JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. A1, PAGES 257–265, JANUARY 1, 1998

Decreases in the antisunward flux of interstellar pickup He^+ associated with radial interplanetary magnetic field

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Abstract. Observations of interstellar pickup He^+ by the Suprathermal Energy Ionic Charge Analyzer (SULEICA) instrument on the AMPTE/IRM spacecraft show significant reductions in the antisunward flux of these particles in the solar wind frame when the interplanetary magnetic field is directed radially. During such times, which can be as short as the 20-min time resolution of our instrument, the typically sharp cutoff in the pickup ion distribution at spacecraft-frame energy $E_c = 2\, M\, V_{sw}^2$, where M is the helium mass and V_{sw} is the solar wind speed, is replaced by a smooth decline to background flux levels over several energy steps. We interpret these reductions as the result of inhibited pitch angle scattering into the observable antisunward region of phase space, implying a strong sunward anisotropy during these times. Thus we unambiguously identify the appearance of such anisotropies with the radial orientation of the magnetic field. We analyze the observations in terms of a steady two-stream model of the ion distribution and use this model to estimate an effective λ, the scattering mean free path of the ions along the field. We obtain values of λ which range from 0.16 to 0.76 AU and discuss the significance of these results.

1. Introduction

Newborn ions in the solar wind arising from the ionization of inflowing interstellar neutral gas initially interact with the average solar wind electric and magnetic fields to form a ring-beam distribution in velocity space. The guiding center velocity of the ring-beam in the frame of the solar wind is sunward along the interplanetary magnetic field (IMF) **B** with speed $V_{sw}|\cos\Theta_{BV}|$, where $\mathbf{V}_{sw}$ is the solar wind velocity, directed radially away from the Sun, and Θ_{BV} is the angle between $\mathbf{V}_{sw}$ and **B**. Although these ions are called pickup ions, at this point the process of pickup by the solar wind is incomplete (unless $\cos\Theta_{BV} = 0$) in the sense that the bulk velocity of the ion distribution is not equal to $\mathbf{V}_{sw}$. The process of pickup is completed by the pitch angle scattering of the initial ring-beam distribution into a closed shell which is nearly isotropic in the solar wind frame. For quasi-parallel configurations, in which **B** and $\mathbf{V}_{sw}$ are nearly aligned, it is important to note that the pickup process is accomplished almost exclusively by scattering.

Simple estimates of the pitch angle scattering rate τ^{-1} from quasi-linear theory predict that $\tau << r/V_{sw}$, where r is the heliocentric radial position of interest [e.g., *Lee and Ip*, 1987]. This result implies that the timescale for the full pickup process is negligible compared to other processes such as the addition of new ions to a solar wind parcel by continual ionization or the adiabatic cooling of the ions in the diverging solar wind. Most of the analysis of pickup ion properties has been based on this assumption of rapid scattering to isotropy. In particular, *Vasyliunas and Siscoe* [1976] modeled the pickup ion velocity distribution throughout the heliosphere, *Holzer* [1972] and *Isenberg* [1986] calculated the effects of addition of this distribution to the solar wind, *Lee and Ip* [1987] predicted wave excitation by the initially unstable pickup ion ring-beam, and *Isenberg* [1987] and *Bogdan et al.* [1991] modeled the energization of the ions by ambient or self-generated waves. When interstellar pickup ions were finally observed, their distributions appeared to be consistent with isotropy. This assumption was then used to infer total pickup ion densities and to model the properties of the interstellar neutral gas [*Möbius et al.*, 1985a, 1988, 1995; *Möbius*, 1990; *Gloeckler et al.*, 1993; *Geiss et al.*, 1994].

Recently, however, *Gloeckler et al.* [1995] reported Ulysses measurements of anisotropic pickup protons in the high-latitude solar wind. In the steady high-speed wind found at high heliocentric latitudes, pickup protons with spacecraft-frame speeds smaller than V_{sw} are still energetic enough that the Solar Wind Ion Composition Spectrometer (SWICS) instrument is able to detect them, though their intensity is low. Gloeckler et al. presented a 30-day integration of the proton measurements at 2.34 AU, which showed a higher phase-space density of protons with radial speeds less than V_{sw} than in the speed range greater than V_{sw}. In this paper, we designate the region of phase space containing particles with spacecraft-frame velocities in the radial direction < V_{sw} as the "sunward hemisphere" and the region with particles moving away from the Sun faster than V_{sw} as the

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Paper number 97JA02771.
0148-0227/98/97JA-02271$09.00

"antisunward hemisphere." The large sunward anisotropy found by Gloeckler et al. can be interpreted as the result of incomplete scattering and pickup. During this high-latitude observation the 1-day averaged IMF tended to lie within 45° of the radial direction [*Forsyth et al.*, 1995], and newly ionized protons would generally have to be scattered through large angles to be detected in the antisunward hemisphere. Gloeckler et al. modeled the distribution of the ions, using a spatial diffusion equation which included convection, adiabatic deceleration, and a radially dependent source term describing the continual ionization of neutral hydrogen. Comparing their theoretical results with the observed proton anisotropy, they inferred a scattering mean free path λ of 1 - 2 AU, where $\lambda = v\tau$ and v is a typical pickup proton speed. However, the use of diffusion theory for such slow particles as pickup ions is problematic, particularly for such large derived values of λ [*Gombosi et al.*, 1993]. Nevertheless, the results of *Gloeckler et al.* [1995] indicate that the scattering mean free path for pickup protons at high heliocentric latitude is comparable with the spatial scales of solar wind convection, energy losses in the solar wind, or the ion source term. Subsequently, a more detailed model of the anisotropic distribution of pickup ions in a steady radial field has been presented by *Isenberg* [1997].

Such a large value of λ, of the order of 1 AU, has important consequences for the spatial distribution of pickup ions in the solar wind, for the excitation of waves by the pickup protons (which only occurs by virtue of the pitch angle scattering), and for the interpretation of pickup ion measurements to infer properties of the interstellar neutral gas. For example, *Möbius et al.* [1995, 1996] have shown that the derivation of the temperature of interstellar helium from the observed width of the pickup He^+ focusing cone at 1 AU depends on the assumed value of λ. Furthermore, *Fisk et al.* [1997] have suggested that the substantial variations observed in the antisunward fluxes of pickup protons and pickup He^+ as well as the puzzling correlation between them [*Gloeckler et al.*, 1994] may be caused by the effects of weak pitch angle scattering on both species.

