The Structure Of The Heliopause

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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 the shock accelerated anomalous component of cosmic rays in the MeV energy range. The sudden disappearance of this component at 121.7 AU from the sun is discussed in terms of three models for the transition into the interstellar plasma flow. Particles trapped flowing parallel to the boundary may penetrate up to one Larmor radius beyond. If the boundary is stationary, Voyager 1 directly samples this distance. The boundary could flap, depending on Heliosheath pressure changes and Voyager 1 then samples the extent of this motion. Finally, a turbulent boundary layer is considered in which the MeV particle distribution falls off with distance thus measuring diffusion within the layer.

Key words: –cosmic rays – solar wind–heliosphere–ISM–magnetic field–diffusion

1 INTRODUCTION

Models and observations related to the interaction of the interstellar medium (ISM) with the heliosphere identify a solar wind terminal shock and a Heliosheath, perhaps comprising a low latitude region where the magnetic structure is determined by reconnection and a high latitude region where field lines connect back to the solar wind (Opher et al. 2012). No interstellar bow shock is expected (McComas et al. 2012) but the external field pressure causes asymmetry in the terminal shock (Opher et al. 2006) and may also explain intermittent observation of shock accelerated cosmic rays (Jokipii et al. 2004, Stone et al. 2005) prior to the terminal shock crossing. Since early models of heliosheath modulation (Potgieter and le Roux 1989, Quenby et al. 1990), it has been assumed that the Heliopause represented the boundary beyond which the interstellar cosmic ray intensity would be encountered (see review by Potgieter (2008)). Strauss et al. (2013) have recently questioned this assumption and mention various possibilities of increased particle scattering as the interstellar field wraps around the Heliopause. The propagation of the anomalous component, believed to be accelerated at the terminal shock, across the heliosheath and into the interstellar medium has been discussed by Scherer et al. (2008)

The dramatic Voyager 1 observation of the sudden and sustained disappearance of the anomalous component at 121.7 AU (Webber and McDonald, 2013a) affords an opportunity to explore the properties of the Heliopause boundary. It is the purpose of this note to provide some simple alternative models for the structure of this boundary especially in terms of it’s effect on low energy anomalous component cosmic rays. Either the boundary is stationary during Voyager 1 passage, or it flaps significantly and in addition there is possibly a finite width particle diffusing layer.

2 VOYAGER DATA

The starting point in this note lies in data obtained by Webber and McDonald (2013a) from the Voyager 1 CRS instrument (Stone et al. 1977). We concentrate on the period of the final drop of the 2-10 MeV proton intensity to ~ 0.2 – 0.3 % of the values seen previously in the Heliosheath. The drop started on 2012.65 and lasted for about 8 weeks (weeks 33-41 of the year) with the spacecraft moving 0.07 AU per week. Because there had been two previous intensity drops, Webber and McDonald (2013a) suggest an interpretation in terms of a pulsating boundary repeatedly crossing Voyager 1. A previous peak in galactic cosmic ray intensity suggests an effective region of enhanced modulation at the Heliopause. Beyond the drop, the anomalous component is thought to have disappeared and intensities close to true interstellar conditions reached. At the lowest energy detected, the > 0.5 MeV channel, the

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fastest rate of decrease represents an e-folding distance $\sim 0.01$ AU assuming a stationary boundary. However, since differentiation between various models is helped by looking at the rigidity dependence of the effect, the decrease is studied between weeks 34 and 35 of 2012 where the final drop-off can be followed up to 40 MeV in a proton channel. Table 1 uses the data from figure 2, Webber and McDonald (2013a) to find the observed fractional intensity change $\Delta N/N$ per 0.1 AU at mean energies of 6 MeV and 25 MeV, using data from weeks 41-45 as an interstellar background level. A stationary boundary is assumed.

| Energy (MeV) | $\Delta N/N$ per 0.1 AU | Larmor Radius (AU) |
|-------------|-------------------------|-------------------|
| 6           | 0.73                    | 0.006             |
| 25          | 0.72                    | 0.016             |

