INTERACTION OF INTERSTELLAR PICK-UP IONS WITH THE SOLAR WIND*

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Abstract. The interaction of interstellar pick-up ions with the solar wind is studied by comparing a model for the velocity distribution function of pick-up ions with actual measurements of He^+ ions in the solar wind. The model includes the effects of pitch-angle diffusion due to interplanetary Alfvén waves, adiabatic deceleration in the expanding solar wind and the radial variation of the source function. It is demonstrated that the scattering mean free path is in the range ≤ 0.1 AU and that energy diffusion can be neglected as compared with adiabatic deceleration. The effects of adiabatic focusing, of the radial variation of the neutral density and of a variation of the solar wind velocity with distance from the Sun are investigated. With the correct choice of these parameters we can model the measured energy spectra of the pick-up ions reasonably well. It is shown that the measured differential energy density of the pick-up ions does not vary with the solar wind velocity and the direction of the interplanetary magnetic field for a given local neutral gas density and ionization rate. Therefore, the comparison of the model distributions with the measurements leads to a quantitative determination of the local interstellar gas density.

1. Introduction

The interaction between the interstellar neutral gas and the interplanetary medium has been a topic of considerable interest for many years in theory as well as experimental investigation. It was not before the early 1970's that by means of spaceborn UV scattering measurements the first observational evidence of interstellar hydrogen in the solar system was presented (Bertaux and Blamont, 1971; Thomas and Krassa, 1971). The first conclusive results on interstellar helium were presented by Weller and Meier (1974). These observations initiated a rapid development of the understanding of the interaction processes. For an overview the reader may be referred to the reviews of Axford (1972), Fahr (1974), Holzer (1977), and Thomas (1978 and references quoted therein).

The solar system is moving with respect to the local interstellar medium (LISM) with a relative velocity of about 20 km s^{-1}. Thereby the interstellar gas is streaming through the heliosphere like an interstellar wind, which – when approaching the Sun – is subject to the forces of solar gravitation and radiation pressure. On the other hand the interstellar neutrals are ionized by solar UV radiation, by charge exchange with the solar wind ions and by electron collisions. These newly created ions are then picked up by the solar wind via interaction with the interplanetary magnetic field and finally swept out of the heliosphere. Therefore, the measurement of the absolute flux of the pick-up ions and of its spatial variation in interplanetary space can be used to determine the

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density, temperature, and relative velocity of the local interstellar medium.

A similar interaction with the solar wind is seen for neutral gas originating from other sources in interplanetary space. Planetary atmospheres and comets are only of local importance. The desorption of gas from interplanetary dust constitutes an extended source of neutrals in the inner solar system, i.e., at distances <0.5 AU (e.g., Fahr *et al.*, 1981).

After their initial pick-up by the interplanetary magnetic field the newly generated ions are subjected to efficient scattering processes by means of intrinsic and self-generated MHD waves (e.g., Wu and Davidson, 1972: Wu *et al.*, 1973: Winske *et al.*, 1985). Recently, Lee and Ip (1987) have shown that the waves generated by the hydrogen pick-up ions beyond 5 AU (i.e., the distance where the maximum ionization occurs) dominate the wave spectrum, while in the case of interstellar helium their contribution to the wave power is negligible compared with that of the intrinsic Alfvén waves in the solar wind at 1 AU. In early studies of the pick-up of interstellar gas by the solar wind it was assumed that the newly created ions are quickly thermalized and assimilated into the solar wind (e.g., Semar, 1970; Holzer, 1972; Fahr, 1974). These assumptions led to a contribution of He^+ to the solar wind, which should be detectable by solar wind plasma experiments for low solar wind temperatures. However, Feldman *et al.* (1974) reported an upper limit for He^+ which ruled out a thermalized He^+ ion distribution in the solar wind. Vasyliunas and Siscoe (1976) have presented a model of the pick-up ion distribution in which they assumed instantaneous isotropization of the ions due to pitch-angle scattering and subsequent adiabatic deceleration in the expanding solar wind. The resulting distribution with a sharp cut-off at the solar wind energy (in the rest frame of the solar wind) was recently found for helium by Möbius *et al.* (1985a). Generalizing the model by Vasyliunas and Siscoe (1976), Isenberg (1987) included the effect of energy diffusion. Comparison with the results by Möbius *et al.* (1985a) showed that the effect of energy diffusion is negligible.

In this paper we will derive an analytical model of the velocity distribution of pick-up ions which, based on the model of Vasyliunas and Siscoe (1976), includes explicitly the effects of pitch-angle diffusion, adiabatic deceleration and the variation of the neutral density with distance from the Sun. By comparing the model distributions with the measured pick-up ion distributions of interstellar helium it is demonstrated that the mean free path for pitch-angle scattering is smaller than 0.1 AU and that the shape of the spectrum puts an upper limit on the ionization rate for the interstellar helium. With the model as presented in this paper the measured pick-up ion distributions of interstellar helium are reproduced in a consistent way. This enables us to use the measurement of pick-up ions as a quantitative diagnostic tool for determining the local neutral gas density in the solar wind. Due to the annual journey of the Earth around the Sun the spatial distribution of the neutrals can be constructed, from which we can derive the temperature and relative velocity of the LISM.

In Section 2 we derive the distribution function of pick-up ions and the basic results of the model calculation. In Sections 3 and 4 we describe the instrumentation and the simulation of the energy spectra as seen by the instrument. The results as seen by the instrument in interplanetary space are compared with the simulated spectra in Section 5. The results are discussed in Section 6 in terms of the processes which determine the observed energy spectra, followed by a summary.

2. The Model of the Pick-up Ion Distribution

2.1. Initial pick-up

In contrast to genuine solar wind ions freshly created ions in interplanetary space are initially at rest. Immediately after ionization they are subject to the combined forces of the interplanetary $v_{sw} \times B$ electric field and the magnetic field B. In the inertial system the ions initially perform a cycloidal motion perpendicular to the local magnetic field. Their velocity varies between basically zero (the relative velocity of the neutral gas, ≈ 20 km s^{-1} for the interstellar gas, is neglected here compared with the solar wind velocity) and a maximum value

$$v_{\perp \max} = 2v_{sw} \sin \Theta \,, \tag{1}$$

which is determined by the solar wind velocity and the angle Θ between its flow direction and the local magnetic field. The maximum energy of pick-up ions then is

$$E_{\perp \max} = 4(m/2)v_{sw}^2 \sin^2 \Theta \,. \tag{2}$$

For constant solar wind conditions the resulting velocity distribution in the solar wind frame is a ring in velocity space with the pitch angle Θ. The ions gyrate with a velocity $v_\perp = v_{sw} \sin \Theta$ and move along the field with $v_\parallel = v_{sw} \cos \Theta$. The signatures of such undisturbed ring distributions have been observed after the artificial injections of lithium clouds into the solar wind (e.g., Möbius *et al.*, 1986).

