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Diagnostics of interstellar hydrogen in the heliosphere

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Determining the LIC H density from the solar wind slowdown

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ABSTRACT

Context. The ionized solar wind interacts directly with the interstellar neutrals which flow into the heliosphere. These neutrals are ionized, mainly by charge exchange, then accelerated to the solar wind speed with the momentum and energy removed from the bulk flow of the solar wind. Thus, by measuring the solar wind slowdown, one can estimate the interstellar neutral density.
Aims. In July 2005, Ulysses at 5 AU and Voyager 2 near 80 AU were at the same heliolatitude. We use this alignment to determine the solar wind speed decrease between these two spacecraft.
Methods. Ulysses data are used as input to a 1-D MHD model which includes the effects of pickup ions. We removed a section of data contaminated by an ICME directed toward Voyager 2.
Results. Comparison of the Voyager 2 speeds with the model results shows that the solar wind speed decreased by 67 km s^{-1} between Ulysses and Voyager 2, consistent with an interstellar neutral density at the termination shock of 0.09 cm^{-3}.

Key words. solar wind – interplanetary medium

1. Introduction

The local interstellar cloud (LIC) has an ionized and a neutral component. The ionized component is deflected around the heliopause, but the neutral component can penetrate deep into the heliosphere. Zank (1999) reviews methods used to estimate the LIC density, speed, and temperature. The neutral inflow speed is 26.4 km s^{-1} and the temperature is 6300 ± 340 K (Witte 2004); for a long time the neutral H density had large uncertainties (Geiss & Witte 1996) but recent works find densities of 0.09 ± 0.01 at the termination shock (TS) and 0.2 ± 0.02 in the undisturbed LIC (Wang & Richardson 2003; Gloeckler et al. 1997). Roughly 50% of the incoming neutral H is removed as a result of H filtration at the heliospheric boundaries before it reaches the termination shock (Gloeckler et al. 1997). The neutrals which enter the heliosphere are ionized by charge exchange or photoionization and are then accelerated to the solar wind speed; their initial thermal energy is equal to the bulk flow energy of the solar wind, about 1 keV. The effects of these pickup ions on the solar wind provide an indirect probe of the LIC neutrals. Since the momentum and energy to accelerate and heat the pickup ions comes from the bulk flow energy of the solar wind, the solar wind speed decreases. A small portion of the energy from the hot pickup ions is transferred to the thermal plasma and heats the solar wind (Isenberg et al. 2005; Smith et al. 2006). These hot ions dominate the thermal pressure of the solar wind in the outer heliosphere and thus provide most of the plasma pressure responsible for the maintenance of pressure balance structures (Burlaga et al. 1994).

Pickup ions are directly observed in the inner heliosphere; Möbius et al. (1985) detected He^+ pickup ions with the Active Magnetospheric Particle Tracer Explorer (AMPTE). Gloeckler et al. (1993, 1997) and Bzowski et al. (2007) observed H^+ pickup ions with the solar wind ion composition spectrometer (SWICS) on Ulysses. They modeled the losses in the heliosphere and estimated of LIC H density at the TS; their best estimate for the H density at the TS is 0.12 cm^{-3} (Bzowski et al. 2007).

Burlaga et al. (1994) use pressure balance structures to show that the pickup ions are present. They derive the pickup ion density necessary to maintain pressure balance. Many studies show that the solar wind temperature decreases less than adiabatically (Gazis et al. 1994; Richardson et al. 1995a). Smith et al. (2006) find that the energy released by isotropization of the pickup ions can couple to the thermal plasma and produce the observed plasma heating. Neither of these techniques provide good constraints on the neutral LIC H density because of uncertainties in the rate of energy transfer from pickup ions to the thermal plasma.

The slowdown of the solar wind does constrain the LIC density. The difficulty is that the speeds observed at two spacecraft must be compared, one in the inner and one in the outer heliosphere. Ideally, these two spacecraft would be at the same heliolatitude and heliolongitude. Given spacecraft constraints, most studies use spacecraft at similar heliolatitudes and relax the constraints on heliolongitude, since heliolatitudinal speed gradients can be large, especially near solar minima. The solar wind evolves from the inner to outer heliosphere, so a model is used to predict speeds in the outer heliosphere using the data from the inner heliosphere as input. These predicted speeds are compared with the measured speeds. Neutrals are included in the models; the neutral H density at the TS is adjusted to give a good fit to the data.