This large value of λ for pickup protons also may be connected with the large scattering mean free paths derived for low-rigidity cosmic rays from observations of solar energetic particles [e.g., *Palmer*, 1982], and insights obtained about pickup ion scattering will likely be applicable to these cosmic rays.

Observations of the phase-space distribution of pickup He^+ by the SULEICA instrument on the Earth-orbiting AMPTE/IRM spacecraft can extend this investigation of the effects of incomplete pitch angle scattering of pickup ions. The larger geometrical factor of the SULEICA sensor and the higher intensity of pickup He^+ within the helium focusing cone allow the construction of antisunward spectra with a higher time resolution than permitted by conditions at Ulysses. Such observations allow us to identify particular characteristics of the pickup ion distribution with particular magnetic field orientations in a manner not possible with long time integrated measurements. Specifically, we find that when the IMF is oriented close to the radial direction, the observed flux of pickup He^+ in the antisunward portion of phase space is reduced relative to the fluxes during quasi-perpendicular conditions. We also find that at these times the sharp cutoff in the distribution seen during quasi-perpendicular periods is often smoothed out and the fluxes can fall more gradually to background levels.

It is the purpose of this paper to report these observations and interpret them in terms of incomplete pitch angle scattering. To this end, we introduce a two-stream model of pickup ion transport, which, in contrast with diffusion theory, takes into account the limited speed of the pickup ions preventing their sunward transport in the frame of the Sun. We use this model to infer values of λ from the observations, obtaining a range of mean free paths from $\lambda = 0.16$ AU to $\lambda = 0.76$ AU.

2. Instrumentation and Observational Characteristics

The measurements presented in this paper were obtained with the SULEICA (Suprathermal Energy Ionic Charge Analyzer) instrument onboard the AMPTE/IRM spacecraft. In a highly elliptical orbit with an apogee of 18.7 Earth radii, the IRM spent approximately 50% of its time upstream of the bow shock between July and January, allowing a study of interstellar pickup ions. The SULEICA instrument combines an energy per charge selection of the incoming ions by a spherical-section electrostatic analyzer with a subsequent time-of-flight analysis to derive the mass/charge of the particles. For ion energies above 40 keV, the residual ion energy is also measured in a silicon surface barrier detector which allows a separate determination of mass and charge. In total, an energy range from 5 to 270 keV/Q can be covered by stepping the analyzer voltage in 24 logarithmically spaced voltage steps synchronously with the spacecraft spin. The fan-like aperture of the SULEICA electrostatic analyzer covers a solid angle of 10° in azimuth and 40° in polar angle symmetric to the plane perpendicular to the spin axis. The directional information in azimuth is provided by a sectoring scheme with 16 sectors for H^+ and He^{2+} and eight sectors for all other ions including He^+. A more detailed description of the instrument may be found elsewhere [*Möbius et al.*, 1985b].

The solar wind data (necessary for the determination of the cutoff energy of the pickup ion distribution) were provided by the AMPTE/IRM 3D-Plasma instrument [*Paschmann et al.*, 1985]. The magnetic field at the spacecraft was measured by the onboard magnetometer [*Lühr et al.*, 1985].

Interstellar pickup He^+ ions are identified by their ionic mass per charge ratio and by the structure of their velocity distribution, which is distinct from the solar wind. Figure 1 shows a schematic cut through a pickup ion distribution in the plane perpendicular to the spacecraft spin axis which contains the solar wind velocity defined in the v_x direction. Figure 1 displays the division of phase space into azimuthal sectors and energy steps as seen with SULEICA. The observations reported here were restricted to time periods when the sensor was operating in its high energy-resolution mode with four steps for every factor of 2 in energy. In this mode (introduced to study the pickup ion distribution in detail) the energy steps between 5 and 134 keV/Q were covered. Generally, the lowest few energy steps have not been used in the analysis because they are contaminated by solar wind heavy ions.

The schematic pickup ion distribution in Figure 1 is taken to be isotropic in the solar wind frame, following the assumption that pitch angle scattering in velocity space is much faster than all other processes. Under this assumption, the ions fill a spherical shell in velocity space immediately after ionization. Subsequently, this shell shrinks because of adiabatic cooling in the expanding solar wind. The shells are indicated by rings with different shading in Figure 2. This picture is accurate in cases when the scattering mean free path λ is small compared to the

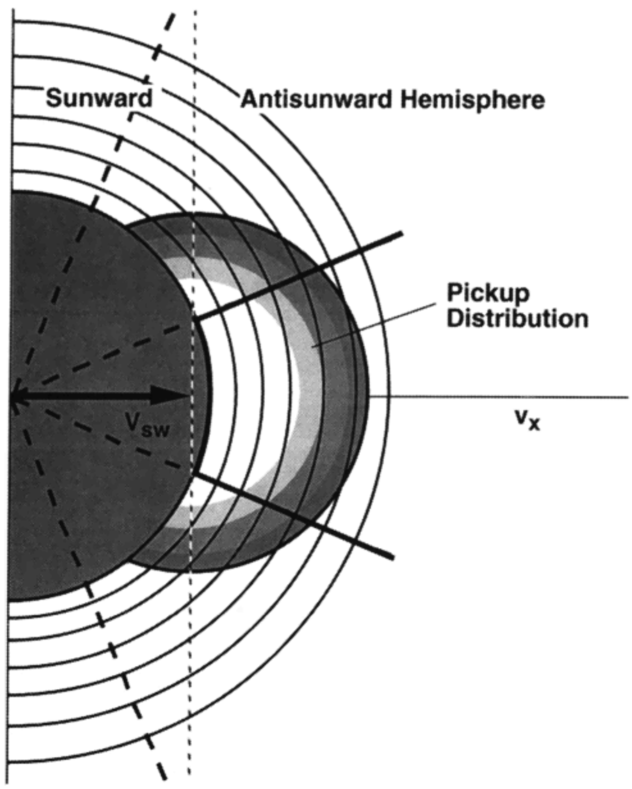

Figure 1. Cut through a pickup ion velocity distribution in the plane perpendicular to the AMPTE/IRM spin axis, which contains the solar wind velocity, assuming a short scattering mean free path. Pitch angle scattering fills spherical shells in velocity space, while adiabatic cooling leads to shrinkage of the shells on a slower time scale. The pattern of SULEICA angular sectors and energy steps is superimposed. The dark shaded area around $\upsilon = 0$ indicates the part of the distribution below the SULEICA energy threshold. Observations presented here are taken from the region of phase space bounded by thick lines.

length scales for ionization and adiabatic effects. In this way, the production rate of pickup ions along the Sun-spacecraft line is mapped into the velocity distribution solely as a function of speed in the solar wind frame [e.g., *Vasyliunas and Siscoe*, 1976; *Möbius et al.*, 1988]. An isotropic distribution of pickup ions allows one to derive the production rate, and thus the neutral gas density, from any angular section of the distribution.

