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Implications of fluctuations in the distribution functions of interstellar pick-up ions for the scattering of low rigidity particles

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Abstract. The distribution functions of interstellar pick-up hydrogen and helium exhibit fluctuations which are correlated. An analysis of these fluctuations reveals that they may be the result of variations in, and provide additional evidence for, large mean free paths for these low rigidity particles. An analysis of the properties of the distribution function of pick-up hydrogen reveals that these particles do suffer considerable adiabatic cooling, and that the likely cause for the long mean free path is the inability of the particles to scatter through 90° pitch angle.

Introduction

One of the enduring problems in heliospheric physics is the long mean free path of low-rigidity particles in the solar wind. Solar flare electrons with rigidities ≤ 10 MV are observed to have mean free paths of a sizable fraction of an AU, despite the prediction by quasilinear theory, and many of its non-linear extensions, that there is ample turbulence in the solar wind to generate much smaller mean free paths [e.g., *Bieber et al.*, 1994; *Palmer*, 1982]. An extreme example of this issue is interstellar pick-up ions (interstellar neutral particles which are ionized in the solar wind). These particles have rigidities of a few MV, comparable to those of very low energy electrons, and are observed by Gloeckler *et al.* [1995] to have mean free paths at high heliographic latitudes of order 1 AU. In this case, not only should ambient turbulence in the solar wind provide for more scattering, but also the distribution functions of these particles should be unstable immediately following their ionization, with the result that the particles generate their own turbulence and scattering [e.g., *Lee and Ip*, 1987].

In this paper we use the observed fluctuations and shapes of the distribution functions of pick-up ions to infer their scattering properties and behavior. The results are based on data obtained with the SWICS instrument [*Gloeckler, et al.*, 1992] on Ulysses. The pick-up ions were observed between January and December 1994. Ulysses was executing its high latitude pass over the south solar pole at this time, i.e. the data are all taken above ~ 45° S latitude, and at radial distances from 2.3-3.8 AU. The conditions were near solar minimum so that Ulysses was continuously in a high speed solar wind flow, with nearly constant speed of 780 km/s, from the polar coronal hole over the south pole of the Sun.

Fluctuations in the distributions

Shown in Figure 1 is a plot of the relative fluctuations in interstellar pick-up hydrogen vs. interstellar pick-up helium. The data are formed by integrating the observed distribution functions over time intervals of 48 hours between January and June 1994, and over a speed range of $1.6 \leq w \leq 2$, where $w = v/V$, the particle speed v divided by the solar wind speed V. The distribution functions have been detrended to remove

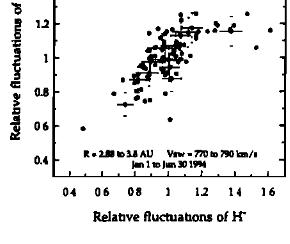

Figure 1. the relative fluctuations of interstellar pick-up hydrogen vs. interstellar pick-up helium. The data are formed by integrating over 48 hours and over the speed range $1.6 < w < 2$.

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long-term spatial variations, and are then divided by their mean value to form the relative fluctuations. Interstellar neutral particles are effectively at rest relative to the Sun; thus, when they are first ionized they have the velocity of the solar wind, in the frame of the solar wind. The particles then spiral about the heliospheric magnetic field, and, depending on their orientation relative to the solar wind flow vector, can have a speed in the spacecraft frame of $0 \leq w \leq 2$. For an integrating time of 48 hours, the distribution functions of interstellar ions can be observed, clearly distinguished from the more dominant solar wind particles, only in the speed range of $1.6 \leq w \leq 2$. To observe the pick-up ions at speeds below the peak of the solar wind distribution, much longer integration times are required, as was done by Gloeckler *et al.* [1995].

Clearly, there are considerable fluctuations in both the pick-up helium, by a factor of order 2, and the pick-up hydrogen, by a somewhat larger factor, and the two fluctuations are correlated; the correlation coefficient is ~ 0.7. The observations presented here at high latitudes are similar to those presented by Gloeckler *et al.* [1994] for low heliographic latitudes. There are large, correlated variations in the fluxes of interstellar hydrogen and helium, and as Gloeckler *et al.* [1994] noted, the variations do not correlate significantly with variations in the solar wind, and thus are likely to be caused by transport following their ionization.