2.2. Scattering processes

The energetic ring distribution with ion velocities $v_{sw} \gg v_A$ in the solar wind frame of reference is unstable to the generation of low-frequency MHD waves as has been discussed by, e.g., Wu and Davidson (1972), Wu *et al.* (1973), and Winske *et al.* (1985). On the other hand there exists already a background distribution of Alfvén waves in the solar wind. The resonant interaction with the ambient and the self-generated waves leads to an isotropization of the original ion distribution. Here scattering of the ions in pitch-angle μ is much more efficient than diffusion in energy E, since according to quasi-linear theory the corresponding scattering efficiencies scale like $(v_A/v_{sw})^2$ for pick-up ions at the solar wind velocity, where v_A is the local Alfvén velocity.

These effects also determine the basic behaviour of the propagation of cosmic rays in interplanetary space. For a review of cosmic-ray propagation (see, e.g., Jokipii, 1971). From an extrapolation of compiled cosmic-ray propagation parameters (Mason *et al.*, 1983) the mean-free scattering length λ of interstellar He^+ pick-up ions (with a typical magnetic rigidity of 5–10 MV in the rest frame of the solar wind) can be estimated to be $\lambda \approx 0.05$ AU. Hence, pitch-angle scattering seems to be rather efficient for pick-up ions from an extended source like the interstellar gas. Within a fraction of 1 AU away from the ionization site the ions fill a spherical shell in velocity space which is essentially comoving with the solar wind. Since the ions are injected into the solar wind with an initial energy of $E_0 = (m/2)\, v_{sw}^2$ the radius of the shell is equal to the solar wind velocity v_{sw}.

The scattering in pitch-angle $\mu = \cos\Theta$ on a sphere in velocity space in the expanding solar wind (with a diverging magnetic field), may be described by (e.g., Roelof, 1969)

$$\frac{\partial f}{\partial t} = \frac{1}{\tau}\frac{\partial}{\partial \mu}\left[\{1-\mu^2\}\frac{\partial f}{\partial \mu}\right] - \frac{v_{sw}}{2L}\{1-\mu^2\}\frac{\partial f}{\partial \mu}\,, \tag{3}$$

where $L \approx R/2$ (R = distance from the Sun) is the typical scale-length for the variation of the magnetic field strength, $1/L = -1/B\,(\partial B/\partial z)$ (z taken along the magnetic field line). The assumptions underlying (3) are the following: the pitch-angle diffusion coefficient $D_{\mu\mu}$ varies like $\sin^2\Theta = 1 - \mu^2$ over the sphere (isotropic scattering). The pick-up ions are convected with the solar wind velocity v_{sw}, which now is the macroscopic transport velocity for the ions. This is different from cosmic-ray propagation theory, where the ion velocity v generally is large compared to the solar wind velocity v_{sw}. Therefore, the ion-velocity v has already been replaced by v_{sw} in the second term of Equation (3). Let $\lambda = v_{sw}\,\tau$ be a scattering mean-free path during the convection of the distribution with the solar wind. Then (3) transforms in the co-moving frame into

$$\frac{\partial f}{\partial R} = \frac{1}{\lambda}\frac{\partial}{\partial \mu}\left[\{1-\mu^2\}\frac{\partial f}{\partial \mu}\right] - \frac{1}{2L}\{1-\mu^2\}\frac{\partial f}{\partial \mu}\,. \tag{4}$$

The asymptotic solution, i.e., $\partial f/\partial R$, or $\partial f/\partial t = 0$, of relation (4) is given (Roelof, 1969) by

$$f(\mu, R) = 1/4\pi\, e^{\lambda\mu/R}\,. \tag{5}$$

This leads to a deviation from an isotropic distribution in the asymptotic case ($t \to \infty$) of the order of λ/R. At distances > 0.5 AU from the Sun this deviation, i.e., the second term on the right-hand side of (4), is small, and the relation can be solved for variations of f with R including only the first term. For λ independent of R the solution then becomes

$$f(\mu, R) = 1/4\pi \sum_{l=0}^{\infty} (2l+1)\, e^{-l(l+1)R/\lambda}\, P_l(\mu)\, P_l(\mu_0)\,, \tag{6}$$

where $P_l(\mu)$ are Legendre polynomials of order l.

2.3. Adiabatic Deceleration

Also known from cosmic-ray propagation is the fact that ion distributions, which are convected with the solar wind, are subject to adiabatic cooling due to the radial expansion of the solar wind. Treating the pick-up ion distribution as an ideal gas (adiabatic index $\gamma = \frac{5}{3}$, the radius v of the spherical shell in velocity space, as seen at the distance R_0 from the Sun, varies as

$$v/v_{sw} = (R_0/R)^{-2/3}\,, \tag{7}$$

where R corresponds to the location of ionization of the ion sample. The ideal gas approximation is valid for immediate isotropization due to pitch-angle scattering, i.e., the scattering mean free path λ is small compared with the typical scale-length for the typical value of $\lambda\,(\approx 0.05)$ as given above. This relation is equivalent to a unique mapping of the distance R from the Sun into velocity space and, hence, the velocity distribution of pick-up ions can be derived from the radial source distribution, as is demonstrated in Figure 1. Since the ions are quickly distributed over a sphere in velocity space, the source function may be written as

$$S(R)\,\mathrm{d}R = v_{sw}(4\pi)v^2 f(v)\,\mathrm{d}v \tag{8}$$

i.e.,

$$f(v) = \frac{S(R)}{v_{sw}(4\pi)v^2\,(\mathrm{d}v/\mathrm{d}R)}\,, \tag{9}$$

where the right-hand side of Equation (8) describes the ion flux radially outward with the solar wind velocity v_{sw}. This relation holds for any functional dependence $v(R)$. For

