GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 20, PAGES 3181-3184, OCTOBER 15, 1999

Direct evidence of the interstellar gas flow velocity in the pickup ion cut-off as observed with SOHO CELIAS CTOF

E. Möbius[1], Y. Litvinenko[1], H. Grünwaldt[2], M.R. Aellig[3], A. Bogdanov[4], F.M. Ipavich[5], P. Bochsler[3], M. Hilchenbach[2], D. Judge[6], B. Klecker[4], M.A. Lee[1], and H. Ogawa[6]

Abstract. He^+ pickup ions as observed with SOHO CELIAS CTOF have been analyzed for the time period DOY 160 - 190, 1996. During this time of the year the Earth is on the upwind side of the interstellar gas flow with respect to the sun. The high-speed cut-off in the frame of the sun is significantly higher $v/V_{sw} = 2$, predicted for pickup ions. The difference increases with lower solar wind speeds. This behavior is interpreted as an effect of the local interstellar gas flow velocity (inflow at large distances including gravitational acceleration by the sun) on the pickup ion distribution. The neutral velocity is added to the solar wind velocity in the determination of the pickup ion cut-off on the upwind side and subtracted on the downwind side of the gas flow. This new observation will provide a valuable tool to determine the interstellar gas flow and will thus complement direct neutral gas measurements.

Introduction

Pickup ions have become a very widely used observational tool to probe the interstellar gas distribution and are a key to the interaction of the heliosphere with the local interstellar medium. Generally the combination of the local neutral gas density and the ionization rate determines the pickup ion fluxes, whereas the details of the pickup ion distribution function depend on the transport of these ions in the solar wind. The experimental study of interstellar pickup ions started with the detection of He^+ on the AMPTE IRM spacecraft [*Möbius et al.*, 1985]. Later the detection of interstellar H^+ (*Gloeckler et al.*, 1993), N^+, O^+, and Ne^+ (*Geiss et al.*, 1994) pickup ions has been reported at distances of 2 - 5 AU from the sun using the SWICS instrument on Ulysses. These studies are of general interest in astrophysics, because they create a direct link between in-situ measurements of the interstellar gas with astronomical remote sensing techniques. Of course, the interstellar parameters outside the solar system have to be inferred from data taken in the inner heliosphere using a detailed modeling of the transport of the interstellar gas into the heliosphere.

[1]Dept. of Physics and Inst for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824

[2] Max-Planck-Institut für Aeronomie, Postfach 20, D-37189 Katlenburg-Lindau, Germany

[3]Physikalisches Institut, Universität Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland

[4]Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany

[5] Department of Physics, University of Maryland, College Park, MD 20742

[6]Space Science Center, University of Southern California, Los Angeles, CA 90089

Paper number 1999GL003644.
0094-8276/99/1999GL003644$05.00

Solar EUV radiation, charge exchange with solar wind ions, and electron collisions ionize the incoming interstellar neutrals, thus creating a cavity in the interstellar cloud. Except in the case of H where radiation pressure is important, the sun acts as a huge gravitational lens creating a cone of focused gas with a substantial density increase on the downwind side. The density increase and the width of the cone depend sensitively on the temperature and relative velocity of the local interstellar medium (LISM) as well as on the mass of the species. It is this structure that allows us to infer the LISM temperature and relative velocity. For overviews on this topic the reader is referred to reviews by, e.g., *Axford* [1972] and Holzer (1989). A first determination of density, temperature and relative velocity of He in the LISM using pickup ion measurements has been presented by Möbius et al. (1995). The use of He^{2+} pickup ions, which are produced through double charge exchange with solar wind He^{2+} (Rucinski and Fahr, 1989), allowed Gloeckler (1996) to derive a more accurate interstellar He density. The accuracy of LISM parameters determined from pickup ions is still limited by this method, as the pickup ion velocity distribution also contains the imprint of their transport in the actual interplanetary magnetic field (IMF) and solar wind. For example, transport leads to a smearing of the inferred spatial structure of the neutral gas distribution. Indeed the scattering mean free path length turned out to be substantially longer than expected (Gloeckler et al., 1995; Möbius et al., 1998). Therefore, the determination of the neutral gas velocity distribution by direct observation of neutrals yields a more accurate result for the LISM flow and temperature (Witte et al., 1996). It was tacitly believed that direct determination of the gas velocity from the pickup ion distribution is prevented by the fact that the LISM flow is very slow compared with the solar wind.

