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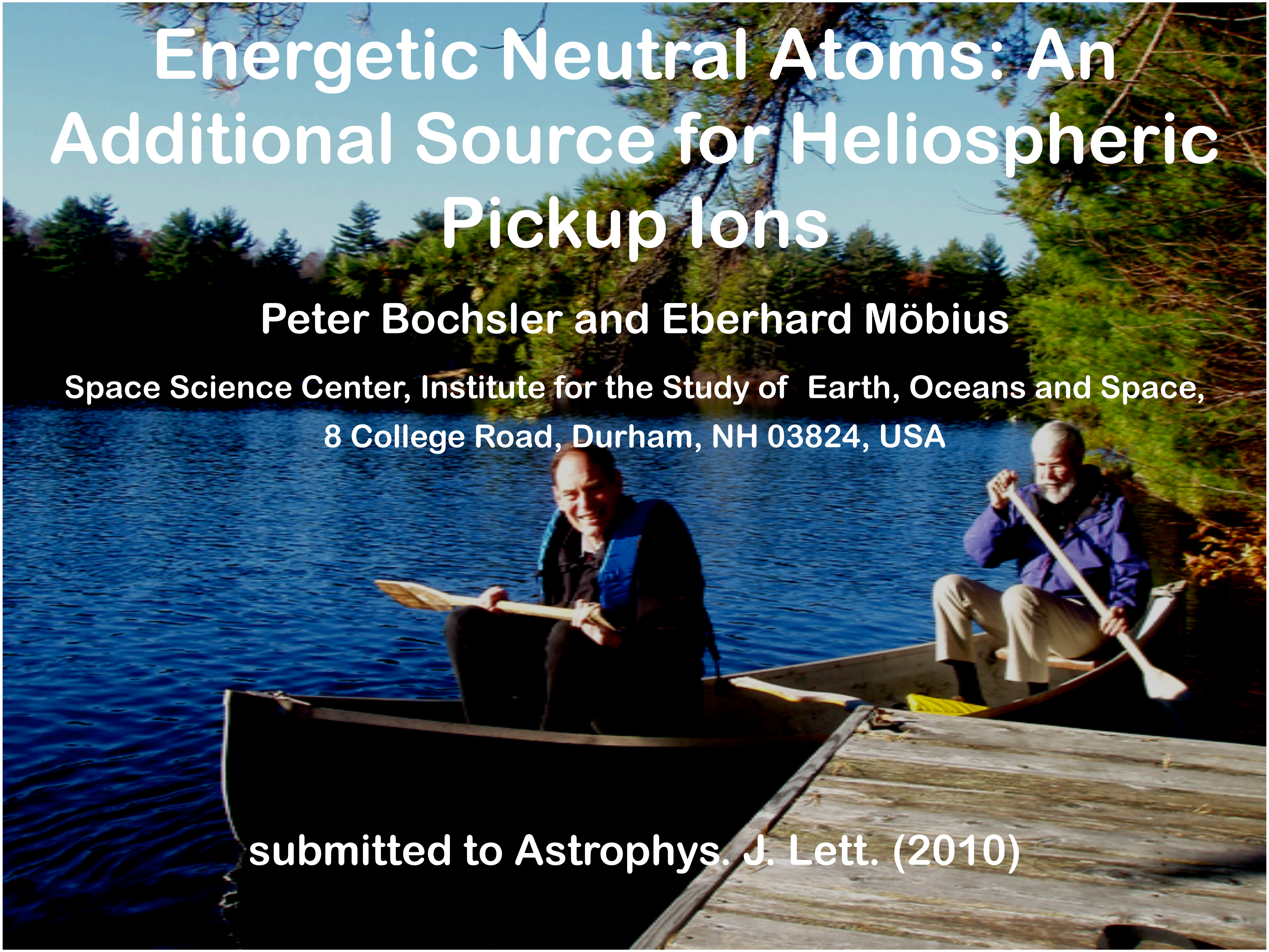