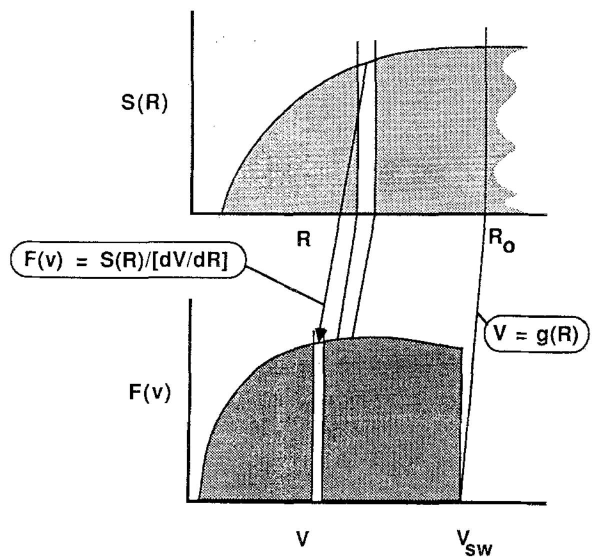

Fig. 1. Mapping of a source distribution over radial distance from the Sun into a velocity distribution, assuming adiabatic deceleration of the ion velocity distribution.

adiabatic deceleration (Equation (7)) this results in a velocity distribution

$$f(v) = \frac{3S(R)R_0}{8\pi v_{sw}^4} \left\{ \frac{v}{v_{sw}} \right\}^{-3/2}, \tag{10}$$

where R is taken as a function of v and, therefore, leads to a simple relationship for the distribution function.

2.4. Ionization of the Interstellar Gas

The source distribution $S(R) = N(R)\nu_{\mathrm{ion}}(R)$ depends on the local neutral gas density $N(R)$ and ionization rate $\nu_{\mathrm{ion}}(R)$. Interstellar neutrals are ionized by solar UV radiation, charge exchange with solar wind protons, and electron collisions. The solar UV flux varies like $1/R^2$ with distance from the Sun and depends substantially on the solar activity (see, e.g., Hinteregger, 1976). For the purpose of this paper we will assume constant UV flux with time. However, for a study of the temporal variations of the ion distribution the variability has to be taken into account. The solar wind flux also varies like $1/R^2$ and depends on the conditions in the solar corona (Hundhausen, 1972). The electron collisional ionization rate depends on the distribution function of the solar wind electrons. In the outer heliosphere, i.e., beyond 5 AU, the electron ionization rate may be enhanced by Alfvén's critical ionization velocity effect (Alfvén, 1954), as has been discussed by Petelski *et al.* (1980). In the inner heliosphere the ionization of interstellar hydrogen is dominated by charge exchange with the solar wind, while UV ionization prevails for interstellar helium (Holzer, 1977), both varying as $1/R^2$ as mentioned above. The newly generated ions are convected with the expanding solar wind, so that (after ionization) the density varies as $1/R^2$ with distance from the Sun. Therefore, the density of ions injected into the solar wind does not vary with distance R.

Thus the velocity distribution $f(v)$ solely reflects the radial variation of the neutral gas density $N(R)$. The distribution of interstellar neutral particles in the vicinity of the Sun is basically determined by the solar gravitation, radiation pressure, and removal by ionization. According to e.g., Fahr (1968), Blum and Fahr (1969), Holzer (1972), and Axford (1972) for a cold interstellar gas the spatial distribution $N(R, \Theta)$ of the neutrals is given by

$$N(R, \theta) = \frac{N_0}{\sin\theta} \left\{ \frac{\partial b_1}{\partial R} e^{\Lambda\theta/b_1} + \frac{\partial b_2}{\partial R} e^{-\Lambda(2\pi-\theta)/b_2} \right\}, \tag{11}$$

with

$$\begin{Bmatrix} b_1 \\ b_2 \end{Bmatrix} = \left[\left(\frac{1}{2} \sin\theta \right)^2 + (1-\sigma) \frac{GM}{V_0^2} R(1-\cos\theta) \right]^{1/2} + \frac{1}{2} R\sin\theta\,; \tag{11a}$$

N_0 being the density at infinity, θ the angle between the direction of the Sun's motion (with velocity V_0) with respect to the interstellar medium and the line connecting the observer with the Sun, GM/R^2 is the gravitational force of the Sun and σ is the relative contribution of the radiation pressure (which is negligible for helium). $\Lambda = R_0^2 \, \nu_{\text{ion}}/V_0$ is a characteristic penetration depth of the interstellar gas, which depends on the ionization rate ν_{ion} at the reference distance R_0 and the velocity of the interstellar wind V_0. Equation (11) neglects the thermal spread in the velocities of the neutral particles, which leads to significant modifications in the close vicinity of the downwind axis. Equation (11) may still be used for angles θ larger than the halfwidth of the gravitational focusing cone on the downwind axis, which is typically 15° for helium (e.g., Dalaudier *et al.*, 1984).

2.5. Resulting Distribution Function

By the combination of Equation (6) with (10) the velocity and pitch-angle distribution function of pick-up ions in the solar wind can be written as

$$f(\mu, w) = \frac{3S(R)R_0}{8\pi v_{sw}^4} \{w\}^{-2/3} \sum_{l=0}^{\infty} (2l+1)\, e^{-l(l+1)R/\lambda} P_l(\mu) P_l(\mu_0)\,, \tag{12}$$

where $w = v/v_{sw}$ is the ion velocity normalized to the solar wind velocity. This solution is exact in the limits of negligible energy diffusion and ideal isotropic adiabatic deceleration, i.e., when separation of the v and μ variables can be applied. Isenberg (1987) modelled the velocity distribution including explicitly the effects of energy diffusion. A comparison with the measurements of pick-up He^+ ions by Möbius *et al.* (1985a) showed that energy diffusion can be indeed neglected compared with adiabatic deceleration for observations at 1 AU. This can be confirmed by taking the velocity distribution function derived by Isenberg (1987) instead of the distribution (12) when comparing with the measurement according to the procedure outlined below. Isotropic adiabatic deceleration in the solar wind requires rapid pitch-angle diffusion compared with the expansion of the volume element in the solar wind. With λ of the order of

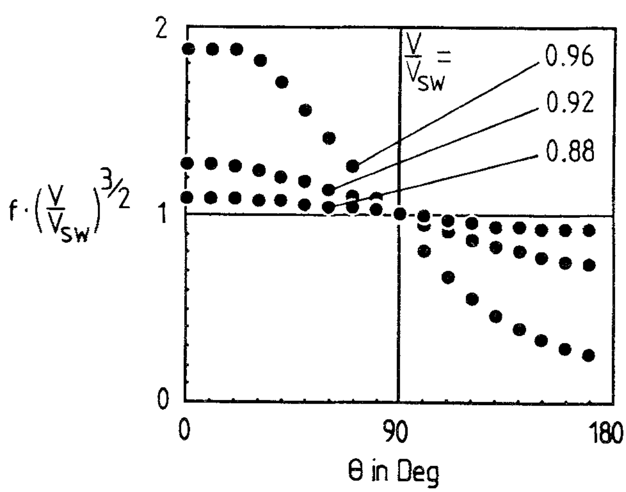

Fig. 2. Normalized velocity distribution function $f(v)\,(v/v_{sw})^{3/2}$ for various values of $w = v/v_{sw}$ as a function of pitch-angle Θ after injection of pick-up ions with an initial pitch-angle $\Theta = 0$.