In this paper we will present the first direct evidence for the interstellar flow velocity as determined with pickup ions using SOHO CELIAS data. On the upwind side of the interstellar gas flow with respect to the sun, i.e. for pickup ion observations taken during June and July, the high-speed cut-off is significantly increased over the usual value of $v/V_{sw} = 2$. In comparison with the modeled pickup ion distribution this observation provides a determination of the local interstellar gas flow velocity at the Earth's orbit.

Instrumentation and Data Analysis

The data presented in this paper have been obtained with the Charge, Element and Isotope Analysis System (CELIAS) on the Solar and Heliospheric Observatory (SOHO). CELIAS contains three sensors (CTOF, MTOF, STOF) that determine the composition of the solar wind and the suprathermal ion populations in interplanetary space, a solar wind Proton Monitor (MTOF PM) to determine the solar wind bulk parameters, and a Solar EUV Monitor (SEM). The data of all sensors

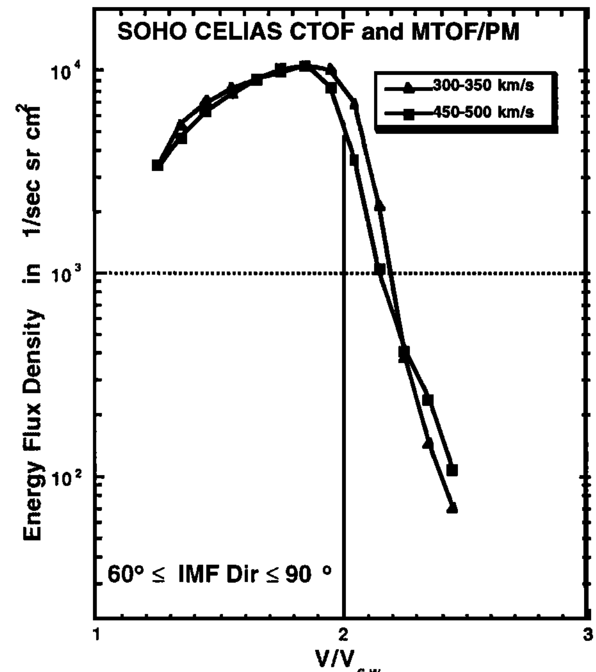

Figure 1. Pickup ion spectra for two solar wind speed ranges. The relative shift in the cut-off speed beyond $v/V_{sw} = 2$ increases as the solar wind speed decreases.

are handled through a common data processing unit (DPU). A detailed description of the sensors and the data system may be found elsewhere (Hovestadt et al., 1995). The pickup ion data have been obtained using the charge-determining time-of-flight (CTOF) sensor. The ionic charge (Q), mass (M) and energy (E) of incoming ions are determined in the energy range 0.3 - 34.8 keV/e. This allows the identification and coverage of the He^+ pickup ion distribution from just above solar wind speed to the high speed cut-off for solar wind speeds of 250 - 900 km/s. The analysis of each ion starts with a selection according to energy/charge in an electrostatic analyzer, followed by post-acceleration to a negative potential and a time-of-flight measurement. The analysis is completed by the determination of the residual energy in a solid state detector. The entrance system of CTOF provides acceptance of ± 25° in the ecliptic and ± 15° in elevation (FWHM) about the viewing direction. Details on the operation, calibration and data analysis of CTOF may be found in Aellig et al. (1998) and Hefti (1997). The solar wind speed has been determined by the Proton Monitor (Ipavich et al., 1998) and the photoionization rate relevant for helium has been derived from the solar EUV flux, as measured by the SEM (Judge et al., 1998).

The SOHO spacecraft was launched on December 2, 1995, and subsequently placed into the Lagrangian point L1, ≈ 1.5 million km towards the sun. SOHO is a 3-axis stabilized spacecraft with a very accurate sun-pointing capability. While SEM is pointed exactly at the sun, the CELIAS particle sensors point at a location 7° west of the sun in order to compensate for the expected average aberration of the flow direction of heavy solar wind ions. This orientation provides a cut through the pickup ion velocity distribution almost exactly in the direction of the solar wind flow with 100% duty cycle.

Because we need the full energy resolution over the complete range of the pickup ion distribution for this investigation and the fluxes of the pickup ions are low, we will make use of the raw pulse height data of CTOF. For the selection of the He^+ pickup ions from the pulse height data we have transformed the measured energy/charge, time-of-flight and residual energy for each event into an M versus M/Q matrix. For the further study of He^+ we have selected all events that fall into a box that is defined by $3.3 < M/Q < 4.7$ and $1 < M < 8$.