Energetic Neutral Atoms: An Additional Source for Heliospheric Pickup Ions

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ABSTRACT

Recently, Schwadron & McComas (2010) discussed the possibility of inner source pickup particles originating from the ionization of energetic neutral particles (ENAs), based on new data from the IBEX mission. This proposition has some interesting features, namely it might be able to explain, why inner source pickup ions have a composition resembling solar abundances and show no indication of overabundance of refractory elements, although this should be expected, if the conventional explanation of solar wind - dust interaction for the origin of this heliospheric component were correct. In this paper we explore further consequences for ENA-related pickup ions and investigate their velocity distributions. We conclude that this model will not reproduce the observed velocity distributions of inner source pickup ions and point out a substantial deviation in their composition. However, it seems likely that the ionization of ENAs as observed with IBEX could contribute a significant amount of suprathermal heliospheric ions. Some possible consequences of our investigation for heliospheric particle populations are briefly discussed.

Subject headings: ISM:general, Sun:heliosphere, Sun:solar wind

1. Introduction

Interstellar pickup ions (PUI) have been found some time ago as a special population of particles in the solar wind flow (Möbius et al. 1985; Gloeckler et al. 1993). A pickup ion is generated when a neutral atom, e.g., a He- or H-atom from the interstellar neutral gas, which penetrates the heliosphere, becomes ionized either by charge exchange with solar wind ions or by photoionization from sunlight. Usually, the newborn pickup ion is not at rest in the solar wind frame; it experiences the Lorentz force from the outward moving magnetic field, and consequently, it begins to gyrate about the ambient magnetic field with its original speed relative to the moving magnetic field. The circular motion is superposed on the linear motion of the magnetic field, hence, the ion executes a cycloidal motion in the frame of an observer at rest. The originally ring-shaped velocity distribution in the solar wind frame is quickly transformed into a distribution on a hemispherical or spherical shell by pitch-angle scattering (Holzer & Axford 1970). As the population travels outward, it cools, and the (hemi)spherical shell shrinks correspondingly. PUIs generated further out replace the exterior shells, and gradually, new shells fill the entire sphere (Vasyliunas & Siscoe 1976). Naturally the most abundant species at 1 AU, $^4He^+$, was the first to be extensively studied. More sophisticated space experiments provided information on many other species in the pickup population, even elements with low ionization potentials such as C, Mg and Si were discovered among PUIs (Geiss et al. 1995; Gloeckler et al. 2000). These observations showed that not all PUIs could be associated with the penetrating interstellar neutrals. Geiss et al. (1995) attributed the origin of this special population – containing refractory elements – to an "inner source", and argued that these ions were generated by the interaction of solar wind ions with dust grains close to the Sun. The discussion of the details of the mechanism producing these inner source ions turned out somewhat controversial. One key feature of the inner source pickup ions was their distinctly different velocity distribution at the location of observation: Whereas the PUIs from interstellar neutrals covered essentially the entire velocity range from zero to twice the solar wind velocity, as was predicted for a cycloidal motion of ions, the inner source PUIs showed a narrow velocity distribution, which peaked somewhere below the solar wind velocity (Gloeckler et al. 2000). In the scheme of the pickup process as discussed before, this indicated extensive adiabatic cooling, and therefore, an origin far away from the observer, i.e., close to the Sun. The elemental composition of inner source PUIs still poses a problem:

