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'Torus' distribution of interstellar helium pickup ions: Direct observation

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[1] A'torus'-like velocity distribution of the helium pickup ions has been detected in interplanetary space by GEOTAIL. A statistical survey shows that the observation probability of the 'torus' distribution amounts to nearly 20% and that the distribution pattern depends on the local magnetic field directions and turbulence levels. These results support the recent finding of a low pitch angle scattering rate and a large mean free path. *INDEX TERMS:* 2152 Interplanetary Physics: Pickup ions; 7823 Space Plasma Physics: Ionization processes; 7859 Space Plasma Physics: Transport processes; 2149 Interplanetary Physics: MHD waves and turbulence

1. Introduction

[2] To date, helium pickup ions (PUIs) of interstellar-origin have been detected in the heliosphere. From their observations, physical parameters of the local interstellar matter are derived under the assumption that pitch-angle scattering (PAS) after pickup process is very efficient and velocity distribution of the PUIs are isotropic [*Vasyliunas and Siscoe*, 1976].

[3] The fast PAS implies short mean free path λ and the size of λ has been of great interest from mainly two aspects. One is the comparative study of λ between observations and simulations which started in association with the cosmic ray transport effect. While the observational constraint of λ disagreed with the 'slab' model of interplanetary magnetic turbulence [e.g. *Palmer*, 1982], it has been argued that a composite model of 2D turbulence as well as the minor 'slab' component is appropriate [*Bieber et al.*, 1994]. While the later argument is only compatible with the observation of higher rigidity, and the mean free path of low rigidity particles such as PUI is still under debate. Indeed, a number of observations have been reported that the scattering mean free path λ of PUIs is of the order of 1 AU and that the ambient IMF turbulence does not lead to efficient scattering [*Gloeckler et al.*, 1995; *Möbius et al.*, 1998; *Fisk et al.*, 1997; *Schwadron et al.*, 1999]. On the other hand, a more recent study considering the effect of the angular distribution of the IMF reported somewhat smaller mean free path ($\sim$0.25AU) [*Németh et al.*, 2000].

[4] The second aspect of the determination of λ is that the velocity distribution of the PUIs is expected to be non-spherical if λ turned out to be large. Owing to the low PAS rate, each of the freshly ionized helium keeps its initial ring configuration, and the accumulation of all the ions yields a 'torus'-like distribution in velocity space.

[5] We report in this paper that we have detected the 'torus' distribution for the first time and show the statistic result of the observation. The confirmation of such a low density, highly structured ion distribution is realized by the 3D instrument onboard GEOTAIL with high sensitivity (g-factor) and angular resolution.

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2. Instrumentation and Observations

[6] We have utilized measurement of the plasma (LEP/EAI, CPI) and magnetic field (MGF) experiments onboard GEOTAIL. The LEP/EAI [*Mukai et al.*, 1994] is an electrostatic analyzer with a resolution of 22.5° in polar angle (7 elevation channels over 157.5°) and in azimuth (16 sectors over one S/C spin of 3 sec). It obtains a complete ion distribution function every four-spin period. The data are obtained in either full (0.02–40 keV/e) or high (5.0–40 keV/e) energy observational mode. 3 sec-sampling data were used for the MGF [*Kokubun et al.*, 1994] data. We have also used the solar wind plasma data from the CPI [*Frank et al.*, 1994].

[7] We came across our sample observation during a 60-min interval on December 4, 2000, on the dawn side of the bow shock $\sim$GSE(4.4, −30.0, 2.5) R_E, when no diffuse ions were detected and LEP was operated in its full-energy mode. The solar wind remained steady during the entire interval, and the average speed was $|V_{sw}| \sim 363$ km/s. Figure 1 shows the phase space density (PSD) accumulated from 16:00:54 and 16:47:15 UT (lower panels) as well as a schematic illustration of the observation for the convenience of image construction (upper panel). The thin lines show the average magnetic field direction during the accumulation, $(|B|,\phi_B,\theta_B)$ = (7.3 nT, −14.4°, 62.4°).