As can be seen from Figure 1, the Sun viewing sector is a natural choice for this analysis. For an isotropic pickup ion distribution, an energy spectrum obtained in this sector exhibits the typical behavior of a cutoff at $E_c = 2\,M\,V_{sw}^2$, where M is the helium mass, and a "plateau" between the cutoff and the solar wind distribution appearing around $\upsilon_x = V_{sw}$. The lower energy threshold of the sensor at 5 keV/Q means that only the antisunward hemisphere of the pickup He^+ distribution is observed with the SULEICA instrument. The fraction not visible to the sensor is indicated by dark shading in Figure 1. In the observations presented below we refer only to the "primary" portion of phase space within the heavy boundary shown in Figure 1.

The time resolution of this measurement is limited by the flux of pickup He^+ at 1 AU. We find that the SULEICA instrument requires integration times ≥ 20 min to construct a reliable spectrum from the fluxes in the Sun-viewing sector. We will see that during times of radial IMF, anisotropies in the pickup ion distribution due to incomplete pitch angle scattering will lead to the detection of reduced ion flux levels in this sector.

3. Sample Events and Data Analysis

In an earlier investigation to obtain the interstellar gas parameters [*Möbius et al.*, 1995] it was found that the pickup He^+ flux in the primary portion of phase space was generally depleted compared to average flux levels during time periods of radial IMF. In one key example [*Möbius et al.*, 1995, Figure 7], the IMF on November 16, 1995, remained almost radial (with Θ_{BV} between 150° and 180°) for 150 min. Under these conditions, a flux reduction by about a factor of 2 was observed in the plateau region of the pickup ion spectrum. Möbius et al. omitted such cases from that analysis on the grounds that these time periods were not representative of the standard conditions.

These cases now become the starting point for the study presented in this paper. We consider those periods in 1985 when the AMPTE/IRM spacecraft was outside Earth's bow shock and encountered steady quasi-radial IMF. Those intervals which were long enough to allow a reliable pickup He^+ measurement (≥ 20 min) are compiled in Table 1. We will illustrate the behavior of the pickup He^+ spectrum with several examples.

The first example is taken from December 3, 1985. On that date, between 630 and 845 UT, the solar wind speed, density and field strength were relatively steady but the IMF direction was variable. Figure 2a shows pickup ion spectra from the Sun-viewing sector for two intervals: from 0630 to 0650 UT when Θ_{BV} was larger than 60°, and from 0800 to 0845 UT when a new steady direction was reached with $\Theta_{BV} \approx 20° - 30°$. Figure 2b shows the temporal variation of the interplanetary parameters during the entire period displaying, from top to bottom, the proton speed (V_p) and density (N_p), the magnetic field strength (B), its direction in azimuth (Φ_B) and in elevation (Θ_B), and the magnetic field direction with respect to the solar wind flow

Table 1. Radial Time Periods in the 1985 SULEICA Data Set

Date	Time, UT	V_{sw}, km/s	Θ_{BV}, deg	N_{obs}/N_{ref}	λ, AU
Sept. 11	1215 - 1315	380 - 400	0 - 30	0.59 ± 0.073	0.33
Sept. 18	1005 - 1240	470 - 500	150 - 180	0.45 ± 0.037	0.52
Sept. 27	1305 - 1330	480 - 520	150 - 170	0.63 ± 0.052	0.28
Oct. 16	1105 - 1155	520	160 - 180	0.77 ± 0.028	0.16
Nov. 11	0920 - 0940	530 - 550	160 - 180	0.49 ± 0.050	0.46
Nov. 16	0800 - 1030	550 - 600	150 - 180	0.41 ± 0.013	0.59
Dec. 3	0800 - 0845	540	20 - 30	0.35 ± 0.036	0.76
Dec. 14	0700 - 0730	490 - 510	140 - 150	0.48 ± 0.018	0.47

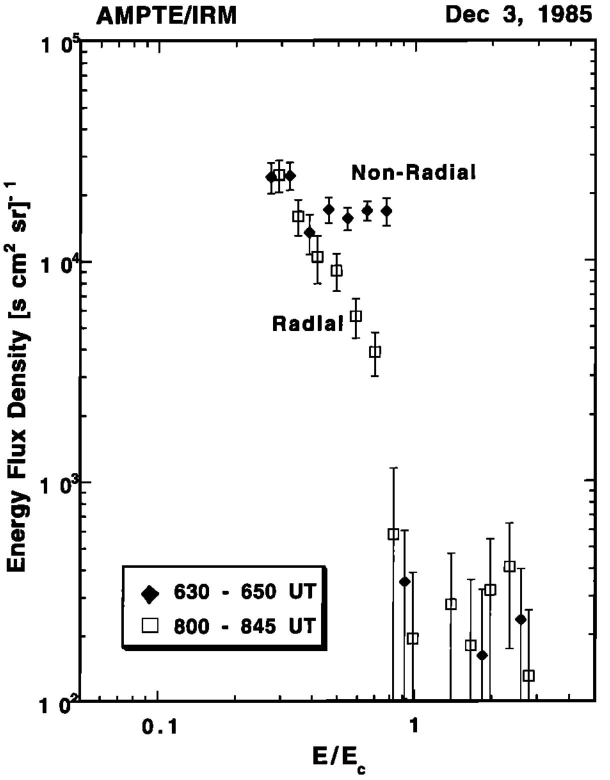

Figure 2a. Energy spectrum of pickup He+ in the Sun-viewing sector for two periods on December 3, 1985. The ion energy has been normalized to the pickup He+ cutoff energy $E_c = 2\,M\,V_{sw}^2$, where M is the helium mass. Diamonds correspond to 0630 - 0650 UT when the IMF was nonradial and open squares correspond to 0800 - 0845 UT when the IMF had turned to the radial direction.

vector (Θ_{BV}). It is evident from Figure 2a that the change in IMF angle from quasi-perpendicular to quasi-radial is accompanied by a change in the pickup ion energy spectrum from the typical plateau with a sharp cutoff near $E_c \sim 24$ keV to a spectrum that falls off continuously with energy. The flux within the original plateau region is reduced substantially and has dropped to the flux level of the ambient energetic particles before reaching E_c.