Richardson et al. (1995b) compare IMP 8 and Voyager 2 data when both spacecraft are within 7.25° of the helioequator and find an average slowdown of 30 km s^{-1} at 30 AU. Gazis (1994) compares PVO, IMP 8, Voyager 2 and Pioneer 10 data at similar distances and finds no compelling evidence that the solar wind speed decreased. Wang et al. (2000a) compare Ulysses and Voyager 2 data from 1990–1991 when Ulysses was at low latitudes and find an average slowdown of 8 km s^{-1} at Voyager 2's distance of 33 AU. Wang et al. (2000bb) compare Ulysses and Voyager 2 solar wind speeds in 1998 when these spacecraft are at similar heliolatitudes and find a speed decrease of 40 km s^{-1} at Voyager 2's distance of 58 AU. One can also look for times when heliolatitudinal speed gradients are small; at these times the requirement that two spacecraft be at the same heliolatitude can be relaxed. Wang & Richardson (2003) show that near the 1999 solar maximum heliolatitudinal speed gradients are small, so ACE and Ulysses speeds can be compared to Voyager 2 speeds; they found a speed decrease of 60 km s^{-1} at 60 AU.

In mid-2005 Ulysses and Voyager 2 were again at the same heliolatitude. Thus we can compare the data from these spacecraft and determine the solar wind speed decrease near 79 AU, the distance of Voyager 2 in 2006 when the solar wind observed by Ulysses mid-2005 arrives at Voyager. This paper discusses the slowdown of the solar wind in mid-2005, the LIC H density these observations imply, and how the slowdown profile derived from these measurements compares with model predictions.

2. Data and model

Figure 1 shows the trajectories of Ulysses and Voyager 2 in the Heliographic Inertial Coordinate System (HGI) from 2005 through 2007. The HGI coordinates are Sun-centered and inertially fixed with respect to an X-axis directed along the intersection line of the ecliptic and solar equatorial planes (see `http://cohoweb.gsfc.nasa.gov/helios/`). In mid-2005, both spacecraft were at 26° S heliolatitude. Thus Ulysses data from mid-2005 can be compared to Voyager data observed 6–9 months (the solar wind propagation time) later.

Figure 2 shows Ulysses SWOOPS data from 2005. The density and speed are normalized to 5 AU. The stream structure dominates the plasma profile as Ulysses encounters fast streams with speeds of 700–850 km s^{-1} and slows streams with speeds of 300–400 km s^{-1} (McComas et al. 2006). The regions where fast streams overtake slow streams are highly compressed and have large densities and magnetic field strengths. In mid-2005, roughly when Ulysses and Voyager 2 were at the same heliolatitudes, the average solar wind speed increased in both the peaks and in the troughs.

We use a one-dimensional (1-D) MHD model which includes the effects of pickup ions (Wang et al. 2000b) to propagate the Ulysses data to Voyager 2. Including the magnetic field is important because it changes the shock propagation speed. Since we only have input data at one point we must use a 1-D model; speed changes due to changes in stream structure should be longitudinally symmetric and thus well-simulated by a 1-D model, but ICMEs are inherently longitudinally asymmetric and thus