3 DISCUSSION OF BOUNDARY MODELS

The published Opher et al. (2006) hydro-magnetic model for the draping of the interstellar magnetic field over the Heliosphere shows a 30$^\circ$ angle between field and heliopause at the Voyager trajectory some 10 AU or more from this boundary, as seen projected in the meridian plane. However by analogy with the Magnetosphere, a tangential discontinuity between ISM flow and Heliosheath flow, which has been deflected along the boundary, is possible. (See also Gurnett et al. (2006)) In this case, magnetic fields parallel to the boundary on both sides can occur. In the ISM field $B$ is pointing in the negative y and z directions where $z$ is solar rotational axis, $x$ in the interstellar velocity direction and $y$ completing the right handed coordinate system. Since the Heliosheath region field is mainly azimuthal and inward pointing in the Northern hemisphere, a tangential discontinuity is likely. If, however, there are fluctuations causing oppositely directed field components, either side, as is suggested by the outward pointing boundary heliosheath field reported by Burlaga et al. (2013), reconnection may take place allowing the post boundary field to be at some angle $\alpha$ to the boundary. Other ways in which field lines cross the boundary are if waves described by rotational discontinuities are present each side or if the boundary is simply a contact discontinuity where the plasmas on each side have no relative motion. Hence there are several possibilities for the lack of large changes in the magnetic field vector as Voyager crosses the Heliosheath. Clearly the anomalous component protons are following field lines and if there is a tangential discontinuity, they can run along the boundary just penetrating one Larmor radius, $\rho$, into the ISM. Hence the radial distribution at the boundary would reflect the pitch angle distribution, presumably isotropic within the Heliosheath. If however field lines cross the boundary, there will be a forward cone where particles immediately escape into the ISM resulting in a small observable intensity and a region of pitch angle space where re-entry into the Heliosheath occurs and the penetration region of pitch dependent intensity is limited to $pcos\alpha$. Using the Opher et al. (2012) field model value at the Voyager 1 crossing point of 3.8$\mu$G, Table 1 lists the ISM values of $\rho$ at the two energies considered. Note the recently published Voyager 1 field values just beyond the apparent crossing point are close to our assumed value although there is doubt as to whether they represent an extension of local heliosheath conditions or those farther out in the interstellar medium flow (Burlaga et al. 2013). The expected increase of penetration distance with energy predicted by the stationary boundary model is not borne out by the data, neither is the observed gradient large enough to match the estimated Larmor radii which set the distance scale. Anisotropy data relating to a pitch angle distribution is not presented in Webber and McDonald (2013a), but anisotropy is seen in an equivalent energy range by the LEPC instrument.(Krimigis et al., 2013)

The observation of three apparent crossings into the ISM suggests boundary motion should be considered when evaluating the anomalous component gradient. Pressure balance across the Heliopause must depend mainly on the near isotropic Heliosheath plasma pressure due to the low energy particles and magnetic field, rather than the ram pressure of the wind which according to modelling and some observation, (Krimigis et al., 2011), is directed nearly parallel to the boundary. Voyager 2 heliosheath data yield daily changes in total pressure of up to 50% (Burlaga et al. 2009). The information that a particular Heliopause equilibrium position can no longer be maintained by the isotropic plasma pressure can only propagate at the speed of the fastest wave mode in the subsonic region. Using the post-shock Mach number given in the Heliosheath by Borovikov et al. (2011) on the Voyager 1 trajectory, $M=0.58$, we obtain a fast mode speed of 228 km/s for the possible collapse rate of the boundary. Table 2 then re-estimates the anomalous component gradients assuming the boundary scans across the effectively stationary spacecraft. Now the observed region of significant intensity change extends over $\sim 1$ AU. Hence the anomalous component disappearance could be due to boundary jitter over 1 AU with an intrinsic boundary width of 0.01 AU, governed by Larmor motion of the Heliosheath trapped particles. Until unambiguous field and plasma flow data become available, the exact location and nature of the Heliopause is open to speculation. Here we now explore the possibility of a turbulent, particle diffusing region corresponding to the extent of the dramatic 1-40 MeV intensity reduction observed by V1. If the boundary moves it may be expected to drive HM waves into the nearby ISM with properties initially similar to those of the Heliosheath, before amplitude reduction due to divergence into the very large medium sets in.