The second example is shown in Figure 3a and 3b in the same format. During the observation period on December 14, 1985, the IMF changed from an angle close to radial ($\Theta_{BV} \approx 140° - 160°$) between 0620 and 0730 UT to an almost perpendicular IMF ($\Theta_{BV} \approx 90° - 110°$) starting at 0745 UT. Figure 3a displays the spectra from 0700 to 0730 UT and from 0745 to 0815 UT. At 0730 UT the spacecraft had a brief encounter with the bow shock as indicated in Figure 3b by a drop in the solar wind speed and an increase in ion density and field strength. The actual encounter with the bow shock has no direct bearing on these observations, and we discuss the effect of bow shock proximity below. As in the first example, the flux in the plateau region of the pickup ion spectrum is substantially reduced during the radial time period compared with the flux level during quasi-perpendicular conditions. The radial spectrum also shows a more gradual drop in ion flux, at a lower energy, than the steep cutoff seen in the perpendicular spectrum.

For a spacecraft upstream of the bow shock, a radial IMF also implies a magnetic connection to the bow shock. This connection is responsible for the increased fluxes of ions seen above the cutoff energy in the radial spectra of Figures 2a and 3a, but these fluxes are still too low to influence the pickup ion plateaus being reported here. However, another aspect of this connection is the presence of increased turbulent activity, as is evident in the different character of the Figure 3b line plots before and after 0730 UT. Such increased turbulence might be expected to produce increased scattering of these ions and a reduction of their mean free path. This effect is likely to be small since the enhanced turbulence is confined to the region only several Earth radii upstream of the bow shock, and the solar wind plasma seen at AMPTE will have been influenced by these fluctuations for only the ~1 min prior to detection. In addition, we will see that the scattering mean free paths derived for these particles are all much larger than the scale of the bow shock. However, some reduction of the mean free path due to bow shock connection cannot be completely ruled out at this point. We will investigate the effects of the bow shock on the upstream pickup He+ population in a future work.

The two examples shown in Figures 2 and 3 are typical of the entire 1985 pickup ion observation period. For all the intervals listed in Table 1, the observed antisunward flux of pickup He+ was reduced. In addition, the sharp cutoff expected at E_c had become smoother and either moved to lower energy or disappeared altogether. In the next section, we present a simple two-stream model to evaluate these observations in the context of finite scattering mean free path.

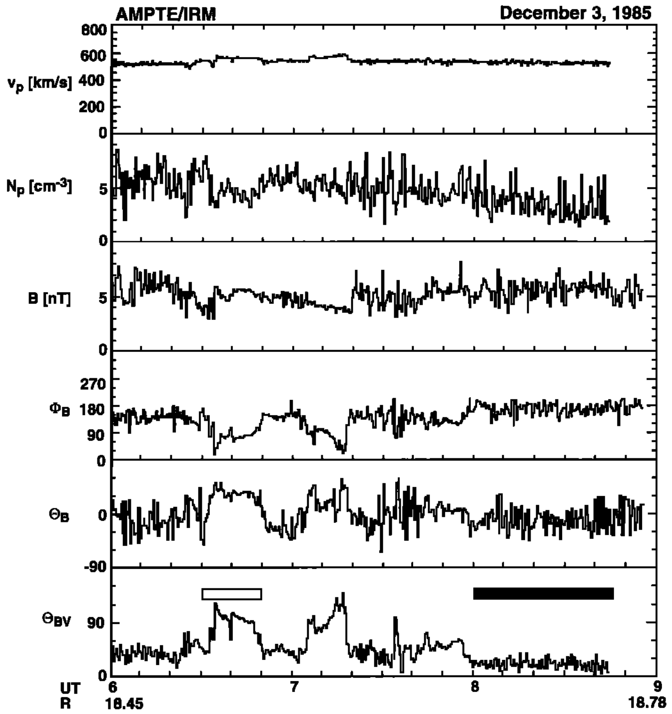

Figure 2b. Temporal variations of the proton speed V_p and density N_p, magnetic field strength B, and magnetic field direction in azimuth Φ_B, elevation Θ_B, and with respect to the solar wind Θ_{BV}, during a time period including the observations shown in Figure 2a. Also shown is the radial position of the AMPTE/IRM spacecraft in units of Earth radii. The spectra in Figure 2a were compiled during the intervals designated by the horizontal bars in the bottom panel, with the shaded bar denoting the quasi-radial period and the unshaded bar denoting the quasi-perpendicular period.

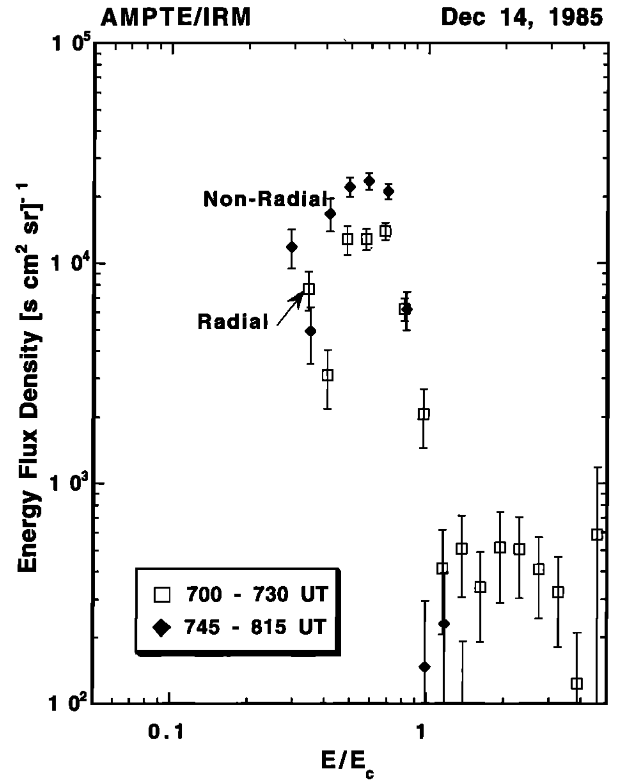

Figure 3a. Energy spectrum of pickup He+ in the Sun-viewing sector for two periods on December 14, 1985. Open squares correspond to 0700 - 0730 UT when the IMF was radially directed and diamonds correspond to 0745 - 0815 UT after the IMF had turned perpendicular to the radial.