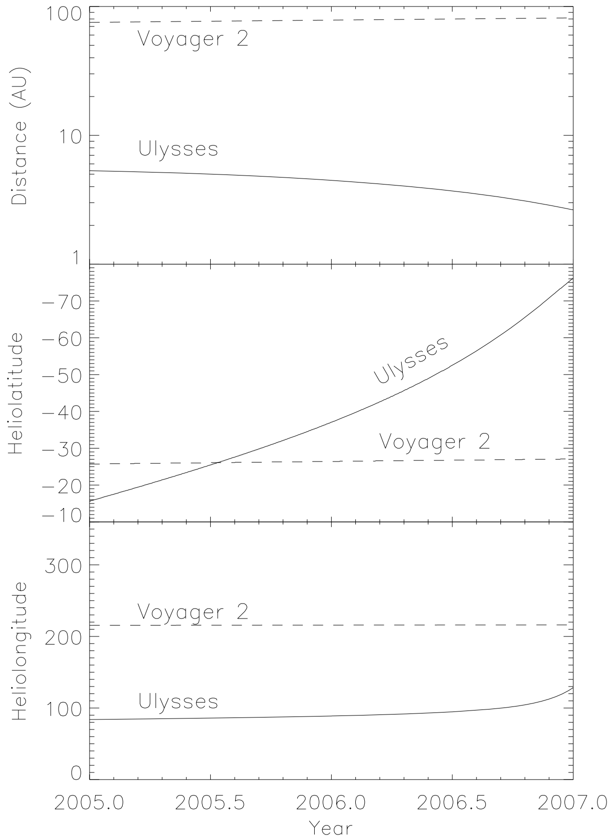

Fig. 1. The trajectories of Ulysses (solid lines) and Voyager 2 (dashed lines) from 2005 through 2007 in the HGI coordinate system described in the text.

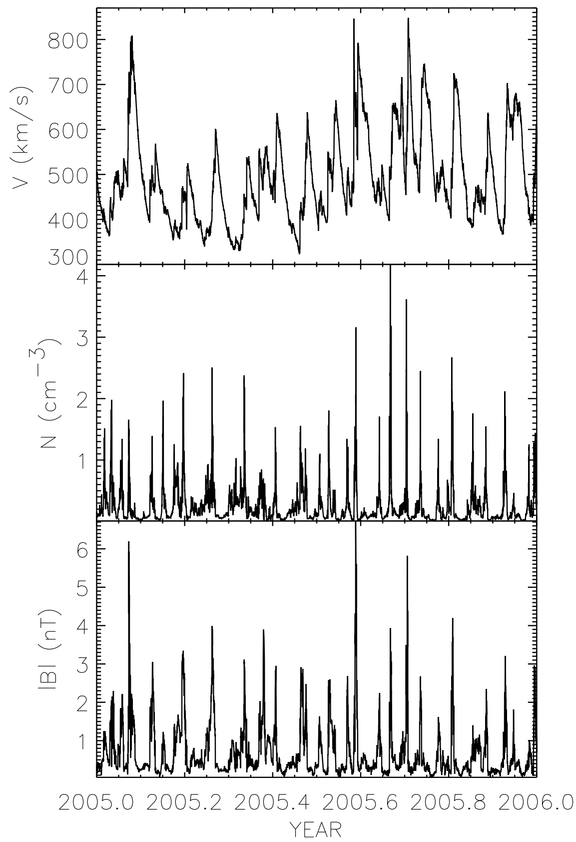

Fig. 2. Ulysses solar wind data 1 h averages from 2005.

not well-simulated by a 1-D model as discussed below. The model assumes a single fluid for the solar wind plasma plus source terms for the momentum and thermal energy which result from the charge exchange of solar wind ions with the neutrals. We neglect the contribution from photoionization; this source should produce about 10% of the pickup ions near solar minimum (Bzowski et al. 2007). The source terms are calculated from the Boltzmann collision integrals (McNutt et al. 1998); 5% of the thermal energy from the pickup ions heats the thermal core of the solar wind protons (Wang & Richardson 2001; Smith et al. 2001). Comprehensive models including multiple neutral H components are published in the literature (i.e., Ismodenov 2007). For both simplicity and to facilitate direction comparison with previous slowdown calculations, we use a cold distribution for the interstellar neutrals penetrating into the heliosphere over the heliocentric distance r (Vasyliunas & Siscoe 1976), i.e.,

$$n_{\mathrm{H}} = n_{\mathrm{H}}^{\infty} \exp(-\lambda/r),$$

where $\lambda = 7.5$ AU and n_{H}^{∞} is the neutral density at the TS. We use the empirical fit of Fite et al. (1962) for the charge exchange cross section, $\sigma(v) = [2.1\times10^{-7} - 9.2\times10^{-9}\ln(v)]^2$ cm^2 where v is the speed in cm/s. The speed (v_{H}) and temperature (T_{H}) of the neutrals we use are $v_{\mathrm{H}} = -20$ km s^{-1} and $T_{\mathrm{H}} = 10^4$ K (Lallement et al. 2003).