To estimate possible values of the diffusion coefficients parallel and perpendicular to the mean field we will use a theoretical formulation which has achieved reasonable agreement with experimental results in the inner Heliosphere, but employing field data obtained far out in the Heliosheath. These
estimates are checked for consistency with modelling of low energy cosmic ray modulation in the Heliosheath. The waves in the field model are composed 80% of a 2-dimensional component with fluctuation vectors perpendicular to both the mean field and wave propagation direction and 20% of a slab component with fluctuations perpendicular to the mean field but with wave propagation along the mean field. As employed by Pei et al. (2010), this composite field model yields a parallel diffusion mean free path

$$\lambda_{\parallel} = \frac{3.13271}{B_{x,slab}} \frac{P}{cB} \left( \frac{\delta B}{4B^2} \right)^{2/3} \lambda_{slab} \times F$$  \hspace{1cm} (1)$$

where $P$ is particle rigidity, $B$ is the mean field, $b_{x,slab}$ is the slab component of field fluctuations, $\lambda_{slab}$ is the correlation length of the fluctuations, assumed valid for all components and $F$ is function very close to unity in the present application. Based upon a similar theoretical formulation, Nkosi et al. (2011) find that low energy electron modulation data are reasonably fitted by a perpendicular diffusion coefficient $K_{\perp} = a (\delta B/4B^2)^2 K_{||}$ \hspace{1cm} (2)

where the constant $a = 0.02$, $\delta B$ is now the total power in fluctuations and $K_{||}$ is the parallel diffusion coefficient obtained from the mean free path of equation (1). The most relevant field data is that obtained by Burlaga and Ness (2010) in the Heliosheath at 110 AU where the field standard deviation is 0.051 nT for a mean field of 0.08 nT. Bearing in mind the assumption that most fluctuation power is in a transverse component, we estimate

$$\frac{sd}{B^2} \approx \frac{\delta B^2}{4B^2}$$  \hspace{1cm} (3)$$

where $sd$ is the standard deviation of the one day Voyager 1 field magnitudes at 110 AU. An estimate for $\lambda_{slab}$ may be obtained from the break in the power spectrum given by Burlaga and Ness (2010) at $2 \times 10^{-7}$ Hz assuming the relative Voyager 1 plasma speed of 8 km s$^{-1}$ (Burlaga and Ness 2012). This approach yields $\lambda_{slab} = 0.27$ AU. Since the relative speed is uncertain, a second estimate comes from assigning the correlation length to the possible sector structure seen by Burlaga and Ness (2010), lasting for about 125 days when convected past Voyager 1. Their value would yield 1.4 AU. Hence using equations (1) and (2) we find Heliosheath values for $\lambda_{||} \approx 1 \rightarrow 3.1$ AU and $\lambda_{\perp} \approx 0.04 \rightarrow 0.124$ AU. Confirmation of this formulation comes from the work of Webber et al. (2013b) who fit the observed cosmic ray modulation beyond 105 AU with a spherically symmetric model approximation. The radial mean free path, which is clearly dominated by perpendicular diffusion, is 0.11 AU at 6 MeV for protons.

Anomalous protons escaping from the Heliopause due to random drift and resonance scattering processes will escape down ISM field lines in competition with perpendicular scattering outwards. Wind sweeping is slow. If the experimental gradient measures the trapping region as about 1 AU thick, we simply estimate the escape time down the field as equal to the perpendicular diffusion time over 1 AU. For motion over $d$, from

$$d = 2(Kt_{esc})^{0.5}$$  \hspace{1cm} (4)$$

we find $t_{esc} = 3 \rightarrow 8 \times 10^4$ s. In this time 6 MeV particles can go $5 \rightarrow 8$ AU along the ISM field. We would require the ISM field to be at a significant angle to the Heliopause for such a movement to be consistent with escape from the postulated turbulent layer.

In conclusion, from the discussion of possible boundary models, a moving boundary driven by changes in solar wind pressure is more likely than a stationary boundary scan by Voyager 1. The particle results available also seem compatible with the existence of turbulent regions at or beyond the Heliopause, of dimension 1 AU wide and up to 10 AU along the boundary, capable of partially trapping an escaping flux of anomalous component particles which are mainly constrained to motion parallel to and inside the Heliopause.

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