4. Two-Stream Model of Pickup Ion Transport

Immediately after ionization, the speed of a pickup ion in the inertial frame of the Sun is in the range 10 - 40 km s^{-1} and may generally be neglected in considering its subsequent motion. The ion is first picked up by the solar wind electric and magnetic fields onto a gyrational ring-beam in velocity space. In the solar wind frame, the gyrational ring-beam is specified by a speed equal to the local solar wind speed V_{sw} and an initial cosine of the pitch angle $\mu_o = \pm \cos\Theta_{BV}$. We define μ in general as the cosine of the ion pitch angle in the solar wind frame with $\mu < 0$ indicating sunward motion along the field in that frame. Although the initial ring-beam propagates sunward in the solar wind frame ($\mu_o < 0$), pickup ion speeds in that frame are always less than or equal to V_{sw} and pickup ions cannot actually move toward the Sun as measured in the inertial frame. The ion guiding center in the inertial frame initially moves with velocity $\mathbf{V}_{sw} + \mu_o V_{sw}\,\hat{\mathbf{e}}_B$, where $\hat{\mathbf{e}}_B$ is a unit vector parallel to $\mathbf{B}$ away from the Sun. The vector $\mathbf{V}_{sw} + \mu_o V_{sw}\,\hat{\mathbf{e}}_B$ is normal to $\mathbf{B}$ and has a component along $\mathbf{V}_{sw}$ equal to $V_{sw}\sin^2\Theta_{BV}$. Thus the ions on the initial ring-beam are partially swept away from the Sun by the solar wind, but that advection is small if $\sin^2\Theta_{BV}$ is small, which occurs when $\mathbf{B}$ is nearly radial. Eventually, the ions are scattered in pitch angle to a more uniform distribution in μ, and they are advected out of the inner heliosphere by the solar wind. However, it is clear that if $\mathbf{B}$ is nearly radial and scattering is weak, ions will remain longer in the $\mu < 0$ region (equivalent to the sunward hemisphere for radial field), leading to a reduced density in the $\mu > 0$ (or antisunward) hemisphere and to distributions with substantial anisotropies. Figure 4 shows the distinction between the μ 0 hemispheres, and the sunward/antisunward hemispheres. They are only equivalent for radial field.

In order to include the restriction that these ions cannot move sunward in the inertial frame, and to accommodate large anisotropies, we must eschew spatial diffusion theory which presumes small anisotropy and permits sunward transport of the ions. An appropriate starting point is the pitch angle diffusion equation

$$\frac{\partial f}{\partial t} + V_{sw}\frac{\partial f}{\partial x} + V_{sw}\,\mu\frac{\partial f}{\partial s} = \frac{\partial}{\partial \mu}\left[(1-\mu^2)D\frac{\partial f}{\partial \mu}\right] + Q(x,\mu,t) \quad (1)$$

where $f(x,\mu,t)$ is the gyrotropic phase-space distribution function, x is the radial distance from the Sun, s is the arclength along $\mathbf{B}$ increasing away from the Sun, $D(\mu)$ is the pitch angle diffusion coefficient, and $Q(x,\mu,t)$ is the production rate of newborn ions. Although the spatial variable x is measured in the inertial frame, we consider the velocity variable $\mathrm{v} = \upsilon\,\mu$ in the frame moving with the solar wind. In this frame, we take the speed of the pickup ions to be equal to the solar wind speed, $\upsilon = V_{sw}$. As such, (1) neglects energy changes due to adiabatic deceleration. We also neglect the effects of spherical expansion of the flow such as the radial decrease in ion density and focusing of the ions toward larger μ in the decreasing magnetic field. Nevertheless, (1) includes the essential transport features necessary to interpret the AMPTE/IRM observations. A more elaborate treatment which includes many of the neglected effects has been recently

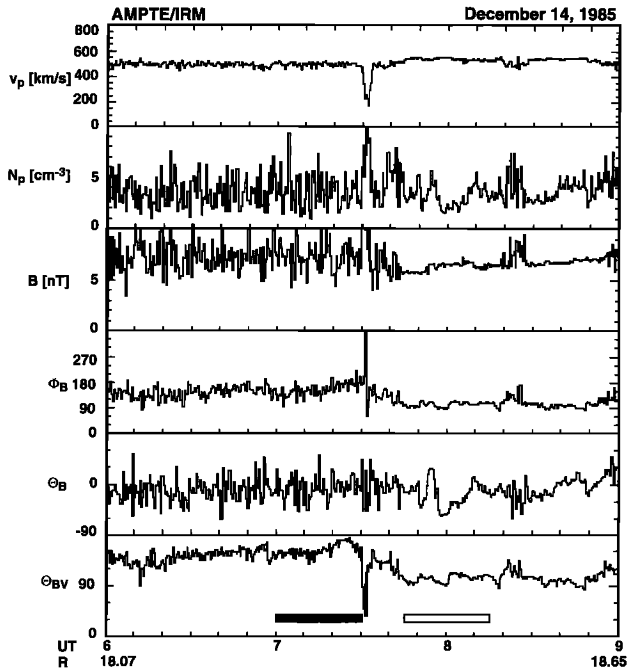

Figure 3b. Temporal variations of the proton speed V_p and density N_p, magnetic field strength B, and magnetic field direction in azimuth Φ_B, elevation Θ_B, and with respect to the solar wind Θ_{BV}, during a time period including the observations shown in Figure 3a. Also shown is the radial position of the AMPTE/IRM spacecraft in units of Earth radii. The spectra in Figure 3a were compiled during the intervals designated by the horizontal bars in the bottom panel, with the shaded bar denoting the quasi-radial period and the unshaded bar denoting the quasi-perpendicular period.