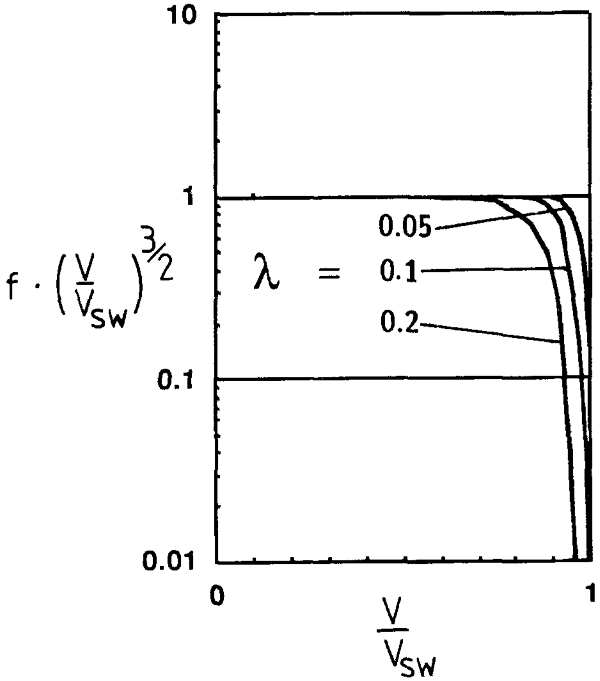

Fig. 3. Normalized velocity distribution function in the solar wind direction (Sun-sector) as a function of V/V_{sw} for different values of the scattering mean free path (λ = 0.05, 0.1, 0.2).

0.05 AU and a typical scale-length for deceleration $1/(\mathrm{d}B/\mathrm{d}R)$ of 1 AU this requirement holds for distances ≥ 0.5 AU. Near the Sun modifications are necessary, which will be outlined qualitatively in Section 6.

Equation (12) presents a description in terms of nested spherical shells with the pitch-angle distribution evolving from a ring at pitch-angle μ_0 to a homogeneous sphere towards lower velocities w, as is illustrated in Figure 2 for an injection pitch-angle $\mu_0 = 1$ and a scattering mean free path $\lambda = 0.1$ AU. Significant deviation from a homogeneous sphere are found only for $v/v_{sw} \geq 0.9$. Figure 3 shows a cut through the distribution at $\mu = -1$ for different values of λ. It is demonstrated that the cut-off is smoothed considerably for $\lambda \geq 0.1$ AU. For smaller values the change is hardly noticeable and will be of no importance in the comparison with measurements.

3. Measurements of the Pick-up Ions

The measurements presented in this paper were obtained with the SULEICA (Suprathermal Energy Ionic Charge Analyzer) instrument of the Max-Planck-Institut and the University of Maryland on board the AMPTE/IRM spacecraft. The IRM was launched on August 16, 1984, into a highly elliptical orbit with an apogee of $\approx 18.7\, R_{\mathrm{E}}$. The satellite and the instrumentation worked until the spacecraft battery failed on August 12, 1986. Between July and December the satellite spent a large fraction of each orbit in the solar wind upstream of the Earth's bow shock. Therefore, a comprehensive data set on interstellar pick-up ions over the two years mission could be obtained.

The SULEICA instrument combines the selection of incoming ions according to their energy per charge by a spherical section electrostatic analyzer with a subsequent time-of-flight analysis and the final measurement of the residual ion energy in a silicon surface barrier detector. With these techniques the ions are differentiated according to their mass, ionic charge, and energy. The energy range of the instrument from 5 to 270 keV e^{-1} is covered by stepping the analyzer voltage in up to 24 logarithmically spaced voltage steps synchronously with the spacecraft spin. In the low-energy range (i.e., below 40 keV total) the signal of the solid state detector does not exceed the noise level. However, for a specific energy step, ions of different mass per charge ratios are clearly separated by their time-of-flight. The major ion species are accumulated on board according to a matrix rate system using look-up tables for time-of-flight and energy pulse heights. In our investigation we rely on the corresponding rate information for the He^+ ions.

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^+ which is of interest here. The center viewing direction of sector number 4 (out of sectors 0 to 7) is pointing towards the Sun (GSE x direction) and will be further called the Sun-sector. A more detailed description of the instrument may be found elsewhere (Möbius *et al.*, 1985b).

4. Simulation of the Ion Measurements

In order to allow a quantitative comparison of the model distributions with the results of the ion spectrometer measurements the quantities, as measured by the instrument, have to be simulated by integration over the instrumental sectors and energy steps, which have been described in the previous section, in the spacecraft frame of reference. Figure 4 shows a cut through a pick-up ion velocity distribution in the plane perpendicular to the spacecraft spin axis together with the sectoring scheme (radial fans) and the energy steps (concentric ring system) of the SULEICA instrument. For the simulation an equidistant grid with 10 points in each direction – velocity, azimuthal angle, and elevation angle (not shown in Figure 4) – is used within each individual channel.