We note that Lindsay & Stebbings (2005) compiled published cross section data and determine a best fit to all these observations. The cross sections we use are higher by 20% than their fit. Bzowski et al. (2007) find that a rate 15% lower than that of Lindsay & Stebbings (2005) best fits their data. A smaller cross section would allow H to penetrate more deeply into the heliosphere, so the density slope would be smaller. The slowdown would occur at smaller heliospheric distances but would be about the same in the outer heliosphere, since in both cases all the H is ionized and contributes to the speed decrease of the solar wind.

The initial values of physical parameters at the inner boundary (5 AU) are set to the average solar wind conditions observed at Ulysses, i.e., density $n_0 = 0.24$ cm^{-3}, speed $v_0 = 440$ km s^{-1}, temperature $T_0 = 4.9 \times 10^4$ K and magnetic field magnitude $B_0 = 0.7$ nT. The model solves for a steady state solar wind using the piecewise parabolic method (Collela & Woodward 1984; Dai & Woodward 1995). The Ulysses observations are then introduced into the model as perturbations and propagated to Voyager 2. Ulysses has data coverage of about 99% in 2005; we linearly interpolate across the few data gaps. We compare the model output with Voyager 2 observations and vary n_{H}^{∞} to get the best fit to the Voyager 2 data.

3. Results

Figure 3 shows a comparison of the propagated Ulysses data and the Voyager 2 observations. The points show daily averages of the solar wind speed observed by Voyager 2 and the dashed line shows the speeds predicted by the model. The model profile does not match the observed shock and surrounding speed structure well. The causes of this discrepancy are probably transient events, ICMEs, which differ in effect at different heliolongitudes. In September 2005 a series of large flares and ICMEs were observed on the Sun [http://www.ngdc.noaa.gov]. The largest flare, X-17 in magnitude, was directed within 30° heliolongitude of Voyager 2 but 120° heliolongitude from Ulysses. Thus we expect Voyager 2 to observe major effects from this solar activity, but the effects at Ulysses would be less. To determine the solar wind slowdown between Ulysses and Voyager 2, we remove

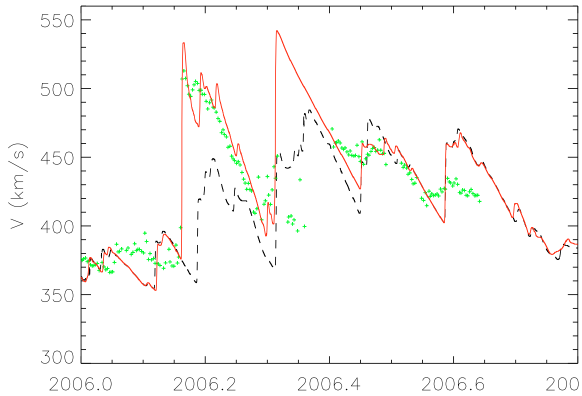

Fig. 3. The solar wind speeds measured by Voyager 2 in 2006 (plus signs), the speed obtained using the model to propagate the Ulysses data to Voyager 2 (dashed line), and the the speed obtained using the model to propagate the Ulysses data with a superposed ICME to Voyager 2 (solid line).

times affected by the transient activity. Richardson et al. (2006) add a simulated ICME to the Ulysses data from day 258–262.3 of 2005, adjusting the speed, density, and duration of the ICME so that the propagation code gives a good fit to the Voyager 2 observations. They use a H density of 0.09 cm^{-3} at the TS. The speed profiles with and without the added ICME are shown in Fig. 3. The two profiles are the same before the shock arrival at 2006.16 and after 2006.5; the 4.3 days of enhanced speed used to simulate the September ICME affect the solar wind for 124 days, 1/3 of a year.