It is important to note that the particles whose distribution functions vary in Figure 2 have speeds $1.6 \leq w \leq 2$, i.e. they have a component of their velocity in the solar wind frame that is aligned with the solar wind flow vector. They are moving away from the Sun in the solar wind frame. When interstellar particles are first ionized, they will move inward along the magnetic field towards the Sun in the solar wind frame. It is the scattering process which causes them to move outward in this frame. Clearly, then, the fluctuations seen in Figure 2 may simply be the result of variations in the mean free path of the particles.

To explore this possibility consider a simple model. Let n_+ be the number of pick-up ions moving outward from the Sun in the solar wind frame; we assume that these particles have a mean speed of $\bar{v}$ in this frame. Let n_- be the number of pick-up ions moving inward towards the Sun, with mean speed $-\bar{v}$, in the solar wind frame. For simplicity, we assume that pick-up ions are created at a rate $\beta_0 n_n (r/r_0)^2 \exp[-\gamma/r]$, after which they propagate inward towards the Sun. Here, n_n is the density of interstellar neutral particles at infinity and r is heliocentric radial distance; β_0 is the ionization rate at $r = r_0$ and γ is the characteristic radial distance for the reduction of the interstellar neutral density as the particles approach the Sun. In a more definitive model, γ would be a function of the angle between the solar wind flow vector and the upstream direction of interstellar neutrals [*Thomas*, 1972]. Finally, we assume that pick-up ions are scattered at a rate τ, such that n_+ are created from n_- at this rate, and vice versa.

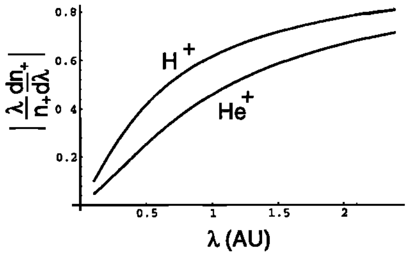

Figure 2. the dependence of the number of particles, n_+, propagating away from the sun in the solar wind frame on the mean free path, λ.

The equations governing n_+ and n_- are then:

$$\frac{1}{r^2}\frac{d}{dr}\left[r^2(V \pm \bar{v})n_\pm\right] = Q_\pm(r) + \frac{n_\mp - n_\pm}{\tau} \qquad (1)$$

with $Q_-(r) = \beta_0 n_n (r_0/r)^2 \exp(-\gamma/r)$ and $Q_+(r) = 0$. (1) can readily be solved to yield that:

$$\begin{aligned} n_+ &= \frac{\beta_0 n_n}{2V}\left(\frac{r_0}{r}\right)^2 \left[\int_0^r \exp\left(-\frac{\gamma}{r'}\right) dr' \right. \\ &\quad \left. - \int_0^r \exp\left(-\frac{2V(r-r')}{\lambda(V+\bar{v})} - \frac{\gamma}{r'}\right) dr'\right] \qquad (2) \end{aligned}$$

where $\lambda = (V - \bar{v})\tau$ is the mean free path of inward propagating particles.

Clearly, varying λ in (2) results in varying n_+, or equivalently, varying the mean free path of inward propagating pick-up ions can yield variations in the distribution function of outward propagating particles, as is observed. One way to consider the sensitivity of n_+ to λ is to calculate the quantity $|(\lambda/n_+)(\partial n_+/\partial\lambda)|$. If this quantity is of order unity, then variations of n_+ by the observed factor of ~ 2 require variations in λ by the like amount; conversely, if this quantity is small, very large variations in λ are required to yield the observed variations in n_+.