[8] The lower left panel shows the 3D cut by elevation #5 (latitudinal angle $\sim$22.5°) projected to the spin-equatorial plane. A depletion of the PSD is apparent at the center of the distribution, and the configuration can be interpreted as a torus viewed from the top. A caution here is that LEP/EAI does not discriminate ion species. Therefore, the solar wind protons are detected at the same time appearing as the orange spot at the center of the panel. The inner part of the depletion at the center of the torus is probably masked by the heavier component of the solar wind, colored in green.

[9] In the lower right panel, a vertical cut through sector #13 (solar wind direction) is presented, but only for $V_x < 0.0$ (anti-sunward direction). It is evident that particles (we temporally regard them as protons here) with a speed between 800 to 1300 km/s are concentrated in elevation #5 although a minor portion of ions ($|V| \sim 500$–900 km/s) are detected in elevation channels #4 and #6. This configuration can be interpreted as the side view of the torus. We tentatively associate the ion distribution with helium PUIs of interstellar-origin.

[10] Figure 2 shows the PSD along the line of intersection of the two cuts in Figure 1 (elevation #5, sector #13). Note that the velocity scale is drawn as if all ions were protons. The cut-off velocity is therefore to be multiplied by $(M/Q)^{-1/2}$ for ions of mass M and charge Q. Similarly, the PSD (unit: m^{-6} sec^3) should be multiplied by $(M/Q)^2$. The maximum velocity of a gyrating PUI can be estimated by $V_{\perp\ max} = 2V_{sw} \sin\theta_C$ where θ_C is the angle between the solar wind and the IMF. For this case ($\theta_C = 63.3°$, $|V_{sw}|$ $\sim$ 363 km/s) $V_{\perp max}$ becomes $\sim$ 643 km/s. On the observational part, a cutoff is evident in this figure at $\sim$1225 km/s, which corresponds to $\sim$613 km/s for He^+, and is in good agreement with the observation within the instrument resolution of $\sim$50 km/s. In Figure 1, the predicted center of the expecting He^+ distribution is indicated as a pink spot in the two lower panels.

[11] The calculated PSD of He^+ at the peak of the distribution ($V \sim 1120$ km/s in Figure 2 corresponding $V_{He+} \sim 560$ km/s) was $\sim 8.1 \times 10^{-15} s^3 m^{-6}$. The date of the observation, December 4, is

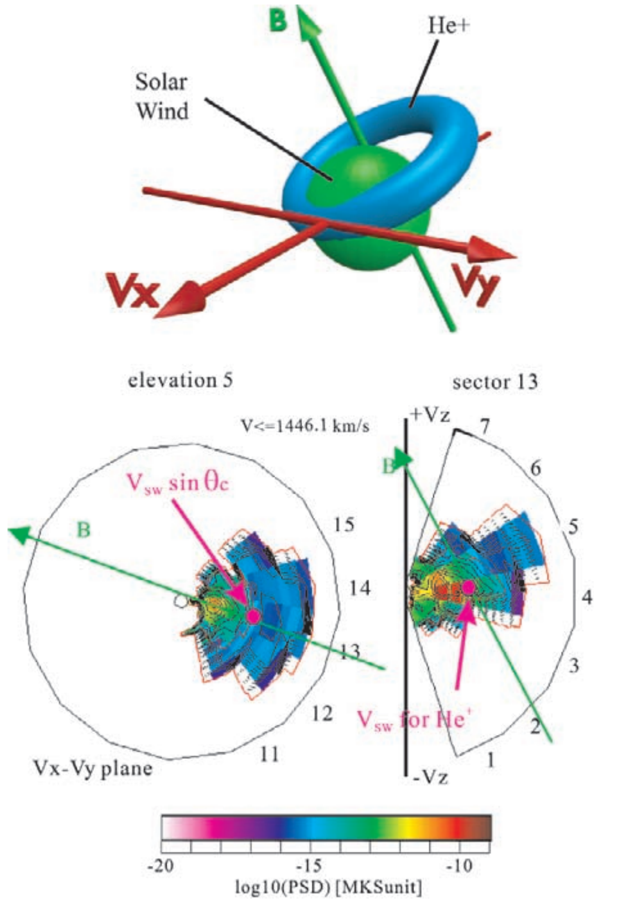

Figure 1. Observed torus distribution: (top) schematic view into the ecliptic plane from above, (left) cut through elevation channel #5 (nearly Vx-Vy plane), (right) cut through sector #13 (Vx-Vz plane).