Although the transmission of pulse height events is limited by the telemetry, the transmitted events indeed represent the total flux of pickup ions in the relevant energy range and are not affected by instrument dead time. It has been confirmed that the complete set of pulse height events of pickup ions is transmitted and that the observed rate of He^+ ions accurately reflects their absolute flux for energies with $v/V_{sw} > 1.2$. v is the speed of pickup ions in the solar wind frame and V_{sw} the solar wind speed. For lower energies the observed fluxes are affected by a competition of pickup ions and heavy solar wind ions for the transmission capacity of pulse height events, which leads to reduction of the observed count rates. In addition, the stepping sequence of CTOF is halted when the total count rate of

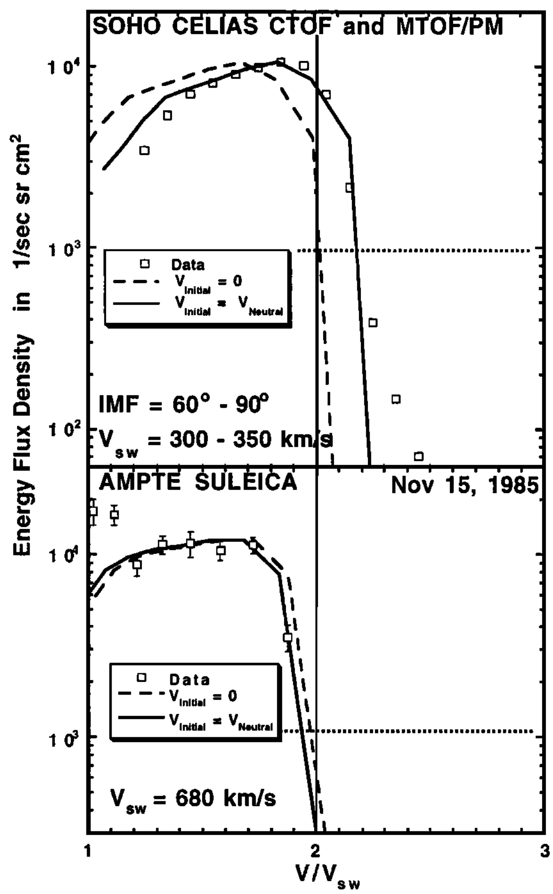

Figure 2. Upper panel: Comparison of the pickup ion spectrum as observed by SOHO CTOF with a model based on injection of He^+ at $V_{Initial} = 0$ (dashed) and at $V_{Initial} = V_{Neutral}$ (solid). The observed cut-off is consistent with pickup ions starting at the LISM flow speed towards the sun, including gravitational acceleration. The vertical scale has been extended to include the suprathermal tail, visible in the CTOF data. Where 10% of the maximum is reached is indicated by a dotted line.
Lower panel: Similar comparison with an observation by AMPTE SULEICA on the downwind side of the sun. The cut-off speed is consistent with a slight shift to lower speeds, i.e. a LISM flow away from the sun.

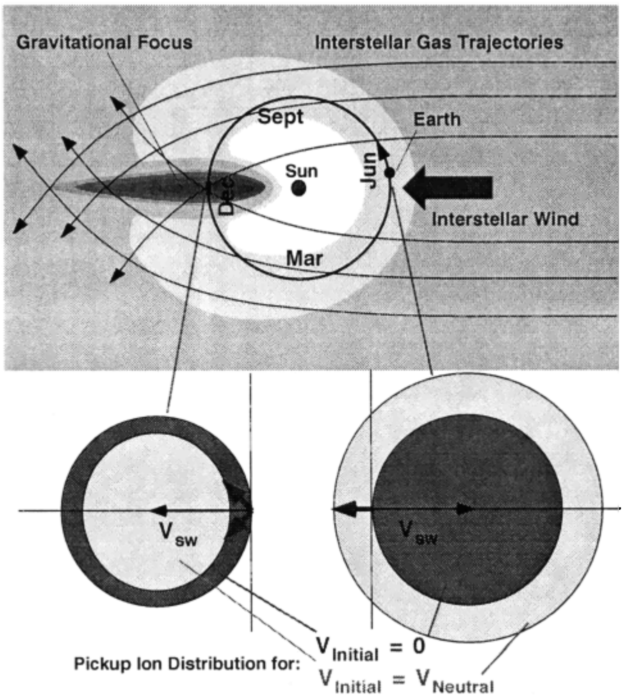

Figure 3. Flow pattern and density distribution of interstellar He in relation to Earth's orbit. Cuts through the pickup ion velocity distribution are shown below for newly created ions starting at rest (dark gray) and at the appropriate neutral gas velocity at 1 AU (light gray) downwind (left) and upwind (right) of the sun with respect to the LISM flow.

