Mass transport in the heliosphere by energetic neutral atoms

Mike Gruntman

Astronautics and Space Technology Division, Viterbi School of Engineering, University of Southern California, Los Angeles, California, USA

Vlad Izmodenov

Department of Aeromechanics and Gas Dynamics, Faculty of Mechanics and Gas Dynamics, Moscow State University, Moscow, Russia

Received 8 August 2004; revised 12 October 2004; accepted 25 October 2004; published 28 December 2004.

[1] Energetic neutral atoms (ENAs) are recognized as a powerful tool for remote probing of distant hot space plasmas, in particular the plasmas abundant at the heliospheric boundary where the expanding solar wind meets the surrounding local interstellar medium. We show here for the first time that the heliospheric ENAs originating in the heliospheric sheath between the termination shock and the heliopause and reaching the inner heliosphere also provide an important and heretofore unaccounted source of atomic hydrogen in the Sun's vicinity. These ENAs are a major contributor to the density of interplanetary hydrogen at heliocentric distances <1 AU and could dominate in the downwind (interstellar wind) region under typical solar and interstellar conditions. Mass transport by heliospheric ENAs may become especially important for determining the origin of the pickup ions attributed to the inner source of neutral particles in the Sun's vicinity and for characterization of the three-dimensional solar wind flow by imaging in extreme ultraviolet. *INDEX TERMS:* 2151 Interplanetary Physics: Neutral particles; 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 2124 Interplanetary Physics: Heliopause and solar wind termination; 2199 Interplanetary Physics: General or miscellaneous; *KEYWORDS:* heliosphere, energetic neutral atoms, pickup ions, heliospheric sheath, heliospheric boundary, mass transport in the heliosphere

Citation: Gruntman, M., and V. Izmodenov (2004), Mass transport in the heliosphere by energetic neutral atoms, *J. Geophys. Res.*, *109*, A12108, doi:10.1029/2004JA010727.

1. Interplanetary Neutral Atoms in the Sun's Vicinity

[2] Presence of atomic hydrogen in interplanetary space was first derived in 1963 by *Patterson et al.* [1963] from the earlier sounding rocket measurements by *Morton and Purcell* [1962]. It is established now that the main source of interplanetary hydrogen is neutral atoms penetrating the solar system from the surrounding local interstellar medium (LISM). The inflow of interstellar gas in the heliosphere is well understood [*Fahr*, 1968a, 1974; *Holzer*, 1977; *Meier*, 1977; *Thomas*, 1978; *Bertaux*, 1984], with the theoretical concepts supported by various experimental measurements. The neutral population in the immediate Sun's vicinity, <1 AU, remains perhaps the least characterized because atoms are strongly depleted there by ionization and experimental techniques are usually not especially sensitive to neutrals in this region. Measurement of the solar wind pickup ions is an exception, specifically probing neutrals close to the Sun.

[3] Interplanetary neutral atoms are ionized (mainly charge exchange and photoionization) and picked up by the solar wind flow [*Holzer and Axford*, 1970; *Fahr*, 1973; *Vasyliunas and Siscoe*, 1976]. Most of these pickup ions are singly charged and characterized by a velocity distribution function essentially distinct from that of the bulk of the solar wind plasma. The pickup ion flux and velocity distribution function at a given point are thus an effect accumulated along the line of the solar wind propagation from the Sun to this point, combining the processes of neutral ionization and ion transport.

[4] *Moebius et al.* [1985] were the first to measure the pickup (helium) ions in the solar wind. The existing theoretical models of the interstellar gas penetration into the heliosphere could quantitatively predict the distributions of neutrals in the inner heliosphere, and the first measurements of the pickup ions were successfully explained by the ionization of the inflowing interstellar helium [*Moebius et al.*, 1985; *Moebius*, 1990].

