length relevant within a sector is obtained by using $\int_0^{f_c} P(f) df \approx (sd(f_c))^2$, where the power spectrum $P \propto f^{-1.67}$ is assumed. This procedure yields an average correlation frequency of 2.28 d^{−1} for the three sector periods. Using the previous wind speed values, a correlation length ranging from 8.8×10^{-3} to 2×10^{-2} au is obtained. Note the similarity of these values of λ_{sl} to those found within the inner heliosphere, a result more in accord with the predictions of Le Roux et al. (1999) who suggest a slight fall in value with distance than with those of Pei et al. (2010) who suggest an order of magnitude increase. Table 4 employs the lower of these values to yield reasonable lower limits to the mean free paths.

Table 4. Parallel and perpendicular diffusion coefficients and mean free paths derived from Table 2 data for 200 MeV protons with $\lambda_{sl} = 8.8 \times 10^{-3}$ au.

Period	DOY 150–171	DOY 176–202	DOY 204–238
$K_{ } \text{ au}^2 \text{ s}^{-1}$	2.22×10^{-4}	3.38×10^{-4}	2.38×10^{-4}
$\lambda_{ } \text{ au}$	0.585	1.025	0.632
$K_{\perp} \text{ au}^2 \text{ s}^{-1}$	1.91×10^{-7}	8.77×10^{-8}	1.63×10^{-7}
$\lambda_{\perp} \text{ au}$	5.04×10^{-4}	2.3×10^{-4}	4.33×10^{-4}

Using the 2D turbulence model as expressed by Le Roux et al. (1999), we obtain $K_{\perp,2D} = 6.62 \times 10^{-4} \text{ au}^2 \text{ s}^{-1}$ and $\lambda_{\perp,2D} = 1.75 \text{ au}$ for mean parameters of Table 3. The Chuvilgin & Ptuskin (1993) expression yields $K_{\perp,2D} = 2.79 \times 10^{-3} \text{ au}^2 \text{ s}^{-1}$ and $\lambda_{\perp,2D} = 7.5 \text{ au}$. With the mean parameters of Table 4, we obtain with the Le Roux et al. (1999) model, $K_{\perp,2D} = 3.43 \times 10^{-6} \text{ au}^2 \text{ s}^{-1}$ and $\lambda_{\perp,2D} = 9.05 \times 10^{-3} \text{ au}$. For the Chuvilgin & Ptuskin (1993) model, $\lambda_{\perp,2D} = 0.439 \text{ au}$.

Pei et al. (2010) provide a comprehensive theoretical computation of the perpendicular mean free path out to 100 au based upon non-linear guiding centre theory models of the field fluctuations ranging from undriven turbulence, through stream and pick-up ion-driven turbulence to fully driven turbulence. At 100 au, they find 100 MeV particles have $\lambda_{\perp,2D}$, almost independent of rigidity and ranging from 5×10^{-4} to $3 \times 10^{-2} \text{ au}$. These values are based on extrapolation of inner heliosphere conditions, unlike all the above estimates which employ heliosheath measurements. A range of intermediate models lying between the extremes of equations (3) and (5) may be found in the work of Shalchi et al. (2012). Recent studies yielding reduced values for the drift diffusion coefficient as compared with guiding centre theory include those by Engelbrecht & Burger (2013) and Tantz & Shalchi (2012). Suggestion that drift can be diffusive is made by Florinski et al. (2012) while a suggested requirement for a very low value of the perpendicular diffusion coefficient is found in Guo & Florinski (2014).

4 A TRANSIENT 3D MODULATION APPROXIMATION

In the first model of the approximation of this section, the aim is to attempt to explain the observed large radial gradients near the heliopause in terms of transient radial velocities and diffusion parameters which seem to be possible according to the limited plasma information available. The argument could be reversed to make use of the cosmic ray data to suggest necessary values for the plasma parameters. No attempt will be made to provide a 3D modulation solution encompassing a large heliospherical volume. Instead, a Cartesian geometry is adopted to describe a limited region close to the heliopause, rather than spherical polar coordinates which are better as a basis for overall heliospheric modulation modelling. It is envisaged that there exists a region of plasma moving outwards with a speed considerably greater than that given by the steady-state model. The positions of maximum, transient outward flow in general lie within the outer magnetosheath and do not encompass the instantaneous heliopause boundary, except at onset of the event. A quasi-steady state will be assumed, as has been applied previously to the modelling of short-term changes in the inner heliosphere where field structure, convected past the observer, carries a particle distribution which only changes slowly in time (e.g. Quenby et al. 2008; Mulligan et al. 2009). We further justify this simplification by noting that in the time to achieve anisotropy, $\lambda_{||}/v$, for