Any type of interaction of solar wind ions or solar energetic particles with dust grains will sputter dust particles. In this context it is a puzzle, why a large fraction of inner source ions comes as Ne^+ (Gloeckler et al. 2000). Gloeckler et al. (2000) attributed the surprisingly large abundance of Ne to the release of solar wind implanted elements from dust grains. Apart from not explaining the lack of sputtered dust material among PUIs, this scenario also required amounts of dust much larger than those actually observed in the inner solar system. The so-called trapping/desorption scenario of volatiles proposed by Gloeckler et al. (2000) seems also contradicted by the observation of Kehm, Flynn & Hohenberg (2006), who found that interplanetary dust particles are far from being saturated with solar wind implanted volatiles. Specifically, while expected residence times for these grains in the inner heliosphere are of the order of 10,000 years, their solar wind argon dose indicated an exposure of at most a few hundred years. The difficulty of large amounts of dust required to produce the observed flux of inner source pickup ions (e.g., Schwadron et al. 2000) led Wimmer-Schweingruber & Bochsler (2003) to propose an alternative, more efficient scheme, in which dust is merely implied as catalyst for discharging solar wind ions. This scenario, however, also predicts considerably larger refractory/volatile elemental abundance ratios in pickup ions than factually observed.

Now, a different, possible solution of the problem of elemental abundances has been offered by Schwadron & McComas (2010), who argue that a large fraction – if not all – of the inner source pickup ions are due to re-ionization of energetic neutral atoms (ENAs) in the inner heliosphere. While this naturally explains the absence of large amounts of sputtered material, we conclude that velocity distributions of ENA-generated pickup ions will appear distinctly different from what has been observed for the inner source ions. Instead, we propose that ENAs are a substantial contributor to suprathermal particles in the heliosphere.

In fact, already several years before IBEX measurements became available, Chalov & Fahr (2003) have shown that suprathermal tails in pickup proton velocity distributions during quiet solar wind conditions could be qualitatively explained by ENAs from the innner heliosheath, which undergo charge exchange and photoionization near the Sun.

2. Energetic Neutral Atoms as the Origin of the Inner Source?

Schwadron & McComas (2010) showed that the fluxes of ENAs detected by IBEX (McComas et al. 2009) would suffice to account for the observed inner source pickup ion flux. If ENAs are sufficiently energetic, even ENAs from refractory elements such as C, Mg, Fe etc. with low ionization potentials, may be fast enough to penetrate into the innermost heliosphere before being ionized and converted into pickup ions. As pointed out before, this scenario seems attractive for the origin of inner source ions because it does not involve dust and thus avoids the overproduction of refractory ions, which should be observed because of the concomitant sputtering of dust material, whenever dust is involved in the production process. It also might provide a natural explanation for the apparent overabundance of neon in the inner source, since this element has the second highest first ionization potential. However, it is not clear whether this scenario also explains the particular features of inner source pickup ions with respect to their observed velocity distributions. Unlike the interstellar neutrals, which penetrate with low initial speeds of $\approx$ 26 km/s, ENAs travel practically on straight trajectories at velocities comparable to those of solar wind ions. They are expected to enter the heliosphere almost isotropically, and in general they have substantially higher velocities in the solar wind rest frame than neutrals from the interstellar medium. Correspondingly, we expect a wider spread of the resulting pickup ion distribution. The initial velocity vectors of ENA-pickup ions are not randomly distributed about a sphere in velocity space: Their initial velocity is preferentially directed towards the Sun, because ENAs traveling away from the Sun are depleted due to prior ionization.