[5] The increasingly sophisticated space experiments detected various atomic (H, C, N, O, Ne, Mg, and Si) and even molecular pickup ions [*Moebius*, 1990, 1996; *Gloeckler et al.*, 1993, 2000; *Geiss et al.*, 1994, 1995; *Gloeckler*, 1996; *Gloeckler and Geiss*, 1998, 2001; *Schwadron et al.*, 2000; *Schwadron and Geiss*, 2000]. These measurements have revealed that a new source of neutral atoms, additional to the inflowing LISM interstellar gas, was needed to explain the observed pickup ion elemental composition and fluxes [*Geiss et al.*, 1995; *Gloeckler et al.*, 2000; *Schwadron et al.*, 2000]. The heliocentric dependence of

0148-0227/04/2004JA010727$09.00

the observed pickup ion properties puts this new source, called the "inner source," close to the Sun.

[6] The Poynting-Robertson effect [*Robertson*, 1937] causes interplanetary dust to concentrate in the Sun's vicinity. The dust has been invoked as a possible and important source of noninterstellar gas neutrals within 1 AU from the Sun [*Banks*, 1971; *Holzer*, 1977; *Fahr et al.*, 1981; *Gruntman*, 1994, 1996; *Gloeckler et al.*, 2000; *Schwadron et al.*, 2000]. The contribution of interplanetary dust to populations of neutrals in interplanetary space remains, however, a major uncertainty. The estimates of the dust-produced neutrals and ions suffer from poor knowledge of the interplanetary dust composition and abundance and from the uncertainty in the quantitative description of complex processes of dust evaporation, outgassing, and sputtering. In addition, many dust-produced pickup ions are born in the solar wind undergoing acceleration close to the Sun, with the resulting not-completely-understood evolution of the velocity distribution of ions on their way to observation points (spacecraft) at 1 AU and beyond.

[7] The exact nature of the inner sources has not been unambiguously established and a fully consistent explanation of the experimental observations of the pickup ions has not been developed yet. The pickup ion measurements reveal, for example, that a significant fraction of the observed pickup protons could be produced by the inner source, but the abundance of these inner source "protons relative to oxygen falls significantly below the universal abundance" [*Schwadron et al.*, 2000]. The exact cause of the observed depletion remains unknown and a number of mechanisms such as photon resonance scattering and transport effects have been invoked as an explanation of the depletion [*Schwadron and Geiss*, 2000; *Schwadron et al.*, 2000].

[8] *Wimmer-Schweingruber and Bochsler* [2003] noted that the abundance of dust (characterized by the so-called Γ factor) necessary to explain the flux of oxygen pickup ions "is almost two orders of magnitude larger than other typical values [of Γ]." In contrast, the upper limit on the dust-produced atomic hydrogen [*Fahr et al.*, 1981; *Gruntman*, 1994, 1996] has been found to be significantly lower than expected [*Yatchmenoff and Gruntman*, 1998; *Gruntman*, 2000] in the SWAN/SOHO [*Bertaux et al.*, 1995] Lyman-α sky maps. *Wimmer-Schweingruber and Bochsler* [2003] even proposed a hypothetical population of ultra-small dust particles in the Sun's vicinity to explain the properties of the inner source pickup ions. In addition, the recently identified outer source of pickup ions [*Schwadron et al.*, 2002], particularly important for understanding of the causally related anomalous cosmic rays, further complicates interpretation of the pickup ion measurements and establishing the nature of the inner source. The reliable interpretation of the measurements of the inner source pickup ions clearly requires that all possible major sources of neutrals in the Sun's vicinity are quantitatively described as accurately as practical.

[9] Another effect where atomic hydrogen in the Sun's vicinity plays an important role is the emissions of the solar wind plasma in extreme ultraviolet. These characteristic emissions are produced by charge exchange of the solar wind alpha particles on interplanetary hydrogen [*Gruntman*, 2001a]. The examination of the predicted sky maps of these emissions suggests that they will enable highly promising remote monitoring of the three-dimensional flow pattern (velocities and number densities) of the solar wind in the heliosphere, including in the regions over the Sun's poles [*Gruntman*, 2001a, 2001b]. The region within a few AU from the Sun would contribute to the observed emissions, and accurate characterization of interplanetary atomic hydrogen in this region is essential for interpretation of such solar wind imaging in extreme ultraviolet.