200 MeV particles, the intensity would change by only 0.002 of the total magnitude of the decrease for day 240 event if $\lambda_{||} = 0.75 \text{ au}$. Even at the less likely value of $\lambda_{||} = 25 \text{ au}$, this change is 0.07 of the decrease magnitude. Moreover, the experimental data from the LECP *Voyager 1* detector shows no evidence of anisotropies greater than 5 per cent throughout the heliopause crossing region (Krimigis et al. 2013) with an upper limit < 2.5 per cent within the heliopause. Hence large, unbalanced energetic particle flows seem unlikely.

Jokipii (1971) sets out the manner in which a diffusion equation approximation to a Fokker–Planck equation description of interplanetary energetic particle transport is obtained. Rapid scattering in pitch angle space to achieve both cylindrical symmetry and near isotropy is required to employ the diffusion coefficients reviewed in the previous section. Note the expression for $K_{||}$ includes variable ratios of (r_g/λ_{sl}) . We have already discussed various evidence for near isotropy and reinforce the argument by noting that with the adopted parameters the ratio of diffusive or convective current to current of an isotropic particle distribution, $4CVU/Uv \sim 3 \times 10^{-3}$, where the symbols are defined in the following. While the original Fokker–Planck includes both energy gain and loss, we justify only including the energy loss term in a fluctuating solar wind by comparing the likely magnitude of Fermi acceleration with the adiabatic loss term which must be included. The ratio M of Fermi to adiabatic terms if δV is the average fluctuation is

$$M = \left[\frac{8}{3} \left(\frac{\delta V}{c} \right)^2 \frac{1}{\lambda_{||}} (p^2 c^2 + m_0^2 c^4)^{0.5} \right] / \left[\frac{2}{3} \frac{\delta V}{r} p \right] \quad (8)$$

for momentum p at radial position r from the Sun. Even with $\delta V = 30 \text{ km s}^{-1}$ and $\lambda_{||} = 0.75 \text{ au}$, $M \sim 0.05$ and hence it is valid to neglect acceleration.

Setting $\mathbf{x}$ in the radial direction $\mathbf{y}$ in the azimuthal direction and $\mathbf{z}$ to complete the right-handed set, the diffusion equation approximation in the Sun's reference frame for the differential number density $U(\mathbf{r}, t)$ is (e.g. Quenby (1984)).

$$\frac{\partial U}{\partial t} + \nabla S + \frac{\partial}{\partial T} \left(\frac{dT}{dt} \right) U = 0, \quad (9)$$

where the streaming is

$$S = CVU - \mathbf{K} \cdot \nabla U \quad (10)$$

and the Sun frame kinetic energy, T , loss rate is

$$\frac{dT}{dt} = \mathbf{V} \cdot \nabla \left(\frac{\alpha T U}{3} \right), \quad (11)$$

where $\alpha = (T + 2m_0)/(T + m_0)$. m_0 is rest mass and the Compton Getting factor C is

$$C = \left(1 - \frac{1}{3U} \frac{\partial}{\partial T} \alpha T U \right). \quad (12)$$