all ions exceeds a preset threshold in order to protect the sensor from the high fluxes of solar wind alphas. This leads to further modifications. Therefore, only observations for $v/V_{sw} > 1.2$ are used. The fluxes are computed from the pulse height event rate using the geometric factor of CTOF and the energy and species dependent detection efficiency, as determined by simulations and calibrations of the original flight sensor and a flight spare that is still available (Hefti, 1997).

Observations

For our analysis we have accumulated data from DOY 160 to DOY 190, 1996. We have subdivided the data set according to solar wind speed and IMF direction. For effects on the cut-off speed it is particularly important to select data according to IMF direction, because it is known from earlier studies that during a radial orientation of the field the flux close to the cut-off is substantially reduced (Möbius et al., 1998). Since SOHO does not carry a magnetometer, we have used data from WIND/MFI (Lepping et al., 1995) and convectively propagated the results to the position of SOHO.

Figure 1 shows two energy flux density spectra of pickup ions as a function of v/V_{sw} that were accumulated for IMF directions from 60° to 90° with respect to the solar wind. The data that originally were taken in energy/charge steps with increments of 4.1% are accumulated in v/V_{sw} with increments of 10%. We have chosen energy flux density because this quantity is independent of the substantial variations in solar wind speed (Vasyliunas and Siscoe, 1976; Möbius et al., 1995). The relatively large angle between the IMF and the solar wind was chosen in order to eliminate the reduction of the pickup ion fluxes near the cut-off due to incomplete pitch-angle scattering that is observed for nearly radial IMF (Möbius et al., 1998). The two spectra represent averages over the entire observation period for solar wind speed ranges that differ by 150 km/s. The energy flux in the plateau region is almost identical for the two spectra, as expected. It is apparent that the cut-off for these spectra (defined by falling below 0.1 of the maximum, as indicated by a dotted horizontal line in Fig. 1) reaches substantially beyond the theoretical value of $v/V_{sw} = 2$ that has been confirmed with previous observations. Furthermore, this excess increases for lower solar wind speed. In particular, the cut-off for the solar wind speed range of 300 - 350 km/s is more than 10% above the nominal value, which corresponds to more than 20% in energy or approximately five energy steps of CTOF (with a separation of 4.1% each).

The difference becomes even more apparent when the pickup ion spectrum for $300 < V_{sw} < 350$ km/s is compared in Fig. 2 with a typical one as obtained by AMPTE SULEICA in 1985. For a quantitative analysis it is necessary to compare the observed spectra with simulations of the pickup ion distribution. The results of such simulations for the observations by SOHO CTOF in 1996 and by AMPTE SULEICA in 1985 are represented by the curves in Fig. 2. We have assumed a spatial distribution of neutral gas according to a hot model for interstellar neutral He (Wu and Judge, 1979). The gas is represented by a shifted Maxwellian far upstream of the sun, and individual atoms follow Keplerian trajectories. Upon ionization pickup ions start with $V_{Initial} = 0$, i.e. the neutral gas flow is neglected in the formation of the pickup ion distribution. The ions are picked up by the IMF and then scattered in pitch angle to isotropy, which is appropriate for IMF angles of 60° - 90°. The final velocity distribution is formed by adiabatic deceleration (Vasyliunas and Siscoe, 1976) in the radially expanding solar wind. The energy flux spectra are computed by integrating the distribution function over the appropriate solid angle and energy steps for each sensor. The procedure is identical to the one described by Möbius et al. (1995). Except for the appropriate density, ionization rate and solar wind conditions, the same parameters were used (dashed curves in Fig. 2).

In comparison with the simulations, in which the pickup ions start at $V_{Initial} = 0$, the spectrum obtained with CELIAS appears to be substantially shifted to higher velocities, whereas the cut-off obtained with AMPTE appears to be slightly below the prediction of the model. The difference in the AMPTE result cannot be considered significant, because it is less than the energy bandwidth of the SULEICA analyzer. However, the difference between observation and prediction for the CELIAS data is about five energy steps and is substantial.