The dependence of $|(\lambda/n_+)(\partial n_+/\partial\lambda)|$ on λ at $r = 2.5$ AU is shown in Figure 2 for $\bar{v} = V/\sqrt{3}$, and $\gamma = 4$ AU for hydrogen and $\gamma = 0.5$ AU for helium [*Axford*, 1972]. Clearly, the quantity $|(\lambda/n_+)(\partial n_+/\partial\lambda)|$ approaches unity only for values of λ greater than or of order 1 AU, i.e. modest variations in the mean free path can account for the observed fluctuations in the distribution function provided that the mean free path is of order 1 AU. We note also that for the same variations in λ, the fluctuations in helium are smaller than for hydrogen, as is observed. Alternatively, the observed fluctuations would appear to be another confirmation of the long mean free paths found by Gloeckler *et al.* [1995].

The variations in the mean free path envisioned here should be primarily spatial, i.e. the mean free path varies from field line to field line. Ulysses, then, as it crosses co-rotating field lines will experience different mean free paths, with resulting variations in the observed pick-up ions.

The role of adiabatic cooling

The observed distribution functions can also be used to estimate the extent to which the pick-up ions suffer adiabatic cooling in the solar wind. We consider the distribution functions observed in 24-hour intervals and we use them to form two different ratios.

The first ratio is the fraction of particles propagating outward relative to the solar wind, i.e. it is the ratio of the average value of the distribution function f observed in the speed range $1.6 \leq w \leq 2$ to the expected average value of the distribution function in this speed range, $f_{\rm ISO}$, for an isotropic distribution. The expected distribution function is calculated from the formula provided by Vasyliunas and Siscoe [1976]. The choices of the interstellar density of hydrogen ($0.08\ {\rm s}^{-1}$) and the production rate of ionized pick-up particles ($4 \cdot 10^{-7}\ {\rm s}^{-1}$) are taken from Gloeckler et al. [1995].

The second ratio is formed by dividing the average value of the distribution function observed in the speed range $1.8 \leq w \leq 2$ by the average value in the speed range $1.6 \leq w \leq 2$. This ratio is sensitive to whether the distribution function in the solar wind frame is a shell, with most particle having speeds near the solar wind speed (the ratio is then unity), or whether the distribution function is filled in, with particles having all different speeds (the ratio is then ~0.6). The former occurs if the particles are simply isotropized with a speed equal to the speed they acquire during the initial pick-up process. The latter occurs when the particles suffer substantial adiabatic cooling in the solar wind.

In Figure 3 the two ratios are plotted relative to each other. Clearly the points cluster around a fraction of outward propagating particles of 0.5. This is simply a statement that the mean free path is long and that only a fraction of the particles are moving outward in the frame of the solar wind; the bulk of the particles must be moving inward in this frame and have not yet experienced sufficient scattering to turn around. Indeed, if $n_+/n_- \approx 0.3$, then from (1) and (2), the mean free path must be $\lambda \approx 1$ AU, consistent with the fluctuations discussed in the previous section, and with the mean free path found by Gloeckler *et al.* [1995].

The observed points also cluster around the expected value for a filled distribution, as would be expected if the particles suffer considerable adiabatic cooling. It may seem counter-intuitive for particles that experience little scattering to suffer substantial cooling. It is important, however, to remember that the source of the outward propagating particles are inward propagating particles, which are convected outward through the heliosphere relatively slowly. Such particles can have a longer than average dwell time in the inner heliosphere, and whether through scattering that they experience, or simply due to the expansion of the magnetic field in the solar wind frame, they should be adiabatically cooled. Presumably, then, the cooling occurs primarily while the particles propagate inward in the solar wind frame; they are then scattered into the outward propagating direction at this lower energy.

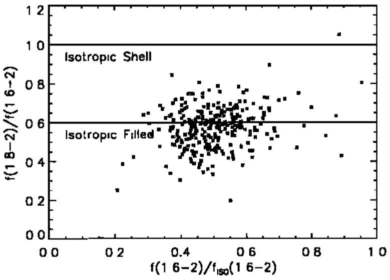

Figure 3. the ratio of $f(1.8-2)/f(1.6-2)$ plotted vs. $f(1.6-2)/f_{\rm ISO}(1.6-2)$ reveals that the distribution is filled in velocity space due to adiabatic cooling.