The slopes of the energy spectrum and α are assumed to be constant over the limited region of application of the above diffusion equation, thus both C and the pressure term in the expression for kinetic energy T are independent of position. The spectral slopes at 200 MeV for protons and 10 MeV for electrons are obtained from Stone et al. (2005). Resolving components, we notice that perpendicular diffusion applies in the x - and z -directions while parallel diffusion applies in the y -direction. We also allow the transverse diffusion coefficient to yield a drift velocity $V_{d,z}$ in the direction perpendicular to the plane of the spacecrafts orbit due to the large-scale Parker field structure and a possible drift $V_{d,x}$ due to a field gradient in the z -direction arising from lack of symmetry about the equatorial plane. Note that the Burlaga & Ness (2014) data in the

heliosheath region considered show average field directions close to 90° and 270° . The steady-state diffusion equation becomes

$$K_\perp \frac{\partial^2 U}{\partial x^2} - (CV_x + V_{d,x}) \frac{\partial U}{\partial x} + K_\parallel \frac{\partial^2 U}{\partial y^2} - CV_y \frac{\partial U}{\partial y} + K_\perp \frac{\partial^2 U}{\partial z^2} - (CV_z + V_{d,z}) \frac{\partial U}{\partial z} = 0. \quad (13)$$

Spatial variation in V and K are neglected. First, this is because the solution to equation (13) will only be applied to conditions within about 4 d containing the period of maximum spatial intensity gradient within the travelling disturbance. Secondly, the calculations of the diffusion coefficients employing measured field deviations reveal no correlation between particle intensity and diffusion coefficient magnitude in the period day 150 to day 238. Hence another cause for the step-like modulation must be sought. Note that despite a field magnitude gradient ~ 100 per cent au^{-1} , the diffusion coefficients do not vary by more than a factor 2, suggesting that the conditions under which the diffusion equation approximation was obtained are not violated. Energy-dependent variations in v and C are neglected over the region considered. These assumptions are justified using the modulation potential approximation to the modulation in the step increase which amounts to about 40 MV. Then the total change through the step in v would be by 0.6 per cent and in C would be by 7 per cent. Error in the force-field approximation to the total modulation in a step seems to be limited to about 13 per cent according to the fit shown to this model in Webber & Quenby (2015) and thus the above estimate of energy loss seems reasonable. Specifying U_0 as the differential number density at the origin of coordinates, that is at the bottom of the region of sudden intensity increase, the exact, separable solution is

$$U = U_0 \exp \left(\frac{(CV_x + V_{d,x})x}{K_\perp} + \frac{CV_y y}{K_\parallel} + \frac{(CV_z + V_{d,z})z}{K_\perp} \right). \quad (14)$$

This solution neglects any spatial cross-correlations $K, V(x_{i,j})$ of the plasma-related parameters within the assumed region of partial evacuation of particles inside the travelling plasma ‘pulse’, our heliosheath analogue of the region of a Forbush decrease. Gradients along a boundary of the ‘pulse’ in any particular direction need to be small relative to gradients within the pulse in that direction. The solution represents the initial, outward rise in intensity. U_0 is determined by the boundary conditions on the plasma pulse. We do not expect the solution to apply on the boundaries of the pulse where a steady-state cannot be assumed.

The whole point of the proposed model is that any residual modulation in the radial direction outside the region of transient changes must be relatively small because of the lack of significant contribution to outward particle bulk motion and hence any extra investigation of the diffusion equation over regions outside the plasma pulse will add little insight at this stage. *Voyager* data and a 3D simulation for a steady-state flow model (Strauss et al. 2013) are both consistent with radial gradients at 100–200 MeV proton energies ~ 2 per cent au^{-1} in the outer heliosheath. Since the model considered here deals with x -directed gradients ~ 50 per cent au^{-1} , the effects of neglecting spatial variation outside the plasma pulse would not seem to be great. It is however, necessary to assume azimuthal particle currents are not dominant in the solution, in order to prevent in-filling from the sides of the plasma pulse. An argument is that the scale of any steady-state particle gradients must be > 1000 au, that is the distance downwind along the wound spirals till the interplanetary medium is reached, rather than < 1 au, the radial distance to the boundary. The condition that the ratio