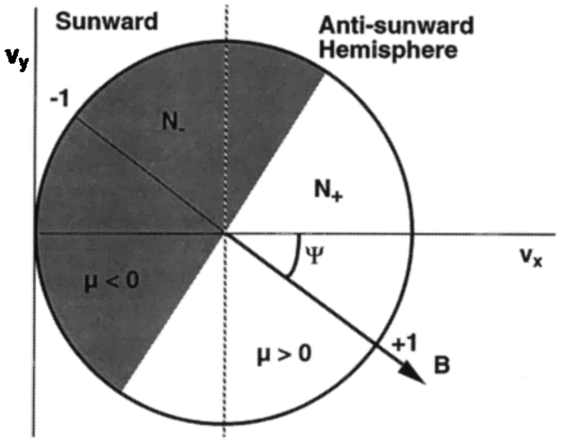

Figure 4. Schematic view of a pickup ion distribution which has been divided into $\mu < 0$ (shaded) and $\mu > 0$ (unshaded) hemispheres, and into sunward and antisunward hemispheres.

presented by *Isenberg* [1997]. In a steady state situation, (1) becomes

$$V_{sw}\left(1 + \mu\left|\cos\Theta_{BV}\right|\right)\frac{\partial f}{\partial x} = \frac{\partial}{\partial\mu}\left[(1-\mu^2)D\frac{\partial f}{\partial\mu}\right] + Q(x,\mu) \quad (2)$$

Since $V_{sw}(1 + \mu|\cos\Theta_{BV}|) \geq 0$, we note that there is no transport of pickup ions toward the Sun, and $f(x)$ cannot be influenced by $f(x')$ when $x' > x$.

A further simplification occurs if we replace the continuous variable μ by a finite number of "streams" in μ space. Although any number could be chosen, two is sufficient. This is the basis of the two-stream model [e.g., *Fisk and Axford*, 1969]. We first define

$$N_+ = \int_0^1 f\,d\mu \qquad N_- = \int_{-1}^0 f\,d\mu$$

$$Q_+ = \int_0^1 Q\,d\mu \qquad Q_- = \int_{-1}^0 Q\,d\mu$$

Integrating (2) over μ from 0 to 1 then yields

$$V_{sw}\frac{\partial N_+}{\partial x} + V_{sw}\left|\cos\Theta_{BV}\right|\frac{\partial}{\partial x}\int_0^1 f\mu\,d\mu = -D(0)\left.\frac{\partial f}{\partial\mu}\right|_0 + Q_+ \quad (3)$$

In order to evaluate the integral

$$I = \int_0^1 f\mu\,d\mu$$

we assume that $f(x,\mu)$ is uniform in the hemisphere $\mu > 0$ so that $f(x,\mu > 0) = N_+(x)$ and $I = N_+/2$. Next, we note that the pitch angle gradient at $\mu = 0$ on the right-hand side of (3) can be written as $(N_+ - N_-)/\delta$, where δ is some scale in μ. In what follows we define $D(0)/\delta \equiv \Delta$, a characteristic pitch angle diffusion coefficient near $\mu = 0$. Integrating (2) over μ from −1 to 0, followed by similar manipulations generates an equation for N_-. Together the two-stream equations are

$$V_\pm\frac{dN_\pm}{dx} = \mp\Delta(N_+ - N_-) + Q_\pm \quad (4)$$

where $V_\pm = V_{sw}(1 \pm 1/2\ |\cos\Theta_{BV}|)$. As in (2), since $V_\pm > 0$, we find that $N_\pm(x)$ cannot be influenced by $N_\pm(x')$, when $x' > x$.

Although utilizing more than two streams would provide a finer resolution in μ space, there is some physical justification for the two-stream model. $D(\mu)$ is not uniform in μ space but depends on the power spectrum of the various resonant wave modes present[e.g.,*Schlickeiser*, 1988, 1989]. Near $\mu = 0$, one must also consider the relevant dissipation scales of these waves [*Davila and Scott*, 1984; *Smith et al.*, 1990; *Schlickeiser et al.*, 1991] and the effectiveness of nonlinear processes such as mirroring [*Goldstein*, 1980]. These processes are likely to result in reduced pitch angle scattering near $\mu = 0$, and the cyclotron resonance condition [e.g., *Rowlands et al.*, 1966; *Dusenbery and Hollweg*, 1981] suggests that this reduction will be more pronounced for low-energy ions such as pickup ions. Furthermore, analysis of the high-latitude Ulysses observations of pickup protons by *Fisk et al.* [1997] indicates that the antisunward particles appear isotropic in this hemisphere, consistent with reduced pitch angle scattering at $\mu = 0$. We also note, however, that the dissipation of resonant waves will not affect heavy ions, such as He^+, as much as protons. Nonetheless, it is reasonable to anticipate a distribution $f(\mu)$ which is fairly uniform throughout most of the $\mu < 0$ hemisphere and most of the $\mu > 0$ hemisphere with a possibly steep transition between the two hemispheres controlled by $D(\mu \approx 0)$. This is a configuration precisely suited to the two-stream approximation.

In the simple picture presented here, we will take the angle between the IMF and the solar wind velocity to be a constant. In this context, we will model the observed response of the pickup ion distribution to changes in the IMF angle by comparing the two-stream results for different constant values of Θ_{BV}. A model of pickup ion transport which allows for different values of Θ_{BV} along a flux tube is currently being developed [*Isenberg and Lee*, 1997].

Under the conditions that $Q_\pm \to 0$ and $N_\pm \to 0$ as $x \to -\infty$, the two-stream equations (4) have an integral

$$V_+N_+ + V_-N_- = \int_{-\infty}^x (Q_+ + Q_-)\,dx' \quad (5)$$

representing conservation of pickup ion flux. If we write (5) as

$$V_{sw}(N_+ + N_-) = \int_{-\infty}^x (Q_+ + Q_-)\,dx' + V_{sw}\left|\cos\Theta_{BV}\right|(N_- - N_+)/2 \quad (6)$$

and note that $N_- \geq N_+$ since these ions are picked up predominantly into the $\mu < 0$ hemisphere, then we see that the total pickup ion density, $N_+ + N_-$, is greater for periods of quasiparallel magnetic field ($|\cos\Theta_{BV}| \sim 1$) than for those with quasiperpendicular field ($\cos\Theta_{BV} \sim 0$).