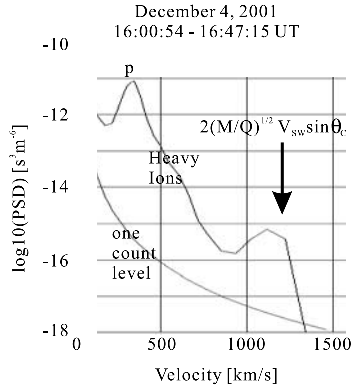

Figure 2. Observed PSD along the intersection line of the two planes in Figure 1.

located inside the gravitational focusing cone, and the result is consistent with the expected PSD of interstellar He^+ during the cone crossing at 1 AU, $(1-20) \times 10^{-15} s^3 m^{-6}$ [*Möbius et al.*, 1985; *Noda*, 2000]. Assuming the inner and outer radii of the torus to be 512 and 613 km/s respectively, the total density is estimated as 1.1×10^{-4}/cc.

3. Statistical Study

[12] Having found that a torus-like distribution of He^+ PUIs can be observed in interplanetary space, we scrutinized all the available GEOTAIL data to investigate the observation probability of such configurations. The search period is from February 1994 to September 2001.

[13] The observation periods are carefully selected from the solar wind data to make sure that GEOTAIL is in upstream of the bow shock, that LEP/EAI is in the full energy mode, and that diffuse ions are excluded. The observations are restricted to the full energy mode because the bulk of the He^+ PUIs is confined below 5 keV, the lower detection limit of the high-energy mode. Meanwhile, LEP is automatically operated with the high-energy mode for most of the solar wind observation time, limiting the total time of available data. We also required more than 20 minutes of continuous accumulation. The total observation time period of available data is 55.1 hours. The number of individual samples is 41, and the average accumulation time per sample is 1.34 hours. Most of the samples are obtained in the fall because the total time of GEOTAIL in the upstream increases in fall due to the orbital configuration.

[14] A caveat for our analysis is that our data sample is biased towards the solar wind conditions of large cone angle and low temperature. The average cone angle of our observation ($\sim$56.5°) is somewhat larger than the nominal value of the Parker spiral ($\sim$45°). This is due to the lack of samples with cone angles $\leq$15° as we have eliminated all data contaminated with upstream diffuse ions. The solar wind density N_{sw}, velocity V_{sw}, ion temperature T_{sw} (from CPI), and the magnitude of the magnetic field $|B_{sw}|$ averaged over our samples are, $N_{sw} = 7.5$/cc, $V_{sw} = 372.6$ km/s, $T_{sw} = 4.1$ eV, and $|B_{sw}| = 6.3$ nT, respectively. It is noted that while the values of N_{sw}, V_{sw}, and $|B_{sw}|$ are more or less nominal, T_{sw} is less than 1/2 of the nominal temperature of $\sim$10 eV. This is because the automatic mode selector of LEP/EAI has a tendency to choose the full energy mode during cold solar wind intervals.

[15] The distribution functions are categorized into four groups: 'torus-like', 'spherical', 'unidentified', and 'unclassifiable'. We carried out the categorization by the following steps. First, we examined the solar wind sectors (elevation #1–7, latitudinal angle −45° $\sim$+45°) to confirm the cutoff at around $2|V_{sw}|\sin\theta_C \sim 2|V_{sw}|$. The cutoff is the main feature of interstellar pickup ions [*Möbius et al.*, 1985]. An event will thus be classified as 'unidentified' if the cutoff cannot be confirmed.

[16] If the nominal cutoff is confirmed, we investigated each sector and elevation if the PSD level consistent with interstellar He^+ is at least one order of magnitude above the PSD one-count-level after background subtraction, and then counted the number

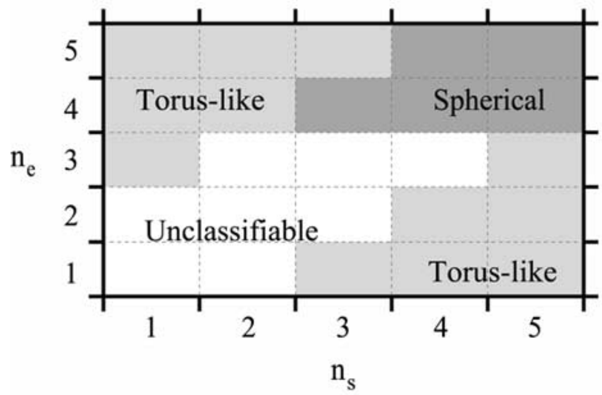

Figure 3. Categorization criteria relative to n_s and n_e.