of diffusion current perpendicular to $\mathbf{B}$ to current parallel to $\mathbf{B}$ is $K_\perp \text{grad}_\perp U / K_\parallel \text{grad}_\parallel U > 1$ is satisfied. As the postulated plasma pulse propagates in azimuth as a bend in the field lines, there would be some additional contribution to the step-like modulation. However, this effect would be reduced by a factor $\cos^2 \psi$ with respect to the effect of the radial propagation of the pulse where ψ is the angle between the field and the radial direction. This is because the perpendicular diffusion current must be resolved in the azimuthal direction to oppose the plasma flow in this direction. This azimuthal increase in the modulated region however increases the azimuthal gradient driving parallel diffusion. A mainly radially moving plasma pulse would be subject to leakage into the evacuated volume due to parallel diffusion via field lines connected to the surrounding region of higher particle intensity, increasing azimuthal gradients. If the pulse geometry is the only reason for such an increase, to prevent particles refilling the evacuated volume within $\tau_r = 4$ d it would need a volume radius r_r of 19 au, if we use $r_r = [K_\parallel \tau_r]^{0.5}$ and the Table 4 diffusion coefficient value. More attractively, we can consider two geometries where perpendicular diffusion dominates infilling. If the plasma pulse took on the magnetic topology of a flux rope, there is inner heliosphere evidence that in such a travelling disturbance associated with a Forbush event, the dominant diffusion process was perpendicular (Quenby et al. 2013). Alternatively, the pulse region might be a growing O-shaped reconnection region due to boundary instability similar to those described by Swisdak, Drake & Opher (2013). When only perpendicular diffusive leakage occurs an evacuation volume dimension $r_r \sim 1$ au would suffice.

The work described is not attempting a complete 3D solution, especially as the plasma parameters along the three directions are poorly known. Rather we point out the expected result that a local radial, x , directed gradient requires a matching radial, outward directed flow. (A small additional effect due to an azimuthally directed variation in azimuthal flow can presumably be an independent source of flux balance.) In the absence of a suitable drift velocity, such a flow does not exist, close to the heliopause in the time-independent heliosphere model of Opher et al. (2012). Therefore, radial gradients close to this boundary may require transient radial flows.

We first explore a ‘drift-free’ model. To obtain modulation below the GCR level near the heliopause, sudden bursts of radial plasma velocity need to appear sufficiently frequently so there is always one event within about 1 au of the boundary if the series of steep depressions shown in fig. 1 of Webber & McDonald (2013) are to be explained. It is within this region that the intensity switches from near the GCR level to a modulated level. Any lesser occurrence frequency would mean a further encroachment of the GCR level within the heliosheath.

As source of the transient radial plasma flows, it could be that the radial plasma flow is triggered by the flow required by Quenby & Webber (2013) who suggested that the heliopause flapped with the speed of the fast mode, here identified as the sound speed in the hot solar wind plasma. The flapping could be caused by pressure imbalance with the external medium as the solar wind plasma pressure varies. Mass flow across the heliopause is not implied here. Other models of boundary turbulence which might cause transient flow in the outer heliosheath are the reconnection models of Strumik et al. (2013) or Swisdak et al. (2013) and the instability model of Borovikov, Pogorelov & Ebert (2012). It should be emphasized we postulate that the plasma pulse represents a region of active plasma and field redistribution which is sequentially experienced deeper and deeper within the magnetosheath. It cannot occur

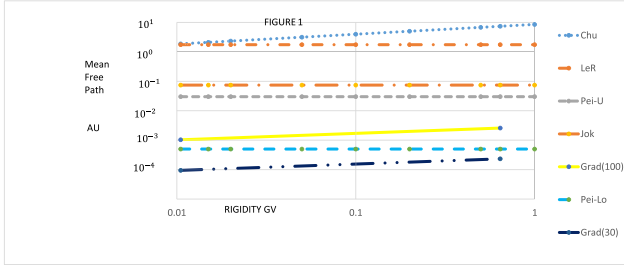


Figure 1. Perpendicular diffusion mean free path estimated from the transient model. Either radial wind velocities of 30 or 100 km s^{−1} are used with DOY 240 data and plotted versus particle rigidity. Various theoretical estimates of the mean free path obtained from the data of Table 3 are also shown. The line types are referred to abbreviations in the text as follows: Chu (dotted), LeR (short dash–dotted), Pei-U (short dashed), grad(100) (continuous), Pei-Lo (long dashed), Jok (long dash–dotted), grad(30) (dash–double dot).

instantaneously at all depths where the previous equilibrium is to be disturbed. Thus the region of cosmic ray depletion associated with local extra radial plasma flow is not in contact with the heliopause except at the onset of the event.