Now, taking Δ to be independent of x, the solution of (4) using (5) is given by

$$N_\pm = \frac{1}{2V_{sw}}\int_{-\infty}^x \left(Q_+ + Q_-\right)dx' + \frac{1}{2V_{sw}}\int_{-\infty}^x \left[\frac{V_\mp}{V_\pm}Q_\pm - Q_\mp\right]\exp\left[\frac{2V_{sw}\Delta}{V_+V_-}(x'-x)\right]dx' \quad (7)$$

The source term for new pickup ions in (2), $Q(x,\mu)$, is centered on $\mu = \mu_o$ in phase space, but with a spread determined by fluctuations in magnetic field direction on a length scale larger than the ion gyroradius [*Isenberg*, 1996]. The two-stream sources, $Q_\pm$, depend on this spread. To avoid these calculational complications we consider the separate cases of parallel field ($|\cos \Theta_{BV}| = 1$) and perpendicular field ($\cos \Theta_{BV} = 0$). In either case, the SULEICA instrument only observes ions in the antisunward hemisphere of phase space ($v_x > V_{sw}$) as described in section 2. For parallel field that hemisphere has density $N^{\parallel}_+$ and for perpendicular field that hemisphere has density $(N^{\perp}_+ + N^{\perp}_-)/2$.

For parallel field, no particles are ionized into the $\mu > 0$ hemisphere, $Q_+ = 0$, and (7) yields

$$N_+^{\parallel} = \frac{1}{2V_{sw}} \int_{-\infty}^{x} dx' \, Q(x') \left\{ 1 - \exp\left[\frac{8\Delta}{3V_{sw}} (x' - x) \right] \right\} \tag{8}$$

where the total ionization source is $Q \equiv Q_- + Q_+$. For perpendicular field, we take the ionization source to contribute equally to both pitch angle hemispheres $Q_+ = Q_- = Q/2$, so $N^{\perp}_+ = N^{\perp}_-$ and the antisunward density is given by $N^{\perp}_+$. Then (7) yields

$$N_+^{\perp} = \frac{1}{2V_{sw}} \int_{-\infty}^{x} Q(x') \, dx' \tag{9}$$

The integrand of (8) is the product of the ionization source which can increase rapidly in the inner heliosphere, and a function in curly brackets which decreases from 1 to 0 with a scale of $3V_{sw}(8\Delta)^{-1}$. This quantity corresponds to λ, the scattering mean free path parallel to the magnetic field, which can be seen as follows. The spatial diffusion coefficient of the ions parallel to the magnetic field is given by

$$\kappa_{\parallel} = \frac{v^2}{8} \int_{-1}^{1} \frac{1 - \mu^2}{D(\mu)} d\mu$$

[*Jokipii*, 1966; *Hasselmann and Wibberenz*, 1968, 1970]. We note that $\kappa_{\parallel}$ is dominated by the range of μ where $D(\mu)$ is smallest, near the resonance gap $\mu \sim 0$ in our model. Then, we obtain $\kappa_{\parallel} = 1/8 \, V_{sw}^2/\Delta$ and $\lambda \equiv 3\kappa_{\parallel}/V_{sw} = 3V_{sw}(8\Delta)^{-1}$.

The behavior of the integral in (8) is governed by the ratio of λ to the characteristic length over which Q is significant. For purposes of comparing $N^{\parallel}_+$ and $N^{\perp}_+$, noting that $Q(x)$ has a steep onset, it is sufficient to take $Q(x) \propto S[x - L]$, where $S(x)$ is the step function and L is the radial extent of the ionization cavity for the interstellar neutral particles. When $x > L$, we obtain

$$\frac{N_+^{\parallel}}{N_+^{\perp}} = 1 - \frac{\lambda}{x - L}\left[1 - \exp\left(-\frac{x-L}{\lambda}\right)\right] \tag{10}$$

Equation (10) is easily interpreted. In the perpendicular configuration (9), ions are initially ionized with equal rates in the two streams, and within an ion gyroperiod, half of them gyrate into the antisunward hemisphere independent of λ. In the parallel configuration (8), however, ions are generated in the sunward hemisphere and only reach the antisunward hemisphere by scattering. If $\lambda << x - L$, scattering between the hemispheres is rapid and the distribution is close to isotropic, so that $N^{\parallel}_+/N^{\perp}_+ \cong 1$. However, if $\lambda >> x - L$ in the parallel configuration, the ions are only weakly scattered out of the sunward hemisphere and $N^{\parallel}_+/N^{\perp}_+ \cong (x - L)/(2\lambda)$, which is small.

5. Two-Stream Interpretation of the AMPTE/IRM Observations

We now seek to apply the two-stream model of section 4 to the flux reductions in the SULEICA data during the periods of radial field listed in Table 1. For this comparison, the measured fluxes need to be transformed into the ion densities treated by the model. To form a quantity proportional to the ion density, one divides the measured flux in each energy channel F_i by the ion speed at the center of the channel v_i and sums this ratio over the energy range of interest, namely,

$$N_{obs} \propto \sum_i f_i \, v_i^2 \, \Delta v_i \propto \sum_i F_i / v_i \tag{11}$$

In comparing the data with the model, we concentrate on the density in the plateau region of the spectrum. This restriction insures that we are dealing with pickup He^+ with minimal contamination by other particles. We define the plateau region as the five energy channels below the cutoff, except for the September intervals at the edge of the interstellar helium focusing cone. Here the pickup He^+ fluxes are lower and the relative contribution of solar wind related background counts in the lower energy channels becomes important, so we are limited to using four energy channels. Thus we construct a normalized density N_{obs} corresponding to $N^{\parallel}_+$ in the model by taking the fluxes in the plateau region during the quasi-radial periods and summing them according to (11). We then obtain a quantity N_{ref} corresponding to the model perpendicular density $N^{\perp}_+$ by applying the same procedure to the calculated spectra for the same dates from the global pickup He^+ model of *Möbius et al.* [1995]. The detailed parameters of the Möbius et al. model were derived by fitting the quasi-perpendicular time periods of this same 1985 SULEICA data set, so this model provides a consistent set of reference densities even in the absence of a stable perpendicular time period for comparison.

The density ratios N_{obs}/N_{ref} from the data corresponding to the model ratio $N^{\parallel}_+/N^{\perp}_+$ of section 4 are given in Table 1, for the radial time periods we have chosen. We also include the errors in this ratio from the root-mean-squared observational errors in N_{obs}. The radial field leads to significant density reductions, with an average value of $N_{obs}/N_{ref} = 0.52$. There is a considerable range in these values, from a moderate reduction of 23% on October 16 to a factor of 3 decrease on December 3.