We have used a Monte Carlo procedure to simulate such particles. We injected energetic neutrals from a spherical shell at 200 AU radius with power-law energy distributions as suggested by Schwadron & McComas (2010), but with slightly different parameters. We used $j = j_o(E/E_o)^{-\kappa}$ with $\kappa \approx 1.5$ and $j_o \approx 90$, taking into account that the majority of ENAs have energies below 1 keV and that the measurements of McComas et al. (2009) exhibit a slightly flatter distribution than the overall distribution adopted by Schwadron & McComas (2010). We assumed trajectories on straight lines at constant velocities. This approximation is suitable for hydrogen atoms, as for this species the radiation pressure from solar EUV roughly compensates the solar gravitation. Our adopted ionization rate of hydrogen at 1 AU is $8.1 \cdot 10^{-7} s^{-1}$, typical for the quiet Sun. Furthermore, we assume a uniform solar wind velocity of 400 km/s. The ionization of the incoming ENAs was simulated taking into account the $1/\mathrm{r}^2$-dependence of the ionization probability. In order to compare our computed phase space distributions with those reported by Geiss, Gloeckler & Fisk (2006) we assumed that an observer was placed at 2.34 AU from the Sun. Hence, we only considered particles, which were ionized within a sphere of 2.34 AU around the Sun. Inspection of the statistics of particles, which are ionized within the sphere of 2.34 AU shows a weak trend of particles with high speeds being injected more frequently close to the Sun. There are two reasons for this trend: First, as discussed before, the portion of ENA distribution with particles traveling antiparallel to the solar wind tends to be enhanced, because ionization effectively suppresses ENAs that pass close to the Sun. Second, very fast ENAs have a higher probability of approaching the Sun before being ionized than low-energy ENAs. From the initial velocity vector of the freshly ionized particle the local velocity vector of the outward moving solar wind plasma was then subtracted to obtain the initial velocity of the pickup ion in the frame of the solar wind.

In the next step, we assume that pickup ions are instantaneously pitch-angle scattered, filling a spherical shell in the solar wind frame, which has a radius corresponding to the initial speed in this frame. Subsequently, particles are carried outward and undergo adiabatic cooling following the model proposed by Vasyliunas & Siscoe (1976), i.e., $v^{2\nu} r = const.$, with $\nu = 3/4$. We have noted elsewhere (Bochsler, Möbius & Wimmer-Schweingruber 2006) that this model neglects heating due to wave particle interaction as is observed for solar wind species. By applying $\nu = 3/4$ we therefore tend to underestimate the width of pickup ion distributions at the site of the observer. Figure 1 shows the resulting velocity distribution at 2.34 AU. The distribution differs strongly from the typical distributions found by Geiss et al. (1995) for inner source pickup ions. It exhibits a wide velocity spread ranging from 0.2 to 2 v_{sw} with a strong decrease towards higher velocities. For comparison and as a consistency check, we also simulated a velocity distribution for pickup ions of interstellar origin, which start at rest in the inertial frame. Using a simple analytical model we estimate the upstream density of interstellar hydrogen pickup ions at 2.34 AU to be $5.1 \cdot 10^{-4}$cm^{-3}. In analogy with Schwadron & McComas (2010) we estimate from our adopted ionization rate and from our adopted ENA flux distribution a typical ENA density at 2.34 AU of $6.1 \cdot 10^{-4}$cm^{-3} or $3.05 \cdot 10^{-4}$cm^{-3}, depending whether the lower energy cutoff is at 50 or 100 eV. The phase space densities in Figure 1 have been scaled accordingly.

In Table 1 we show the probability of different ENA-species to reach 2.34 AU before being ionized, hence, of being detected as a pickup species for an observer at 2.34 AU, normalized to a survival probability of 1 for helium. We have used the same parameters for the ENA fluxes and energy distributions as above, with a lower cutoff energy of 100 eV. Ionization rates at 1 AU are given in columns 2 to 7. Typical uncertainties in the ionization rates, which translate in a complicated way into the survival probabilities, are of the order of 20%. The most relevant conclusion is that silicon has practically no chance of surviving, even as very fast ENA under very quiet solar conditions because of its exceedingly large photoionization cross section, which is 66 Mb just below its ionization limit (Nahar & Pradhan 1993; Verner et al. 1996)

3. Conclusions

Given the results of our simulations of the PUI velocity distribution and given their composition, inner source pickup ions most likely cannot originate from ENAs. However, the estimates of ENA-pickup fluxes of Schwadron & McComas (2010) derived from the observations of IBEX, seem fairly robust. Therefore, the related pickup ions are probably part of the so-called heliospheric suprathermal population of H^+.