In order to see if the diffusion and flow parameters discussed in Sections 2 and 3 can satisfy the observed gradient employing the transient modulation model, we find the following equation for the radial cosmic ray gradient from the adopted solution for both 10 MeV electrons and 200 MeV protons since by a numerical coincidence, $C = 1.1$ is the same for these species at the energies measured,

$$K_{\perp} \frac{\partial U}{\partial x} = 1.15 V_x + V_{d,x}. \quad (15)$$

On DOY 240, 2012, $\frac{\partial U}{\partial t_s} = 0.032 \text{ d}^{-1}$ (protons) is the rate of intensity change in the reference frame of V1. In the adopted model DOY 240 is regarded as corresponding to the end of a field structure convected past V1 as the heliopause expands. The gradient then refers to the entry of particles into the region of reduced intensity by diffusion in competition with the wind outward sweeping. Since the measurement of the actual spatial gradient is determined by the adopted radial wind speed, the above equation for 200 MeV protons can be written as

$$K_{\perp} = 1.39 \times 10^{-6} V_{x,100}^2 + 1.19 \times 10^{-6} V_{d,x,100} V_{x,100} \text{ au}^2 \text{ s}^{-1}, \quad (16)$$

where $V_{x,100}$ and $V_{d,x,100}$ are, respectively, the radial and drift velocities in units of 100 km s^{−1}. The fit of the diffusion equation approximate solution to data represented by various estimates of the diffusion coefficients is illustrated by plotting values of $\lambda_{\perp}$ obtained from equation (15) applied to 200 MeV protons and 10 MeV electrons, which incorporates the measured gradient, as a function of particle rigidity P neglecting the drift term on the right-hand side. Figs 1 and 2 illustrate the solution used.

Two values of radial wind velocity, 30 and 100 km s^{−1} are chosen and labelled grad(30) and grad(100), respectively. Theoretical estimates of $\lambda_{\perp}$ due to Chuvilgin & Ptuskin (1993), Le Roux et al. (1999), upper and lower bounds of Pei et al. (2010) and Jokipii (1971) are also plotted and labelled, respectively, Chu, LeR, Rei-Up, Pei-Lo and Jok. Fig. 1 shows these plots, being based upon a correlation length $\lambda_{sl} = 1.7 \text{ au}$ while Fig. 2 is labelled similarly and based upon $\lambda_{sl} = 8.8 \times 10^{-3} \text{ au}$. If the radial flow is $\sim 100 \text{ km s}^{-1}$, only the undriven turbulence or stream-driven turbulence models of Pei et al. (2010), i.e. the Pei-Lo curve value of $K_{\perp}$, seem to provide

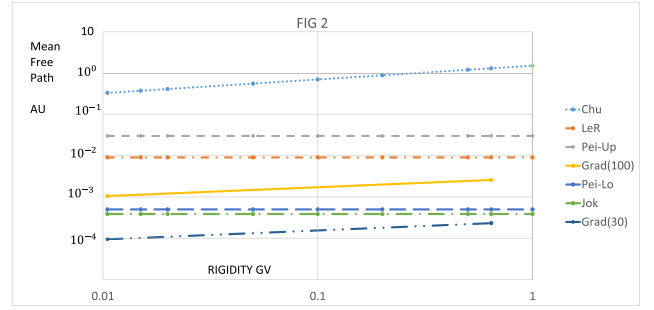


Figure 2. Perpendicular mean free path versus rigidity, as in Fig. 1 except data from Table 4 is used.

the order of magnitude obtained from the measured gradient. Suitable flow values are the sound speed estimated from post terminal shock conditions or the Opher et al. (2012) model which ignores the sector structure. However, this second, model estimate does not provide transient effects. In Fig. 2, it is seen that the Jokipii (1971) slab model provides a value well within the bounds of the two gradient based estimates of $K_{\perp}$. Therefore, according to equation (3), a dominant slab component could be possible, implying wave propagation mainly directed along the mean field. Models for $K_{\perp}$ which add 2D turbulence on to the slab turbulence field line wandering so as to yield the dominant effect are less likely to satisfy the cosmic ray data.