The reduced antisunward He^+ densities observed during our radial time periods indicate the concurrent existance of enhanced densities in the sunward hemisphere, representing a strong sunward anisotropy. This situation is complementary to the Ulysses observations by *Gloeckler et al.* [1995] of a pickup proton anisotropy in the high-latitude solar wind, and shows that anisotropic pickup ion distributions can appear at 1 AU over short timescales. These observations are also likely related to the substantial variations in antisunward flux of both pickup proton and He^+ seen at Ulysses at high latitude [*Fisk et al.*, 1997] and in the ecliptic plane [*Gloeckler et al.*, 1994]. The Ulysses measurements required long time averages (19.5 hours in the ecliptic data and 2 days in the high-latitude case) so identification of anisotropic behavior with specific IMF angle was not possible.

With the analysis presented here, we unambiguously identify the appearance of anisotropy and reduced antisunward fluxes with the occurrence of quasi-radial IMF. To the extent that the same processes responsible for reduced antisunward fluxes at AMPTE are also operative at Ulysses, these observations should provide further clues to the cause of the Ulysses variations.

The two-stream model connects the reductions in antisunward particles to the value of the scattering mean free path through (10). Since the ionization rate of interstellar helium becomes significant at about 0.3 AU from the Sun, and $x = 1$ AU for these observations, we set $x - L = 0.7$ AU in (10). Then the values of λ obtained by inverting (10) for the density reductions in each of the radial time periods are given in the last column of Table 1. The average λ for these radial intervals is 0.45 AU, and these mean free paths are also spread over a considerable range. The October 16 value is only slightly larger than the earlier estimate of ~ 0.1 AU which was based on the standard picture of uniform pitch angle scattering [*Möbius et al.*, 1988]. At the other extreme, the December 3 value is comparable with the length scale for accumulation of pickup ions at 1 AU.

These values of λ should be not be taken too literally in light of the simplicity of the two-stream model. The primary drawback of the model is the assumption of a stationary radial field, where a real flux tube will be oriented radially only for some finite distance. In the radial orientation of our steady two-stream model, antisunward particles will be present only if they scatter out of the sunward hemisphere through $\mu = 0$. In this case, the antisunward density is directly related to the scattering process. However, on a nearly perpendicular flux tube, ions will be picked up into both streams, and these ions can travel along the field in both directions for distances comparable to λ. This streaming transport can result in the mixing of ions which were picked up under different conditions. For example, if the IMF is only radial for some finite distance, antisunward particles can stream into the radial segment at its sunward end from the adjacent nonradial portion of the flux tube. Such a process is particularly important if the length of the radial segment is comparable to, or smaller than, the scattering mean free path. This additional source of antisunward particles can yield a larger value of the density ratio $N^{\|}_{+}/N^{\perp}_{+}$ than given by our simple model, leading to a lower derived value of λ. Thus we expect that the values of λ resulting from application of this two-stream model to the observations are at best underestimates of the true value.

Our two-stream model also neglects the effects of adiabatic deceleration in the spherically expanding solar wind. This process will systematically remove older pickup ions from the measurable plateau region and clearly influence the interpretation of the observed density.

Finally, in comparing these scattering mean free paths with those inferred from Ulysses data by *Gloeckler et al.* [1995] and *Fisk et al.* [1997], it may be important to note that we are dealing with He^+ while the Ulysses analyses were primarily treating protons. It has been assumed, in this paper as well as in the previous work on anisotropic pickup ions, that the long mean free path of these particles is essentially due to inhibited pitch angle scattering through $\mu = 0$. If this assumption is correct, the reduced scattering is related to the fluctuation levels of the dispersive, possibly dissipative, wave field around the cyclotron frequencies of the ions. The scattering rate in this wave field may be significantly different for the higher rigidity He^+ than for protons, but the details of this aspect of the wave-particle interaction are not well known. Continued improvements in the modeling of these anisotropic pickup ions, coupled with further observations, could provide valuable new information on this important process.

6. Conclusions

We have presented observations of interstellar pickup He^+ during periods of steady quasi-radial IMF. The measurements were made by the SULEICA instrument onboard the AMPTE/IRM spacecraft during its excursions upstream of Earth's bow shock. We find that whenever the magnetic field remained near radial for the ≥ 20 min required to construct a pickup He^+ spectrum, the flux of antisunward pickup ions was reduced compared to the levels obtained by *Möbius et al.* [1995] from periods of quasi-perpendicular IMF. During these times the spectral shape also changed, with the standard sharp cutoff at $E_c = 2\ M\ V_{sw}^2$ replaced by a smoother decline at lower energies. When considered as a change in the particle density in the plateau region of the spectrum, we found decreases ranging from 23% to 65%, with an average value of the radial-to-perpendicular density ratio of 0.52.

We interpret the antisunward flux reductions as the result of incomplete pitch angle scattering from the sunward hemisphere of phase space, implying that the sunward fluxes of these particles have increased during these radial periods. Thus these He^+ distributions seem to be manifestations of the same strong sunward anisotropy reported for pickup protons by *Gloeckler et al.* [1995]. In this work, we have shown that the presence of such a sunward anisotropy is directly dependent on a radial orientation of the IMF.

Additionally, we analyzed these observations in terms of a steady two-stream model of the pickup ion distribution. In the context of this model, we derived an effective scattering mean free path for these ions which ranged from $\lambda = 0.16$ AU to $\lambda = 0.76$ AU. We feel that the significance of these specific values is limited by the simplicity of the model, but they indicate that the mean free path for these particles can be comparable to the spatial scale of the system.

Acknowledgments. The authors are grateful for helpful and stimulating discussions with M. Bzowski. They are indebted to H. Lühr for the magnetic field data and to G. Paschmann for the solar wind data. E.M. and M.A.L., would like to thank the Polish Academy of Sciences for their hospitality and the stimulating atmosphere during their visits at the Space Research Centre in Warsaw. Likewise, D.R. would like to thank the University of New Hampshire for their hospitality during his visits at the Institute for the Study of Earth, Oceans and Space. The work presented here was performed under a collaboration between the University of New Hampshire and the Space Research Centre of the Polish Academy of Sciences. It was supported by NSF grants INT-9116367 and ATM 9215279, NASA grant NAG5-4818, by the NASA Space Physics Theory Program under grant NAG5-1479, and by grant 2 P03C 013 11 from the Committee for Scientific Research, Poland.

The Editor thanks N.A. Schwadron and another referee for their assistance in evaluating this paper.

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(Received April 14, 1997; revised September 24, 1997;
accepted September 24, 1997.)