The shock takes about 170 days to travel from Ulysses to Voyager 2 with an average speed of about 770 km s^{-1}. The average speed of the solar wind observed by Ulysses before the shock is about 500 km s^{-1}. This speed would give a propagation time to Voyager 2 of 0.67 years; if we assume the average speed decrease from pickup ion slowdown is 7.5% then the propagation time would be 0.73 years. The shock arrived at Voyager 2 at 2006.16; thus the solar wind ahead of the shock passed Ulysses at 2005.57, about the time the two spacecraft were at the same heliolatitude. The solar wind observed by Voyager 2 after the shock effects end at 2006.5 passed Ulysses at 2005.91, after Ulysses had moved to higher heliolatitudes than Voyager 2. We will compare the data both before and after the shock with model predictions, but expect the estimate of the slowdown and LIC density based on the data before the shock to be more accurate.

We ran the model with a range of values for the LIC H density at the TS: 0.00 cm^{-3} (no pickup ions, to determine the total slowdown of the solar wind), 0.07 cm^{-3} , 0.09 cm^{-3}, and 0.11 cm^{-3}. Figure 4 compares the speeds observed from the beginning of 2006 to the shock arrival (except for the 0.11 cm^{-3} case, where we compare speeds starting after the shock at 2006.03). The measured average speed at Voyager 2 is 376 km s^{-1}. For the model run with no pickup ions, the speed is 443 km s^{-1}, so the from Ulysses to Voyager the solar wind speed decreases by about 67 km s^{-1}. The average speed is 357 km s^{-1} for the $H = 0.11$ cm^{-3} case, 373 km s^{-1} for the $H = 0.09$ cm^{-3} case, and 388 km s^{-1} for the $H = 0.07$ cm^{-3} case. The 0.09 cm^{-3} case comes closest to the observed value; linear interpolation would give a best fit for 0.086 cm^{-3}. This value is consistent with previous work.

If we look at the speeds after the ICME passage, the average measured speed is 428 km s^{-1}. For no pickup ions, the speed is 517 km s^{-1} so the slowdown would be 89 km s^{-1}. The average

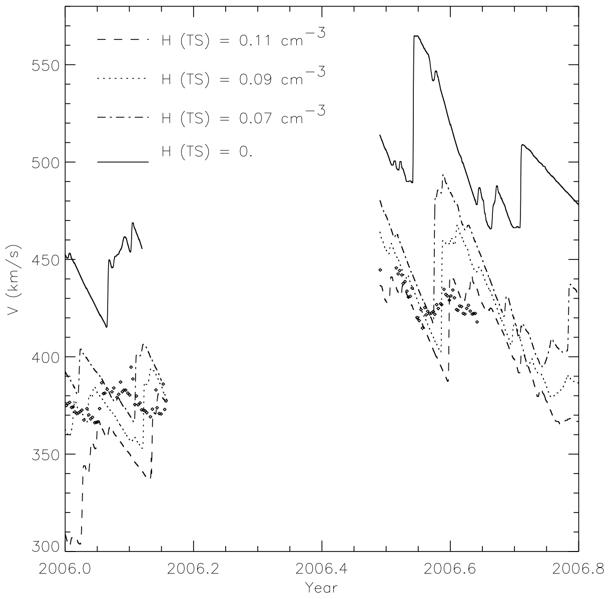

Fig. 4. The solar wind speeds measured by Voyager 2 in 2006 (diamonds) and the model predictions for H densities at the TS of 0, 0.07, 0.09, and 0.11 cm^{-3}. The gap is the region contaminated by the ICME.