The average drift motion at the epoch of observation is northwards for positive charged particles in the northern solar hemisphere because the average solar field is inwards at the time. The drift magnitude V_d from guiding centre theory is

$$V_d = \frac{1}{\omega R} \frac{2}{3} v^2 = \frac{2vPc}{3BR}, \quad (17)$$

where ω is the cyclotron frequency, P the rigidity and R estimates both the field line radius of curvature and the fractional field gradient. Using the mean measured field at 120 au and assuming $R = 120 \text{ au}$, the northward drift speed $V_{d,z} = 54 \text{ km s}^{-1}$. However, transient changes show both a field line polarity switch and a field magnitude gradient which is positive in the outward direction (Burlaga et al. 2013), thus reinforcing the northward proton drift. Hence modulation can be enhanced in the northward direction, as compared with the solar wind sweeping.

For charge e , the field gradient and curvature drift are aligned in the $\frac{1}{e} \mathbf{B} \times \nabla B$ direction. Hence for protons, an episode of outward directed north hemisphere $\mathbf{B}$ together with a limited region of ∇B directed in the $-z$ direction produces an outward, x -directed drift. According to the Opher et al. (2012) model with the sector structure included, gradients $(\nabla B)/B \approx 0.018 \text{ au}^{-1}$ may exist in the southwards or $-z$ -direction on the edge of the sector region. This would lead to a radial drift of 115 km s^{-1} , outwards for outward north hemisphere field epochs. Neglecting for the moment the evidence provided by the electron modulation, one may develop the idea of a drift-dominated flow. Burlaga et al. (2013) observed an unexpected field increase close to the heliopause. Averaging over a time period equivalent to a distance scale of 6 cyclotron radii for a 200 MeV proton, a field gradient $(\delta B)/B \approx 0.78 \text{ au}^{-1}$ is obtained. If this also occurred in the $-z$ -direction, perhaps as a transient effect, a radial drift of 4900 km s^{-1} would be possible. The effect of adding these various values of outward radial drifts on the required value of $K_{\perp}$ can be seen by employing equation (15). As before, it is assumed that the end of the passage of a field structure on DOY 240 is being considered. Additionally, a typical plasma

motion $\sim 100 \text{ km s}^{-1}$ is used in order to estimate the spatial gradient. We find $K_{\perp} = 6.3 \times 10^{-5} \text{ au}^2 \text{ s}^{-1}$ is allowed if the field gradient is 0.78 au^{-1} directed southwards. However, from the equation for the drift speed, it is found that electrons of 10 MV rigidity drift two orders of magnitude slower than 200 MeV protons and are therefore relatively insensitive to field gradient effects. Since the electron modulation is greater than that of protons, it is very unlikely that drift can dominate the modulation near the heliopause. This is because the electron scattering mean free path at 10 MV is unlikely to show a large reduction compared with that of a 200 MeV proton. In any case, there still seems to be shortfall by a factor near 10 as compared with the estimated 2D turbulence model for perpendicular diffusion. It is perhaps significant that two periods of large radial gradient seen by Webber & McDonald (2013) centred on DOY 128 and 209 are in periods of outward pointing field.

Turning to the GCR sudden increase starting on day 128, the lack of detailed correlation with change in magnetic field amplitude led Webber & Quenby (2015) to suggest that the cause lies in structure $\sim 1 \text{ au}$ in extent. On the basis of the model provided here, the necessary sudden, radial increase in solar wind plasma velocity, together perhaps with an outward, radial particle drift speed, must have occurred between V1 and the heliopause and not at the location of V1. In fact, since the major plasma flow is expected to be northwards out of the ecliptic plane this close to the heliopause, there is no necessity for V1 to see the plasma changes responsible for the sudden increase being convected past the spacecraft prior to the event. For our model to explain the day 128 increase, we have two requirements. The first is that the northward plasma flow brings a large plasma pressure increase causing rapid outward expansion at the heliopause with or without a suitable $-z$ -directed field gradient to allow enough outward GCR motion to counter inward diffusion. The second requirement is that the scale size of the changes to the plasma parameters close or at the heliopause provide a depletion region of GCR intensity where particle leakage from the y, z directions is slower than the current due to the outward convection or drift velocities. If our model is reasonable, the occurrence of the day 128 increase is both evidence for dramatic movement at or within 1 au of the heliopause and of a scale size of the movement in directions parallel to the heliopause of several au.