It seems unlikely that the velocity distributions of inner source pickup ions can be reconciled with a source far away from the Sun. Specifically, the ionization of ENAs, as observed with IBEX, will not be able to produce the typical velocity distributions of inner source pickup ions. However, it seems plausible that a significant fraction of suprathermal ions, present also in phases of low solar activity and in the absence of corotating interaction regions, is due to ionization of ENAs in the inner heliosphere. At least for periods of low solar activity – this conclusion shifts the emphasis of heating and acceleration of suprathermal heliospheric particles away from compressive waves in the inner heliosphere (Fisk, Gloeckler, Zurbuchen, & Schwadron 2000) to the turbulent regime at the heliospheric boundary. It might well be that suprathermal ionized particles will undergo charge exchange at the heliospheric boundaries and re-enter as ENAs. A detailed investigation of these processes is necessary. Nevertheless, it is clear that pickup ions from ENAs are particularly well-suited as seed particles for further shock-acceleration within the inner heliosphere.

Further analysis of the composition of ENAs and suprathermal ions might provide additional clues to their origin. For instance, Gloeckler et al. (2000) clearly identified a peak near 28 amu/e of approximately equal height as the peak at mass 24 in the spectrum of inner source pickup ions. Their identification of these ions as Si^{+} and Mg^{+} seems clear and unambiguous. While a certain amount of Mg might survive as fast ENAs deep into the inner heliosphere, this seems much less likely for the case of Si, as this element exhibits a far higher photoionization cross section than Mg.

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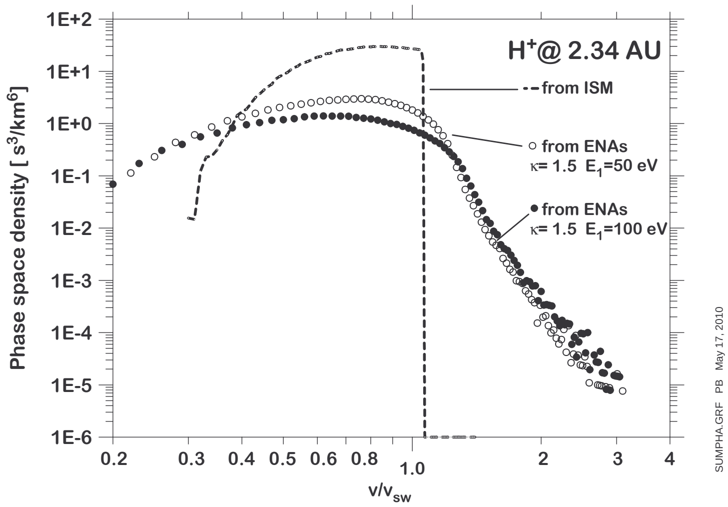

Fig. 1.— Phase space densities of pickup ions in the solar rest frame at 2.34 AU. The dashed line shows a simulation of cold interstellar hydrogen pickup ions, which are ionized practically at rest in the inertial solar frame. The dotted lines show distributions of pickup ions originating from ENAs with an energy distribution $E^{-\kappa}$ ($\kappa \approx 1.5$) as observed at the low energy end of the ENA distribution by IBEX-lo (McComas et al. 2009). Full circles originate from a distribution with a low energy cutoff at 0.1 keV, whereas open circles are from a distribution with a cutoff at 0.05 keV. Both distributions differ strongly from typical inner source pickup distributions, which are much narrower than those of pickup ions from interstellar neutrals. Note that the distribution with the higher cutoff is somewhat flatter at the low velocity end, because more particles enter the innermost heliosphere with a more efficient adiabatic cooling during the transport to the observer. At the high-velocity end we note that the decrease of the phase space density is not following a simple power-law determined by the ENA energy distribution.