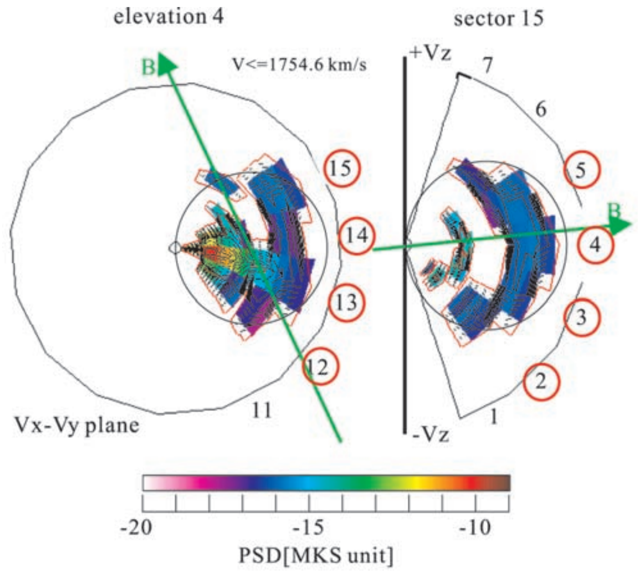

Figure 4. Example of a 'spherical' distribution function obtained on June 12, 1999, during 03:27:03–04:34:17 UT. Channels with a sufficiently high count rate, i.e. well above the ion detection limit, are indicated by red circles on the elevation/sector numbers. The peak value of the He^+ PSD was $\sim 1.8\times 10^{-15} s^3 m^{-6}$.

of sectors n_s and elevations n_e which satisfies the criterion. Then the set of n_s and n_e is referred to Figure 3 for the categorization of the observed distribution. In Figure 3, the dark and light gray regions show 'spherical' and 'torus-like' distributions, respectively. For the sample of the 'torus' in Figure 1, we obtained n_e = 1 and n_s = 4. For the identification of the torus, we have verified that the ring axis is aligned with the average magnetic field direction. The white area shows 'unclassifiable' distribution. The region with n_e = 0 or n_s = 0 is omitted because we have done the categorization only when the cutoff is confirmed at least in one direction.

[17] Figure 4 shows an example of the 'spherical' distribution (n_e = 4 and n_s = 4). It is the result of 67 minutes accumulation on June 12, 1999, on the dusk side of the bow shock. The average solar wind velocity and the magnetic field direction are $|V_{sw}| \sim 407$ km/s and $(|B|, \phi_B, \theta_B)$ = (5.9 nT, −61.4°, 11.8°), respectively. As is expected from the model of fast pitch angle scattering (case 2 of *Vasyliunas and Siscoe* [1976]), the observed distribution seems to have a 'void' inside the circle. However, since the statistical significance of the 'void' is marginal, we do not discuss it in this letter. (The one count level scales as E^{-2} and thus the S/N ratio decreases towards lower energies.)

[18] The resultant fractions of each distribution type relative to the total time of available data (~55.1 hours) are 22.5, 34.1, 33.0, 10.2% for 'torus-like', 'spherical', 'unidentified', and 'unclassifiable', respectively. (The absolute time for each are 12.4, 18.8, 18.2, and 5.6 hours, respectively.) The results are organized in Figure 5a as a function of the cone angle, i.e. the angle between the local magnetic field and the sun-earth line. The 'torus-like' and 'spherical' distributions were biased to the larger cone angle. Still some 'spherical' distributions were detected even when the cone angle was ≤40°, suggesting the possibility that 'spherical' can be found in any range of the cone angle. On the other hand, the 'unidentified' distributions were found mostly during the periods of smaller cone angle.