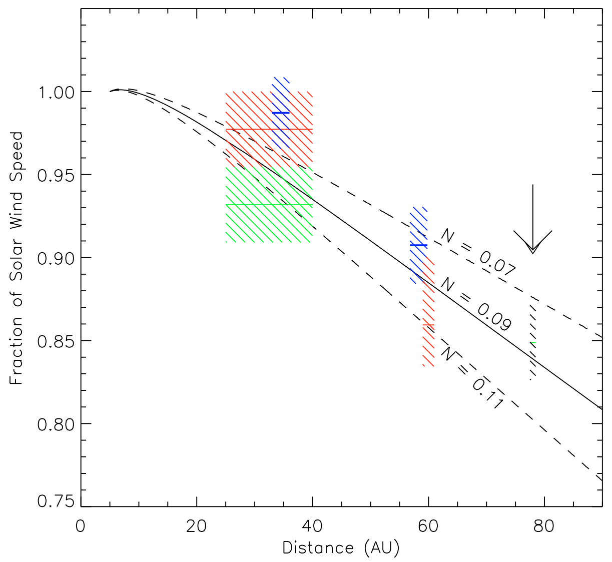

Fig. 5. The fraction of the 1 AU solar wind speed predicted by the model as a function of distance for interstellar neutral H densities of 0.09 cm^{-3} (solid line), 0.07 cm^{-3} (upper dashed line), and 0.11 cm^{-3} (lower dashed line). The lines show reported slowdowns at various distances with error bars shown by the hatched regions. The arrow shows the additional point derived in this work.

speed is 423 km s^{-1} for the H = 0.11 cm^{-3} case, 443 km s^{-1} for the H = 0.09 cm^{-3} case, and 461 km s^{-1} for the H = 0.07 cm^{-3} case. If we again interpolate, the best fit H would be .105 cm^{-3}. As noted above, these data from after the ICME probably passed Ulysses in late 2006, when Ulysses was at 10° higher heliolatitude than Voyager 2. Thus we do not think that the H density was higher; we think the speeds observed at Ulysses at higher heliolatitudes were higher than those directed at Voyager 2.

4. Discussion and summary

Several papers in the literature determine the solar wind slowdown by comparing solar wind speeds at different spacecraft. We summarize these results in Fig. 5. The lines shows the speed profile predicted by the model divided by the input solar wind speed of 440 km s^{-1} at 1 AU for neutral H densities at the TS of 0.07, 0.09, and 0.11 cm^{-3}. We show the percentage slowdown so we can compare slowdown observations from times with different average solar wind speeds. The lines and hatched regions show the percentage of the initial speed derived from the data at various distances. The left red box is from Gazis (1995), who compares PVO, IMP 8, Voyager 2, and Pioneer 11 data and finds a slowdown of 10 ± 10 km s^{-1}. The left green box is from Richardson et al. (1995b), who compare IMP 8 and Voyager 2 data and find a slowdown of 20 ± 10 km s^{-1}. The left blue box is from Wang et al. (2000a), who compare Ulysses data from its initial equatorial trajectory to Jupiter with Voyager 2 data and find a slowdown of 8 km s^{-1}. The right blue box is from a heliolatitudinal alignment of Ulysses and Voyager 2 in 1998; Wang et al. (2000b) find a speed decrease of 40 km s^{-1} at this time when Voyager 2 was at 58 AU. The right red box was derived from data near solar maximum, when the heliolatitudinal solar wind gradient was small; Wang & Richardson (2003) use Wind, Ulysses, and Voyager 2 data to calculate a speed decrease of 53–62 km s^{-1}. The right green box is the result from this paper.

The results are consistent with the speed decrease predicted by the model for a density at the termination shock of about 0.09 cm^{-3}. The data points at larger distances better differentiate between the possible TS H densities since the slowdown becomes greater and difference between the model predictions greater. Other papers in this issue find values for the LIC H at the TS of 0.12 cm^{-3} (Bzowski et al. 2007) and 0.085 cm^{-3} (Pryor et al. 2008). The lower value is consistent with these results; the higher value would predict a slowdown roughly 30 km s^{-1} greater than observed. As mentioned before, the slowdown further out is also less sensitive to uncertainties in the ionization rates of H in the heliosphere. We note that at the time of these observations Voyager 2 was in the foreshock region of the TS; the streaming particles observed in this region do not appear to have a large effect on the solar wind speed.