It should be noted that only the location of the cut-off and to a lesser degree the spectral shape of the pickup ion distribution is important in this discussion. The absolute pickup ion flux values shown here are still somewhat uncertain, because they may contain unresolved systematic errors from a yet incomplete calibration at pickup ion energies. The geometric factor of CTOF has been calibrated under the assumption that the transmission of its electrostatic entrance system is independent of the energy of incoming ions. This is correct for almost the entire energy range of solar wind ions, because here the energy gain by post-acceleration is large compared with the original energy (Hefti, 1997; Aellig et al., 1998). However, at the higher energies of pickup ions the collection efficiency decreases with energy. This is observed as an apparent variation of the pickup ion flux with solar wind speed. Using this dependence on solar wind speed we have empirically corrected the pickup He^+ spectrum observed by CELIAS (upper panel in Fig. 2). The adjusted spectrum is roughly consistent with the model pickup ion flux. A neutral He density at infinity of $n_{He} = 0.015$ cm^{-3} (Gloeckler, 1996; Witte et al., 1996) and an ionization rate of $6.1 \cdot 10^{-8}$ s^{-1} at 1 AU (the average for the observation period inferred from CELIAS/SEM data) were used. The remaining uncertainty in the flux does not affect our conclusions, which are based on the location of the cut-off rather than the spectral shape and absolute flux.

Discussion and Conclusions

To understand the difference in the cut-off between the two observations, let us turn to an illustration of the interstellar gas flow pattern with respect to Earth's orbit in Fig. 3. All the AMPTE SULEICA observations were made downwind with respect to the sun (September through December), and the SOHO CELIAS observations were collected upwind (June through August). As can be seen in the schematic cuts through the velocity distributions of pickup ions in the same figure, the velocity vectors of the LISM flow and the solar wind subtract in December and add in June. Therefore, newly created ions are injected in the rest frame of the solar wind with higher velocity in the upwind region, which leads to a velocity distribution that extends to higher velocities (light gray) compared with ions that are injected with $V_{Initial} = 0$ (dark gray). The opposite holds for the downwind side. Since the spectra are shown as a function of v/V_{sw} the effect of the local LISM flow velocity $V_{Neutral}$ scales with its value relative to the solar wind speed, i.e. with $V_{Neutral}/V_{sw}$. Therefore, the effect is stronger for low solar wind speeds, as seen in Fig. 1.

When compared with typical solar wind speeds the value of the LISM bulk speed at infinity of ≈ 25 km/s (Witte et al., 1996) appears to be negligible. However, the solar wind speeds were rather low during the observation period for SOHO CELIAS (300 - 500 km/s), as compared with the value of 680 km/s for the AMPTE SULEICA example. Secondly, adding the gravitational acceleration of the neutral gas to 1 AU to the original LISM velocity of 25 km/s leads to a final velocity of $V_{Neutral} = 52.5$ km/s at 1 AU. For a comparison with the observations we have modified the previous simulation so that freshly created ions start with a velocity $V_{sw} + V_{Neutral}$ in the solar wind frame on the upwind side. On the downwind side the radial component of the gravitationally deflected gas flow must be subtracted. Applying these modified initial velocities to the pickup ion distributions leads to simulated spectra that are consistent with both sets of observations, as shown in Fig. 2 with solid lines, i.e. the interstellar gas flow velocity is indeed important for the pickup ion distribution.

There is still a visible deviation between the CELIAS observations and the simulated spectrum at the high-energy end, where a suprathermal tail seems to emerge. Here, pickup ions may have been accelerated at interplanetary shocks or by turbulence, as has been discussed by Gloeckler et al. (1994). Since we have not made an attempt to eliminate such events from our data set, a high-energy tail may be expected.

In summary, it has been demonstrated that the interstellar neutral gas flow velocity at 1 AU cannot be neglected in the evaluation of pickup ion distributions, especially for low solar wind speeds. A simplified simulation has produced results that are consistent with pickup He^+ spectra taken in the upwind and the downwind region of the flow. This is encouraging and may be exploited as a diagnostic tool to obtain LISM flow velocities for a variety of species. This possibility is important because so far only neutral He has been observed directly.

Acknowledgments. The authors are grateful for the dedicated work of many unnamed individuals at MPAe, MPE, UoB, UoMd, TUB who contributed substantially to the success of SOHO/CELIAS. We are especially thankful to the WIND/MFI team for providing the key parameters of the IMF for this investigation. The paper benefited greatly from discussions with M. Bzowski, P.A. Isenberg, and D. Rucinski. This work was supported under DLR contracts 50OC89056 and 50OC96059, NASA Grants NAG 5-2754, 5-7097, and NSF Grant ATM-9800781.