Each individual data point ((v', Θ', Φ') in the spacecraft frame is first transformed by a rotation into a system (v'', Θ'', Φ'') with the z-axis pointing into the solar wind direction, followed by a transformation into the solar wind frame of reference (v''', Θ''', Φ''') according to

$$\begin{aligned} v''' &= \sqrt{[v''^2 + v_{sw}^2 - v_{sw} v'' \cos(\Theta'')]}\,, \\ \Theta''' &= \arctan[\sin(\Theta'')/(\cos(\Theta'') + v_{sw}/v'')]\,. \end{aligned} \tag{13}$$

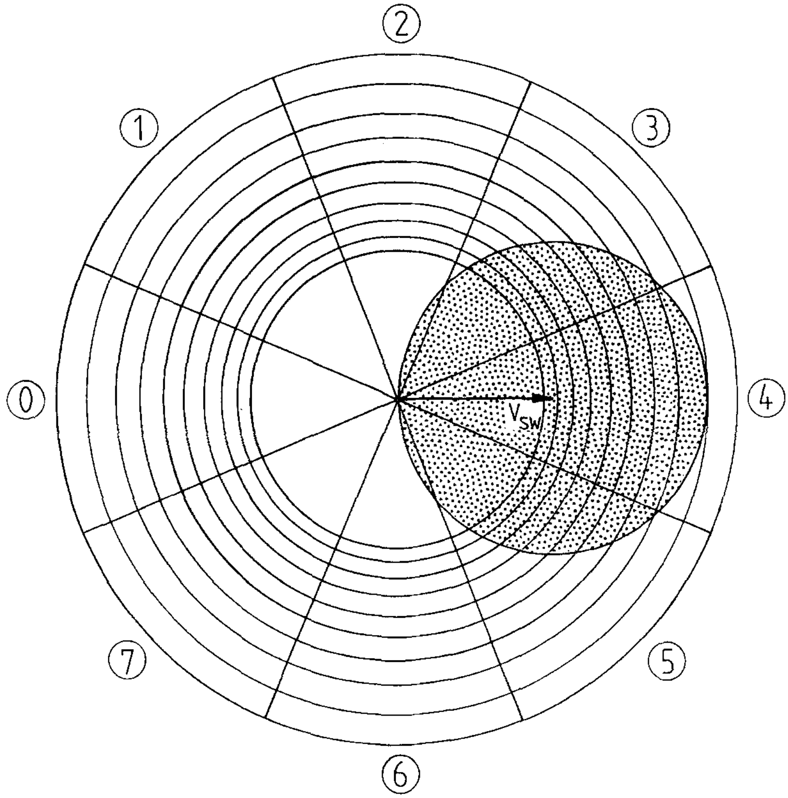

Fig. 4. Cut through the pick-up ion distribution function in the plane perpendicular to the spacecraft spin together with the sectoring scheme (radial fans) and the energy stepping (concentric rings) of the SULEICA instrument.

Finally, a second rotation into the natural frame of reference of the pick-up ion distribution function (v, Θ, Φ), i.e., with the z-axis parallel to the magnetic field, is applied. Due to the gyrotropic distribution $(\partial f/\partial\Phi = 0)$ the calculation is significantly simplified in this way. From the ion distribution, as derived in Section 2, the differential energy flux density $E\,\Delta J/\Delta E$ is computed according to the relation

$$\frac{E\,\Delta J}{\Delta E} = \frac{v_{sw}^4}{\Delta\Omega\,\Delta E}\int f'(\mu', w')\,(m/2)\,w'^2\,w' 2\pi\,\mathrm{d}\mu'\,\mathrm{d}w'\ . \tag{14}$$

The integration is performed over individual instrument channels. The simulation is performed using the actual parameters in the solar wind (solar wind velocity v_{sw} and the azimuth Φ_B and elevation λ_B of the magnetic field), as obtained by the 3D-plasma instrument (Paschmann *et al.*, 1985) and the flux-gate magnetometer (Lühr *et al.*, 1985) on the AMPTE/IRM satellite. It should be noted here that the appropriate quantity to determine the local source strength $S(R)$ is, indeed, the differential energy flux. From

Equations (12) and (14) it can be seen that the relation between the source strength and the differential energy flux density is independent of the solar wind velocity.

The computed quantities can now be compared with the corresponding values, as measured by the SULEICA instrument in the individual sectors and energy steps. Energy and angular response, as well as detection efficiencies of the instrument have been applied already for the determination of the measured differential energy flux densities. For a comparison with the model calculation the data of one pass of the satellite ($\approx$ 8–10 hours of data) are rearranged in terms of the same solar wind velocity and the angle between the solar wind flow direction and the magnetic field vector. In this way pick-up ion distributions for a specific well-defined set of solar wind parameters with reasonably good counting statistics can be compared with the model.

5. Comparison with Measured Energy Spectra

In order to allow a comprehensive comparison of a measured energy spectrum with the stimulated energy spectrum, the data have been selected for:

– Periods with high solar wind velocities (>600 km s^{-1}): since the energy cut-off scales with the solar wind velocity and the SULEICA instrument is limited to energies above 5 keV e^{-1}, the most complete energy spectra can be obtained during periods with high solar wind velocities.

– Periods during November and December: during the early December days the Earth is moving through the gravitational focusing cone of the interstellar gas, where the neutral density is significantly enhanced. This leads to a substantial increase of the pick-up flux (Möbius *et al.*, 1985a) and, therefore, to increased ion count rates.

– Periods, when almost no energetic ions were observed upstream of the Earth's bow shock: although the pick-up ion distribution can be clearly identified in the presence of upstream ions, signatures like the energy cut-off and the angular distribution can be studied best during their absence.

In Figure 5 the measured energy flux density spectra in sectors 3, 4, and 5 are shown for samples with two different interplanetary magnetic field orientations on November 15, 1985, during the time period 3 : 00 UT to 11 : 00 UT. During this day the angle between the solar wind flow and the magnetic field varied from about 70° to 150°, and the solar wind velocity covered about 630 to 690 km s^{-1}. The two samples were accumulated for a solar wind velocity range of 670 to 690 km s^{-1} and angular ranges of 67.5° to 112.5° and 112.5° to 157.5, denoted as 90° in the upper three panels and as 135° in the lower three panels of Figure 5, respectively. The data are shown above 8 keV e^{-1}. At lower energies the He^{+} channel, as derived in the on board data handling of the instrument, does not match exactly with the mass/charge range of these ions and, therefore, is also sensitive to other ions.