Table 1: Fraction of energetic neutrals entering into a sphere of 2.34 AU from the Sun, during periods of low and high solar activity, normalized to helium

Element	Photo-ioniz. quiet	Photo-ioniz. active	electron collis. ioniz.	charge ex-change w. protons	Ionization Rate quiet	Ionization Rate active	Probability of entering r ≤ 2.34 AU for quiet	Probability of entering r ≤ 2.34 AU for active
	(all for conditions at 1 AU and all in units of $10^{-7}s^{-1}$)						He≡1.000	
H	0.62	2.47	0.65	6.86	8.13	9.98	0.912	0.898
He	0.48	1.90	0.11	0.001	0.59	2.01	≡1.000	≡1.000
C	5.00	20.0	12.0	2.46	19.5	34.5	0.695	0.441
N	2.21	8.84	1.04	1.25	4.50	11.1	0.963	0.877
O	2.20	8.80	0.89	3.73	6.82	13.4	0.940	0.819
Ne	1.57	6.28	0.18	1.18	2.93	7.64	0.987	0.933
Na	54.9	219	12.0	14.0	80.9	245	0.092	0.002
Mg	2.67	10.7	10.3	2.88	15.9	23.9	0.766	0.616
Si	130	520	9.76	32.06	172	562	0.008	0.000
Ar	3.28	13.14	2.15	3.24	8.67	18.5	0.916	0.731

REFERENCES

Allegrini F., Schwaddron N.A., McComas D.J., Gloeckler G., & Geiss J. 2006, J. Geophys. Res., 110, doi:10.1029, A05105

Bochsler P., Möbius E., & Wimmer-Schweingruber R.F. 2006, Geophys. Res. Lett., 33, doi:10.1029/2005/GL025178

Chalov S.V., & Fahr H.J. 2003, A&A, 401, L1

Fisk L.A., Gloeckler G., Zurbuchen Th. H., & Schwadron N.A. 2000, in: AIP Conference Proceedings, CP-528, 229

Geiss J., Gloeckler G., Fisk L.A., & von Steiger R. 1995, J. Geophys. Res., 100, 23,373

Geiss J., Gloeckler G., & Fisk L.A. 2006, ISSI Scientific Report No. 5, pp. 137

Gloeckler G., Geiss J., Balsiger H., Fisk L.A., Galvin A.B., Ipavich F.M., Ogilvie K.W., von Steiger R., & Wilken B. 1993, Science, 261, 70

Gloeckler G., Schwadron N.A., Fisk L.A., & Geiss J. 1995, Geophys. Res. Lett., 22, 2665

Gloeckler G., Fisk L.A., Geiss J., Schwadron N.A., & Zurbuchen T.H. 2000, J. Geophys. Res., 105, 7459

Gruntman M. & Izmodenov V. 2004, J. Geophys. Res., 109, doi:10.1029/2004JA010727

Holzer T.E. & Axford W.I. 1970, J. Geophys. Res., 75, 6354

Kehm K., Flynn G.J., & Hohenberg Ch. M. 2006, Meteoritic and Planetary Sciences, 41, 1199

McComas D.J. et al. (2009), Science, 326, 959

Möbius E., Hovestadt D., Klecker B., Scholer M., Gloeckler G., & Ipavich F.M. 1985, Nature, 318, 426

Nahar S.N. & Pradhan A.K. 1993, J. Phys. B: At. Mol. Opt. Phys., 26, 1109

Schwadron N.A., Geiss J., Fisk L.A., Gloeckler G., Zurbuchen Th. H., & von Steiger R. 2000, J. Geophys. Res., 105, 7465

Schwadron N.A. & Mc Comas D.J. 2010, ApJ, 712, L157

Vasyliunas V.M. & Siscoe G.L. 1976, J. Geophys. Res., 81, 1247

Verner D.A., Ferland G.J., Korista K.T. & Yakovlev D.G. 1996, ApJ, 465, 487

Wimmer-Schweingruber R.F. & Bochsler P. 2003, Geophys. Res. Lett., 49–1

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