References

Aellig, M.R., et al., Iron freeze-in temperatures measured by SOHO/CELIAS/CTOF, *J. Geophys. Res.*, *103*, 17215, 1998.

Aellig, M.R., Freeze-in temperatures and relative abundances of iron ions in the solar wind measured by SOHO/CELIAS/CTOF, *Thesis*, University of Bern, 1998.

Axford, W. I., The interaction of the solar wind with the interstellar medium, In: C.P. Sonnett, P.J. Coleman, Jr., and J.M. Wilcox (eds.), *The Solar Wind, NASA SP*, *308*, 609, 1972.

Fahr, H. J., and H. W. Ripken, The physics of the heliospheric interface and its implications for LISM diagnostics, *Astron. Astrophys.*, *139*, 551, 1984.

Geiss, J., et al., Interstellar oxygen, nitrogen and neon in the heliosphere, *Astron. Astrophys.*, *282*, 924, 1994.

Gloeckler, G., et al. Detection of interstellar pickup hydrogen in the solar system, *Science*, *261*, 70, 1993.

Gloeckler, G., et al., Acceleration of interstellar pickup ions in the disturbed solar wind observed on Ulysses, *J. Geophys. Res.*, *99*, 17637, 1994.

Gloeckler, G., L.A. Fisk, and N. Schwadron. Anisotropies of interstellar pickup protons - implications for scattering of low rigidity (≈ 1 to 3 MV) particles, *Geophys. Res. Lett.*, *24*, 93, 1995.

Gloeckler, G., The abundance of atomic ^{1}H, ^{4}He and ^{3}He in the local interstellar cloud from pickup ion observations with SWICS on Ulysses, *Space Sci. Rev.*, *78*, 335, 1996.

Hefti, S., Solar wind freeze-in temperatures and fluxes measured with SOHO/CELIAS/CTOF and calibration of the CELIAS sensors, *Thesis*, University of Bern, 1997.

Holzer, T.E., Interaction between the solar wind and the interstellar medium, *Ann. Rev. Astron. Astrophys.*, *27*, 129, 1989.

Hovestadt, D., CELIAS - Charge, Element and Isotope Analysis System for SOHO, *Solar Physics*, *162*, 441, 1995.

Ipavich, F.M., et al., Solar wind measurements with SOHO: The CELIAS/MTOF proton monitor, *J. Geophys. Res.*, *103*, 17205, 1998.

Judge, D., et al., First solar EUV irradiances obtained from SOHO by the CELIAS/SEM, *Solar Physics*, *177*, 161, 1998.

Lepping, R.P., et al., The wind magnetic field investigation, *Space Sci. Rev.*, *71*, 207 - 229, 1995.

Möbius, E., et al., Direct observation of He^+ pickup ions of interstellar origin in the solar wind, *Nature*, *318*, 426, 1985.

Möbius, E., B. Klecker, D. Hovestadt, and M. Scholer, Interaction of interstellar pickup ions with the solar wind, *Astrophys. Space Sci.*, *144*, 487, 1988.

Möbius, E., D. Rucinski, D. Hovestadt, and B. Klecker. The helium parameters of the very local interstellar medium as derived from the distribution of He^+ pickup ions in the solar wind, *Astron. Astrophys.*, *304*, 505, 1995.

Möbius, E., D. Rucinski, M.A. Lee, and P.A. Isenberg. Decreases in the anti-sunward flux of interstellar pickup He^+ associated with radial interplanetary magnetic field, *J. Geophys. Res.*, *103*, 257, 1998.

Rucinski, D., and H.J. Fahr, The influence of electron impact ionization on the distribution of interstellar helium in the inner heliosphere; possible consequences for determination of interstellar helium parameters, *Astron. Astrophys.*, *224*, 290, 1989.

Vasyliunas, V., and G.L. Siscoe, On the flux and the energy spectra of interstellar ions in the solar system, *J. Geophys. Res.*, *81*, 1247, 1976.

Witte, M., M. Banaskiewicz, and H. Rosenbauer, Recent results on the parameters of the interstellar helium from the Ulysses/GAS experiment, *Space Sci. Rev.*, 78, 2, 289, 1996.

Wu, F. M., Judge, D. L., Temperature and flow velocity of the interplanetary gases along solar radii, *Astrophys. J.*, *231*, 594, 1979.

(Received July 19, 1999; accepted September 1, 1999)