5 MEAN FREE PATH RIGIDITY DEPENDENCE

To discuss the rigidity dependence of the modulation, we simply consider the local values of the intensity gradients during the increases. This however limits the discussion to the relative changes in electron and proton intensity each at a specific energy, these being the species for which we have some detailed information.

From equation (15), the ratio electron to proton gradients in the x -direction if $V_x \gg V_{d,x}$ is

$$\frac{1}{U_e(P_e)} \frac{\partial U(P_e)}{\partial x} \bigg/ \frac{1}{U_p(P_p)} \frac{\partial U(P_p)}{\partial x} = \frac{K_{\perp,p}(P_p)}{K_{\perp,e}(P_e)} = \frac{\beta_p \lambda_{\perp,p}(P_p)}{\beta_e \lambda_{\perp,e}(P_e)}, \quad (18)$$

where P_e, P_p and β_e, β_p are the magnetic rigidities and velocities of the electron and protons observed. From fig. 2 of Webber & Quenby (2015), the ratio of the fractional electron to proton intensity change measured at the step change around day 240, 2012 is 2.6. Taking the electron mean energy as 10 MeV and the protons as corresponding to 200 MeV, a mean free path dependence $\lambda_{\perp} \propto P^{0.4}$ is required to fit the diffusion of both species if the day 240 change represents the ratio of electron-to-proton intensity gradients. For the day 128 step,

the gradient ratio is 1.6 and the exponent of the rigidity dependence is 0.29. This fit favours the rigidity dependence of equation (5) if equation (1) is used to define $K_{\perp}$. However, the absolute value of the perpendicular diffusion coefficient is still an order of magnitude too large to balance the expected transient convective radial flow if the Table 4 parameters are adopted.

A drift-dominated model seems excluded by the relative size of the electron to proton step changes and therefore cannot be used to discuss the mean free path rigidity dependence. As a conclusion to this section it seems that none of the expressions for the perpendicular diffusion coefficient discussed simultaneously satisfy both the absolute magnitude and rigidity dependence implied on either of the two transient modulation models suggested. A small addition to the Jokipii (1971), equation (3), dependent on a $\lambda_{\perp} \propto P^{1/3}$ due to non-resonant interactions would seem to provide the closest overall fit.

6 CONCLUSIONS

In the attempt to explain the unexpectedly large radial cosmic ray gradients observed around 120 au an appeal has been made to the possible existence of transient outward plasma flows, approaching the sound speed in the heliosheath. Interpreting the available magnetometer data to yield a suitable value of the perpendicular diffusion coefficient, it is better to employ a model of scattering dependent only on 20 per cent of the measured fluctuation power. This power would constitute the percentage present in waves propagating along the magnetic field direction. However, a greater percentage of slab power is not excluded. A closed field configuration for the perturbed flow region would be the most favourable case. The resulting modulation model is similar to that expected from a succession of Forbush Decreases in the inner Heliosphere. Field gradient particle drift effects can also play a role in modulation near the heliopause. If these are sufficiently large, additional diffusion based upon 2D turbulent fields may explain the rigidity dependence of the modulation. Transient changes in radial plasma speed or field gradient necessary to cause the observed sudden GCR intensity changes do not necessarily need to be located at the spacecraft but may alternatively occur between the spacecraft and the heliopause. However, although we believe it worthwhile discussing the two transient modulation models we provide, problems arise in satisfying the observed rigidity dependence of the modulation in terms of available models and data relating to diffusion in the heliosheath. Further information on the relevant plasma parameters, especially transient effects, at 120 au is required to determine whether either of the proposed models will remain successful. Also further elucidation of the relation of magnetic field turbulence to the actual cosmic ray diffusion perpendicular to the mean field seems required.

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