To summarize, the coincidence in heliolatitude of the Ulysses and Voyager 2 spacecraft allowed us to make an estimate of the slowdown in the solar wind between 5 and 78 AU. We found a slowdown of about 67 km s^{-1}, or 15%, which implies the pickup ions comprise about 17% of the solar wind plasma at this distance. We compiled all the slowdown estimates in the literature and showed that they are consistent with an H density at the TS of about 0.09 ± 0.01 cm^{-3}. The next time Ulysses and Voyager 2 are at the same heliolatitude is in mid-2007, but Ulysses will be moving quickly in heliolatitude so a slowdown determination may be difficult to make.

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References

Burlaga, L. F., Ness, N. F., Belcher, J. W., et al. 1994, J. Geophys. Res., 99, 21, 511

Bzowski, M., Gloeckler, G., Tarnopolski, S., Izmodenov, V., & Möbius, E. 2007, A&A, this issue

Collela, R., & Woodward, P. R. 1984, J. Comput. Phys., 54, 174

Dai, W., & Woodward, P. R. 1995, J. Comput. Phys., 121, 51
Fite, W. L., Smith, A. C. H., & Stebbings R. F. 1962, Proc. R. Soc. London. Ser. A, 268, 527
Gazis, P. R. 1995, Geophys. Res. Lett., 22, 2441
Gazis, P. R., Mihalov B. A., J. D., & Lazarus, A. J. 1994, J. Geophys., Res., 99, 6561
Geiss, J., & Witte, M. 1996, Space Sci. Rev. 78, 229
Gloeckler, G., Geiss, J., Balsiger, H., et al. 1993, Science, 261, 70
Gloeckler, G., Fisk, L. A., & Geiss, J. 1997, Nature, 386, 374
Isenberg, P. A., Smith, C. W., Matthaeus, W. H., & Richardson, J. D. 2005, in Proc. of Solar Wind 11, Connecting Sun and Heliosphere, ed. B. Fleck & T. H. Zurbuchen, ESA SP-592, 347
Ismodenov, V. V. 2007, Space Sci. Rev., 130, 377
Lallement, R., Bertaux, J. L., & Clarke, J. T. 1993, Science, 260, 1095
Lindsay, B. G., & Stebbings, R. F. (2005), J. Geophys. Res., 110, A12213, doi: 10.1029/2005JA011298
McComas, D. J., Elliott, H. A., Gosling, J. T., & Skoug, R. M. 2006, Geophys. Res. Lett., 33, L09102, doi: 10.1029/2006GL025915
McNutt, R. L., Lyon, J. L., & Goodrich, C. C. 1998 J. Geophys. Res., 103, 1905
Möbius, E., Hoverstadt, D., Klecker, B., et al. 1985, Nature, 316, 426
Pryor, W., Gangopadhyay, P., Sandel, B., et al., 2008, A&A, 491, 21
Richardson, J. D., Paularena, K. I., Lazarus, A. J., & Belcher, J. W. 1995, Geophys. Res. Lett., 22, 325
Richardson, J. D., Paularena, K. I., Lazarus, A. J., & Belcher, J. W. 1995, Geophys. Res. Lett., 22, 1469
Richardson, J. D., Liu, Y., Wang, C., et al. 2006, Geophys. Res. Lett., 33, L23107, doi: 10.1029/2006GL027983
Smith, C. W., Matthaeus, W. H., Zank, G. P., et al. 2001, J. Geophys. Res., 106, 8253
Smith, C. W., Isenberg, P. A., Matthaeus, W. H., & Richardson, J. D. 2006, APJ, 638, 508
Vasyliunas, V. M., & Siscoe, G. L. 1976, J. Geophys. Res., 81, 1247
Wang, C., & Richardson, J. D. 2001, J. Geophys. Res., 106, 401
Wang, C., & Richardson, J. D. 2003, J. Geophys. Res., 108, doi: 10.1029/2002JA009322
Wang, C., Richardson, J. D., & Gosling, J. T. 2000a, J. Geophys. Res., 105, 2337
Wang, C., Richardson, J. D., & Gosling, J. T. 2000b, Geophys. Res. Lett., 27, 2429
Witte, M. 2004, A&A, 426, 835
Zank, G. P. 1999, Space. Sci. Rev., 89, 413