As expected from the schematic of the distribution shown in Figure 4, significant fluxes of the pick-up ions are indeed only found in the Sun-sector and the two adjacent sectors (cf. Möbius *et al.*, 1985a, Möbius, 1986). In the Sun-sector (sector 4) the energy flux density shows a cut-off at 33 keV e^{-1} and a plateau between 30 and 16 keV e^{-1},

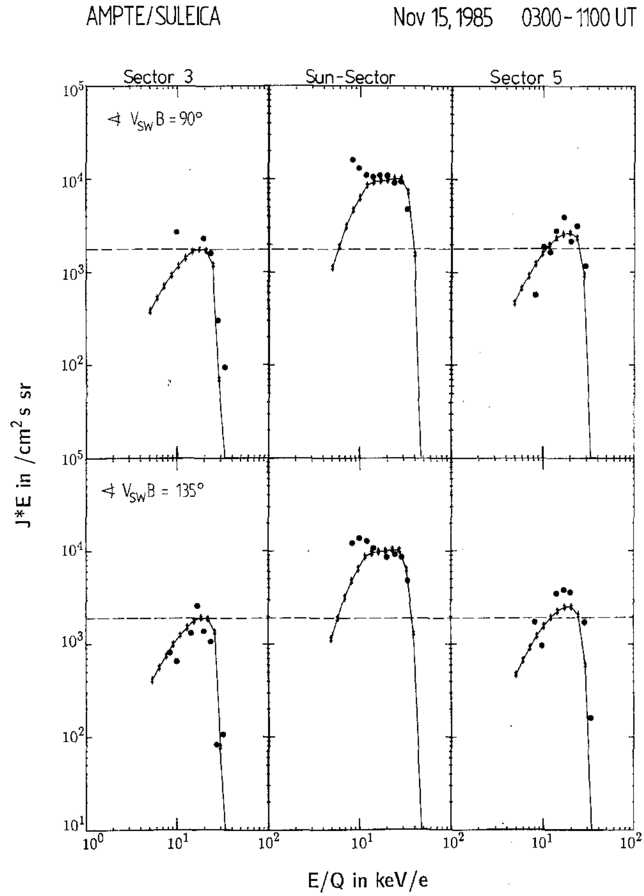

Fig. 5. Comparison of simulated energy flux density spectra (stars) for the actual solar wind parameters (v_{sw} = 680 km s^{-1}, angle ϕ between solar wind and magnetic field direction 90° in the upper panels and 135° in the lower panels) with spectra as measured by the SULEICA instrument for the Sun-sector and the two adjacent sectors.

which are both more pronounced for the 90° orientation. Near 10 keV e^{-1} a clear increase of the ion flux by about 50% is seen. However, at least part of this increase has to be attributed to solar wind ions: due to the limited resolution of the instrument at low energie, also heavy ions like, e.g., O^{5+} and O^{6+} contribute to the M/Q = 4 count rate at $E \approx 10$ keV e^{-1} for solar wind velocities of $\approx$680 km s^{-1}. In the two adjacent sectors the pick-up ions form spectra, which peak between about 15 and 20 keV e^{-1} with a cut-off at $\approx$25 and $\approx$28 keV e^{-1} in sectors 3 and 5, respectively. The energy flux density in these sectors is generally lower by a factor of 6 in sector 3 and a factor of 3 in sector 5 compared to the Sun-sector, i.e., the pick-up ion distribution shows a significant anisotropy with respect to the Sun direction.

The model spectra in Figure 5 have been calculated with a neutral density variation according to Equation (11) with a typical penetration distance Λ = 0.5 AU, which corresponds to an ionization rate $\nu_{\text{ion}} = 6.5 \times 10^8 \text{ s}^{-1}$ at 1 AU and a velocity of the interstellar wind of 20 km s^{-1}. The spectra were normalized to the measured ion fluxes such that the plateau in the Sun-sector matches that of the measured distributions. From this procedure the product $N_0\ \nu_{\text{ion}} = 4.2 \times 10^{-10} \text{ cm}^{-3} \text{ s}^{-1}$ of the helium density at infinity N_0 times the ionization rate ν_{ion} at 1 AU was derived. With ν_{ion} as given above this is equivalent to a neutral He density $N_0 \approx 0.0065 \text{ cm}^{-3}$. In addition, the direction of the solar wind, as taken in the model calculation, has been corrected for the aberration due to the motion of the Earth ($\approx 3°$ for the actual solar wind velocity). Both, the measured and the model spectra are in reasonably good agreement. All the main features of the measured pick-up ion distribution, as the cut-off, the plateau and the flux radio between the Sun-sector and the two adjacent sectors, are well represented in the model spectra. The anisotropy between sectors 3 and 5 seems to be somewhat larger in the measured spectra. Furthermore, it should be noted here that according to Equation (8) the spectral shape depends crucially on the assumptions made for the source distribution, which will be discussed in detail below.

6. Discussion

There are several processes which may add to the observed anisotropy in sectors 3 and 5. They are illustrated in terms of the present model in Figure 6. The upper three panels show the distribution, as derived from Equation (12) for the solar wind blowing into a purely radial direction and a magnetic field orientation of 135° with respect to the solar wind. The injection of pick-up ions into the solar wind with a pitch-angle of 45° leads to higher fluxes in sector 3, which is scanning the distribution function perpendicular to the magnetic field, while sector 5 scans the part of the distribution mainly parallel to the field. A finite mean free scattering length λ produces higher phase space densities perpendicular to the magnetic field in the outer shells of the velocity distribution (cf. Equation (12) and Figure 2). The resulting anisotropy is of the order of 15%. The three center panels of Figure 6 show a distribution, which includes the effects of the adiabatic focusing in the limit of a stationary distribution. In this limit the solution for the distribution on a velocity shell as given in Equation (5) applies. As a result the phase space density is increased in the direction of the diverging magnetic field, i.e., in the anti-solar direction. Therefore, the flux in sector 5, which covers the distribution function parallel to B is higher than the flux in sector 3. The resulting anisotropy is of the order of 20%. These two effects act on the distribution function at the same time, but have only been described separately for illustration. In a realistic approach they are expected to almost cancel each other.