[19] The results are consistent with the earlier studies showing that the PUIs reach their maximum speed in the solar wind frame more easily when their injection pitch angle is closer to 90° and that the ions pile up in the sunward direction and are not effectively pitch-angle scattered in the case of radial IMF [*Gloeckler et al.*, 1995; *Möbius et al.*, 1998]. To investigate the consequence of this

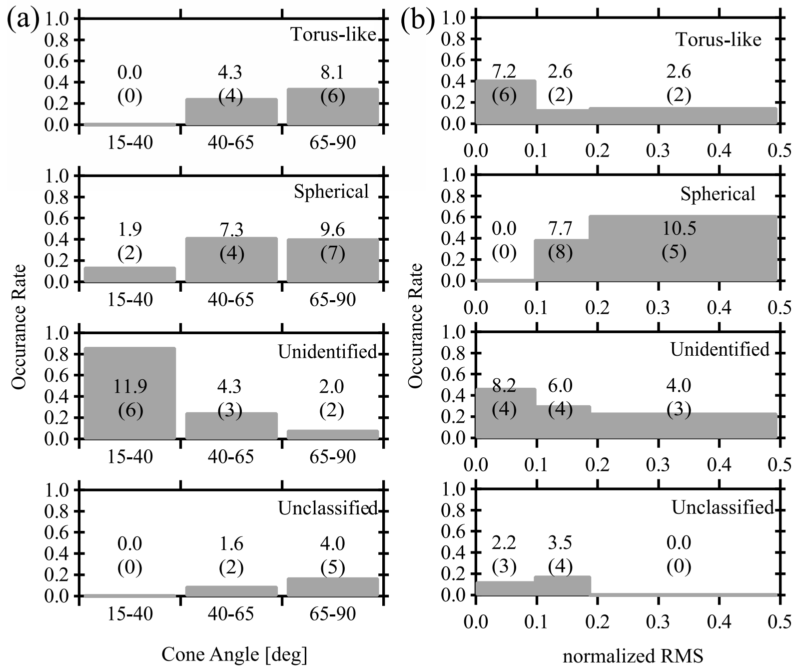

Figure 5. Histogram of the fraction of observation timeas a function of (a) the cone angle and (b) the normalized RMS of the IMF. The numbers in the histogram show the total time of accumulation for each bin and the distribution type, while the numbers in the brackets indicate the number of samples. The sum of the occurance rates over all bins equals unity. To calculate $\delta\vec{B}$, we band-pass-filtered the magnetic fluctuation with the frequency range of $(\alpha\Omega_{He^+}, \pi/3)$ rad/sec, where Ω_{He^+} is the gyro-frequency for He^+, α the numerical factor (≤1) determining the low frequency limit, and $\pi/3$ rad/sec the Nyquist frequency. We have confirmed that the statistical result is not sensitive to the choice of α for $1/3 \sim 1$. Panel (b) corresponds to the choice of α = 1.

anisotropy further, we have made a correlation study between the ion distribution types and the magnetic turbulence level. Figure 5b is the histogram showing the dependence of the observed distribution types on the normalized RMS (root mean square) amplitude of the magnetic field fluctuations ($|\delta\vec{B}| / |\bar{B}|$) (For the calculation of $\delta\rightarrow B$, see the caption of Figure 5). Each bin contains nearly the same total accumulation time ~18 hours. It is apparent that for a higher level of magnetic turbulence (>~0.2) the PUIs suffer more PAS and evolve into spherical distribution with a probability of ~60%. The torus-like distribution dominates over the spherical distribution when the RMS level is relatively low (<~0.1).

4. Discussions

[20] In this paper, we confirmed that the probability of PUI distributions being torus-like is ~20%. There are two points to be noted: 1) those classified as 'unidentified' may include PUI distributions that are piled up in the low-velocity region and 2) those classified as 'spherical' might be the sum of torus: During the high turbulence intervals which often exhibit what we classified as 'spherical' as we saw in Figure 5b, the directions of the IMF as well as the 'torus', if it exists, may vary, and the accumulation over the observation period may yield a 'spherical' distribution.

[21] It is worth noting once more that our data sample is biased to the solar wind condition of larger cone angle and lower temperature. While we leave the analysis for smaller cone angle and higher temperature to future investigations, we still may suggest based on the current analysis that a modification of the current focusing cone model could emerge. In the case of torus distribution, the $E \times B$ drift perpendicular to the field line dominates compared to the radial transport along the field line. Then the PUIs are transported across the gravitational focusing cone leading to the widening and the shifting of the focusing cone [*Möbius et al.*, 1996].

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