Causes of the long mean free paths

There are several potential causes for the long mean free paths:

1. Scattering could be small at all pitch angles, in which case we might expect that the distribution function of particles propagating outward in the solar wind frame is peaked near pitch angles of 90°. To represent such a peaked distribution we take the distribution function proportional to $\sin\alpha$, where α is the pitch-angle.

2. Scattering could be small only near 90° pitch angles, but particles experience scattering at other pitch angles. In this case we would expect that the distribution function of particles propagating outward relative to the solar wind would be nearly isotropic, although at a smaller value than the distribution function of inward propagating particles.

3. Scattering could be small at 90° pitch angles and small at other pitch angles in the direction away from the Sun. In this case, particles would find that their pitch angles are reduced by the expansion of the magnetic field in the solar wind frame, and the particles become focused around small values of the pitch angle. For this case we choose a distribution function proportional to $\cos\alpha$.

Distribution functions that are proportional to $\sin\alpha$ or $\cos\alpha$ are centered on the magnetic field direction. Thus, if these forms are representative of the distribution functions, the ratio of the distribution functions in the speed range $1.8 \leq w \leq 2$ to those in the range $1.6 \leq w \leq 2$, as seen by SWICS, should vary with the magnetic field direction. Conversely, if the distribution function is isotropic there should be no correlation with the magnetic field direction.

We have used the Ulysses Common Data Pool to determine the average magnetic field direction for each of the 24-hour intervals in Figure 3 that has a fraction of outward propagating particles in the range $0.45 \leq f(1.6-2)/f_{\rm ISO}(1.6-2) \leq 0.75$, i.e. has a long mean free path. The distribution functions for each of these intervals are then separated into bins of different values of ψ, the magnetic field direction relative to the

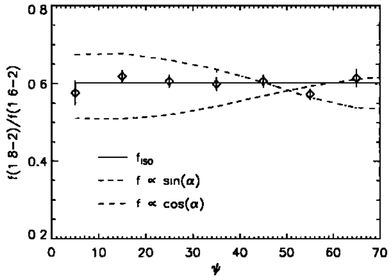

Figure 4. the field angle (ψ) dependence of the ratio $f(1.8-2)/f(1.6-2)$ is compared to theoretical estimates. Only data with $0.45 < f(1.6-2)/f_{\rm ISO}(1.6-2) < 0.75$ is included in the averages.

radial direction; the bin size is 10°. The distribution functions in each bin are then averaged and the ratio of the average distribution function in the speed range $1.8 \leq w \leq 2$ to the average distribution function in the range $1.6 \leq w \leq 2$ is determined. The results are shown in Figure 4.

The magnetic field direction at high heliographic latitudes varies substantially in the 24-hour periods when the distribution functions are observed [e.g. *Smith, et al.*, 1995], and thus some of the angular variation of the distribution function will be smeared. We have used the Ulysses Common Data Pool to calculate the average rms variation of the magnetic field expected for each of the bins. We assume that the field direction fluctuates about its mean direction with a Gaussian distribution with these average rms values. We then calculate the expected ratio of the distribution function in the speed range $1.8 \leq w \leq 2$ to the distribution function from $1.6 \leq w \leq 2$, as a function of ψ, for each of the forms, $\sin\alpha$, isotropic, or $\cos\alpha$, and, consistent with Figure 3, by assuming that the distribution is filled in a low speeds due to adiabatic cooling. The results are also shown in Figure 4.

Clearly, the data is most consistent with a distribution of outward propagating particles that is isotropic. A distribution function that is proportional to $\sin\alpha$ lies noticeably below the observed values; a distribution function proportional to $\cos\alpha$, noticeably above. The data is most consistent with the cause of the long mean free path to be the inability of the particles to scatter through pitch angles of 90°.

Concluding remarks

We have demonstrated that fluctuations in the distribution functions of interstellar pick-up ions may be the result of variations in, and provide additional evidence for, the large mean free paths of these particles. Further, we have provided an analysis of the details of the distribution functions which suggests that the particles do suffer adiabatic cooling, consistent with their spending substantial time as inward propagating particles, and that the distribution function of outward moving particles is quasi-isotropic, consistent with the cause of the large mean free path being the inability of the particles to scatter through 90° pitch angle.

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