It should be noted here that the effect of adiabatic focusing gives also a handle on the scattering mean free path λ, since the lowest ion flux in the Sun-sector would be expected for a magnetic field orientation of 90° keeping all other parameters, like solar wind velocity and ionization rate, constant. For orientations of 135° or 180° the flux would be increased, more and more pronounced with increasing values of λ. According to (5) and (14) a 20% difference between the two orientations in Figure 5 would be

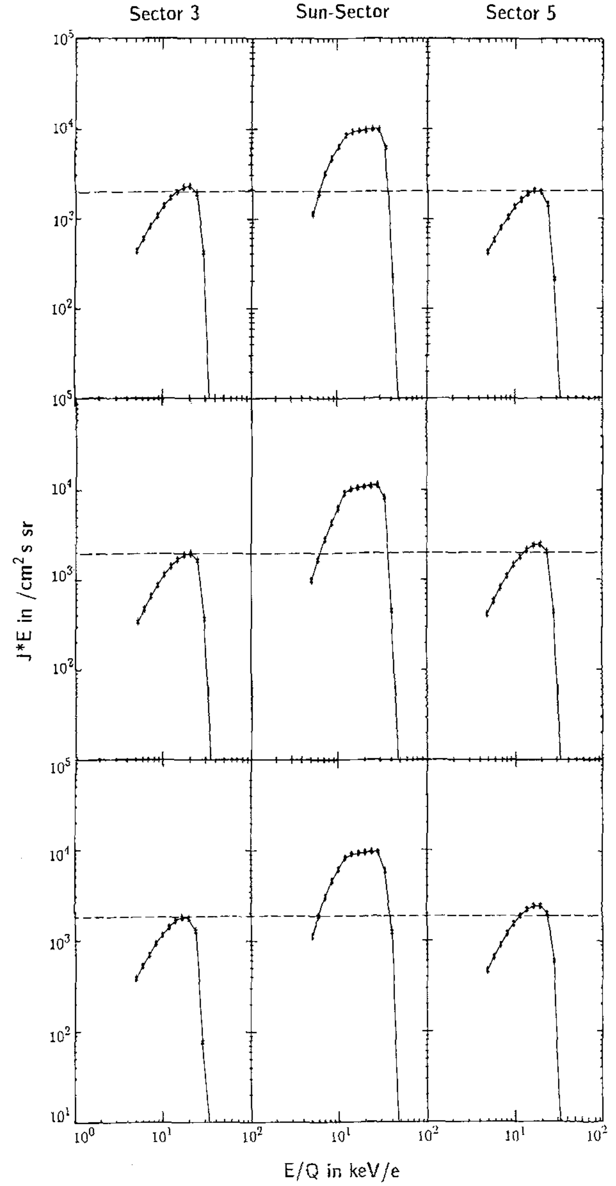

Fig. 6. Simulated energy flux density spectra for the Sun-sector and the two adjacent sectors with $\phi = 135°$ (left) and $\phi = 225°$ (right) under various assumptions. From top to bottom: (a) Time-dependent pitch-angle scattering without adiabatic focusing, solar wind direction 180°. (b) Stationary distribution after pitch-angle scattering with adiabatic focusing, solar wind direction 180°. (c) Time dependent pitch-angle scattering without adiabatic focusing, solar wind direction 177° (mean aberration of the solar wind due to the motion of the Earth).

expected for $\lambda = 0.2$ AU. The experimental results are compatible with values $\lambda \leq 0.1$ AU.

In the lower three panels of Figure 6 an aberration by 3° of the solar wind from the radial direction to 177° in the GSE coordinate system has been applied. This is equivalent to the aberration introduced by the motion of the Earth around the Sun for the given solar wind velocity. The resulting anisotropy between sectors 3 and 5 is a factor of 1.5. It is evident that this is the dominant effect for the anisotropy of the ion distribution. In addition, the direction of the solar wind velocity is variable within a few degrees (e.g., Pizzo *et al.*, 1983) which may lead to larger anisotropies.

As stated already above the spectral shape of the pick-up ions depends crucially on the actual source distribution of the neutrals. The influence of different variations of the neutral density with distance from the Sun is illustrated in Figure 7 for four values of the penetration distance Λ for interstellar helium (0.5, 0.7, 1.0, and 1.5 AU). The measured energy spectra seem to be best represented by the lowest value of Λ. This value is equivalent to an ionization rate $\nu_{\text{ion}} = 6.5 \times 10^{-8}\ \text{s}^{-1}$ at 1 AU, which has been given as a typical value under solar minimum conditions by Rucinski (1985), and a velocity of 20 km s^{-1} for the interstellar wind. The latter value is consistent with the relative velocity of the Sun and the interstellar medium, as derived from the Lα background radiation (e.g., Bertaux and Blamont, 1971; Chassefiere *et al.*, 1986). It should be noted here that the present measurements have indeed been obtained during the solar minimum. The larger values of Λ correspond to increasing values of the ionization rate up to $2 \times 10^{-7}\ \text{s}^{-1}$, which is, according to Ruczinski (1986), the value for the solar maximum. Thus a significantly different energy spectrum of interstellar He ions can be

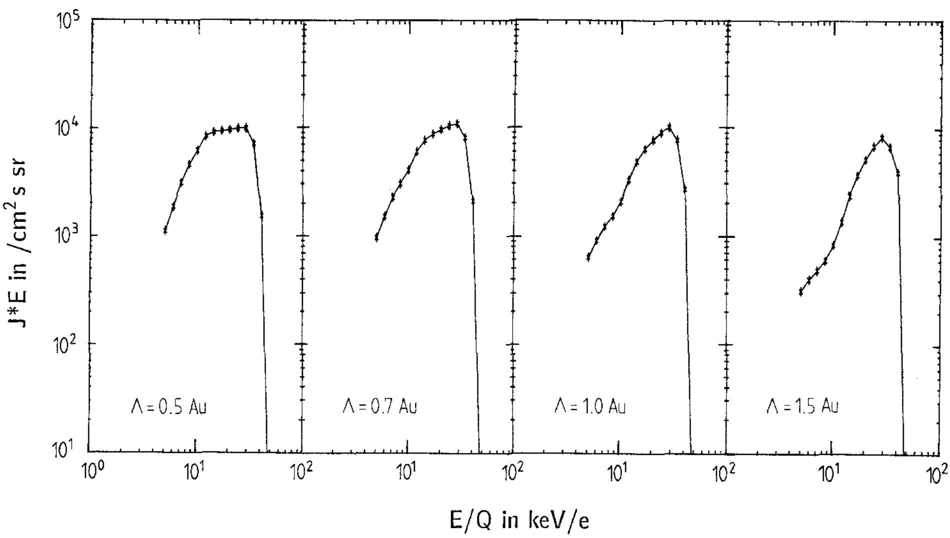

Fig. 7. Simulated energy flux density spectra in the Sun-sector for different radial distributions (see text) of the interstellar He density in interplanetary space from left to right: typical penetration distance $\Lambda = 0.5$, 0.7, 1.0, and 1.5 AU.

expected for the solar maximum. Although we may put constraints on the ionization rate from the comparison with measured spectra, the method is not sufficiently accurate as a quantitative measurement of v_{ion}, since the velocity distribution of pick-up ions also depends on its evolution in velocity space with distance from the Sun (cf. Equation (8)).

In the present model calculation we have assumed that the solar wind velocity does not vary with distance from the Sun. However, a radial variation may substantially change the mapping relation for the radial source distribution. In the following we will discuss these effects.

The main acceleration of the solar wind occurs at a distance of a few solar radii from the Sun. However, there is still a moderate increase of the solar wind velocity at distances between 0.3 to 1 AU, which are of interest here. Hundhausen (1972) discussed a model, which shows a velocity increase of $\approx 20\%$ from 0.3 AU to the Earth's orbit. Statistical studies of the HELIOS solar wind data, which were obtained between 0.3 and 1 AU, by Schwenn *et al.* (1981) showed that this is an upper limit for the observed variations. These authors find a velocity increase between 4 and 17% for high solar wind speeds and almost constant velocities with distance from the Sun for low solar wind speeds. In order to demonstrate the effect of the solar wind velocity variation on the pick-up ion distribution we have plotted in Figure 8 the energy spectra in the Sun-sector for Λ = 1.0 AU for a constant solar wind velocity (left panel) and a solar wind velocity, which varies according to Hundhausen (1972) (right panel). As can be seen from

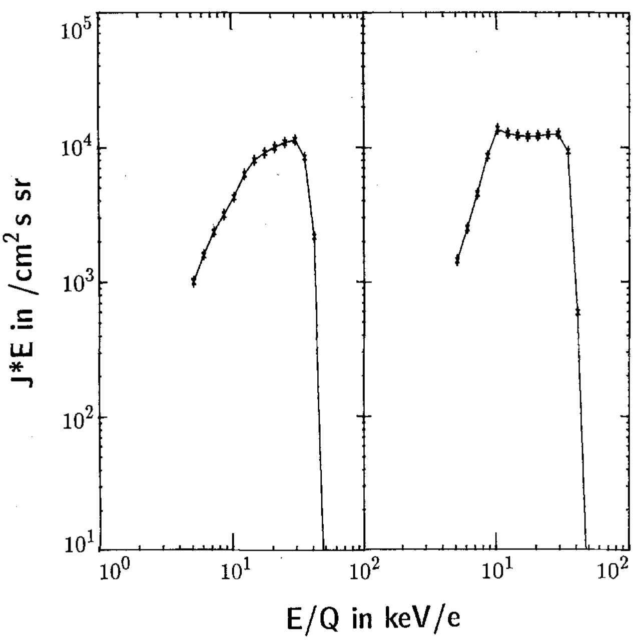

Fig. 8. Simulated energy flux density spectra for a model, which includes the variation of the solar wind velocity with distance from the Sun for Λ = 1.0 AU. *Right panel*: Variation of the solar wind speed v_{sw} after Hundhausen (1972). *Left panel*: Constant solar wind speed.

Figure 8 the main effect is a flattening of the spectrum towards lower energies. This is due to the fact that the shells in velocity space, which originate from a distance closer to the Sun, are nested closer (dv/dR larger) than the outer shells and, therefore, the phase space density of the inner shells is increased. We have used the maximum possible value for the increase of the solar wind velocity with radial distance from the Sun. In general, the effect may be smaller according to the experimental results by Schwenn *et al.* (1981).

With a UV ionization rate $\nu_{\mathrm{ion}} = 6.5 \times 10^{-8}\ \mathrm{s}^{-1}$ for solar minimum conditions in 1985 the measured value of the ion flux is compatible with an interstellar density $N_0 = 0.0065\ \mathrm{cm}^{-3}$. The data were obtained during a period when the Earth was approaching the gravitational focusing cone of the interstellar gas. Therefore, the local density is enhanced compared to the He density outside the heliosphere. It should be noted here that the simple estimate as given by Möbius *et al.* (1985a) is in good accordance with this model. Furthermore, the energy flux density of pick-up ions is independent of the interplanetary parameters, such as magnetic field and solar wind velocity, as has been demonstrated in Section 4. Thus the model calculation, as presented in this paper, forms a diagnostic tool for the quantitative determination of the interstellar gas density and the interstellar helium temperature from the evaluation of the cone structure by means of He^+ pick-up ions. Such an investigation is currently in preparation.

Finalizing our discussion we would like to repeat the limitations of the present model: the model was derived under the strict assumption of a separability of the variables v (ion velocity) and μ (pitch-angle). In particular, the adiabatic deceleration has been treated under the assumption of instantaneous pitch-angle scattering to isotropy. In a more realistic approach one would have to admit that pitch-angle scattering takes a finite time and adiabatic deceleration of magnetized ions works solely perpendicular to the magnetic field. The information of the velocity decrease is transmitted parallel to B via pitch-angle scattering. Qualitatively the combination of pitch-angle scattering and adiabatic deceleration would, therefore, form an elipsoidal shell which is squeezed perpendicular to B rather than an ideal spherical shell distribution. The deviation from the spherical symmetry is still small at 1 AU (of the order of $2\lambda/R = 0.1$), but would become excessively large much closer to the Sun. The adiabatic deceleration becomes more and more inefficient. In this regime the separation of variables, as used here, is not allowed any more. Since interstellar He atoms even reach distances as close as 0.3 AU to the Sun, a rigorous treatment of the distribution function including simultaneously, becomes necessary for the description of the innermost portion of the velocity distribution function. The treatment of this paper can only illustrate trends in this regime. However, for the main portion of the distribution, which originates from distances >0.3 AU, the model is fully adequate.

7. Summary

We have simulated the energy spectra of pick-up ions in the solar wind with an analytical model and compared those with measured spectra. We have shown by modeling of pitch-angle scattering and adiabatic deceleration as well as adiabatic focusing that the mean free path is less than 0.1 AU.

The energy spectra of the pick-up ions can be modelled by incorporating the radial dependence of the solar wind velocity and of the source strength. The shape of the energy spectra puts constraints on the ionization rate of interstellar helium and is compatible with values as low as $6.5 \times 10^{-8}\,s^{-1}$ as has been discussed for solar minimum conditions. The observed anisotropy can be understood by the motion of the spacecraft relative to the solar wind and a possible longitudinal component of the solar wind velocity. The energy flux density turns out to be independent of the interplanetary parameters as the magnetic field and the solar wind velocity and can thus be used to determine the absolute value of the source strength at 1 AU. Together with a measurement of the EUV flux the local interstallar gas density can be derived.

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