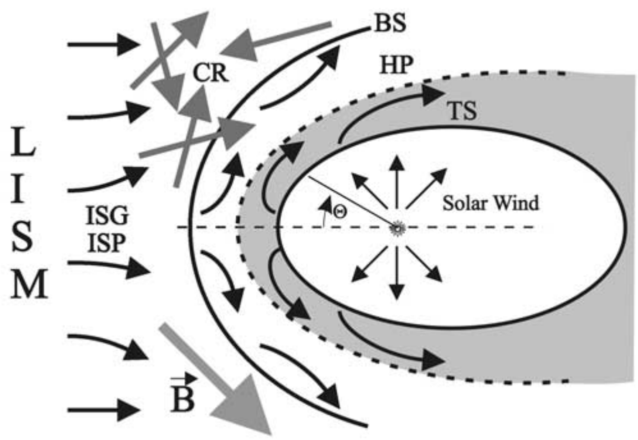

Figure 1. Two-shock model of the interaction of the solar wind with the local interstellar medium. LISM is local interstellar medium, TS is termination shock, HP is heliopause, BS is bow shock, CR is cosmic rays, ISP(G) is interstellar plasma (gas), and B is magnetic field. Angle θ is measured from the upwind direction. The heliospheric sheath, the region (gray) between the termination shock and the heliopause, contains the postshock solar wind plasma and pickup protons.

2. Heliospheric Energetic Neutral Atoms

[10] In this article we identify for the first time an additional important and heretofore unaccounted source of atomic hydrogen in the Sun's vicinity, the low-energy (defined as <5 keV for the purposes of this work) energetic neutral atoms (ENAs) born in the heliospheric sheath.

[11] The interaction of the expanding solar wind plasma with the surrounding LISM creates the heliosphere [*Davis*, 1955; *Parker*, 1963; *Dessler*, 1967; *Axford*, 1972]. The heliosphere is a complex phenomenon where the solar wind and interstellar plasmas, interstellar gas, magnetic field, and energetic particles all play important roles. A possible two-shock Sun-LISM interaction scenario [*Baranov and Malama*, 1993] illustrates the main features of the heliosphere (Figure 1). The interstellar wind approaches the heliosphere with a supersonic velocity and forms the bow shock. The dynamic pressure of the expanding, highly supersonic solar wind decreases with the heliocentric distance. At a certain distance from the Sun, this pressure would equal the external LISM pressure of the interstellar wind and magnetic field. The solar wind expansion transitions to a subsonic flow at the termination shock. There the kinetic energy of the supersonic flow is largely converted into thermal energy in the subsonic plasma beyond

the shock. This subsonic postshock solar wind plasma flows in the heliospheric sheath around the termination shock and down the heliospheric tail. The solar plasma eventually mixes with the interstellar galactic plasma in the tail at distances >5000 AU [*Jaeger and Fahr*, 1998; *Izmodenov and Alexashov*, 2003].

[12] The heliosphere is believed to be filled with fluxes of energetic hydrogen atoms with energies less than a few keV originating in the heliospheric sheath between the solar wind termination shock and the heliopause [*Gruntman*, 1992, 1997]. The number densities of these ENAs are typically a few orders of magnitude smaller than that of interstellar hydrogen in most parts of the heliosphere. Consequently, most of the experimental techniques measuring the neutrals in the heliosphere, such as study of the Lyman-α glow of interplanetary hydrogen, are not especially sensitive to heliospheric ENAs. The notable exception is detection of individual energetic atoms at a given point, which is the basis for ENA imaging of the heliosphere [*Gruntman*, 1992, 1997; *Gruntman et al.*, 2001].

[13] Close to the Sun, however, the fast-moving heliospheric ENAs may become relatively much more abundant. The solar wind and solar extreme ultraviolet (EUV) radiation efficiently ionize the slower-velocity interstellar neutrals producing a region, sometimes called the ionization cavity, with the depleted interstellar hydrogen number densities. In contrast, the faster-velocity ENAs originating in the heliospheric sheath are less subjected to ionization and, consequently, the relative abundances of hydrogen ENAs and interstellar hydrogen could be significantly different in the Sun's vicinity. Therefore mass transport by heliospheric ENAs may become important. We note that there is another example of important transport of mass, energy, and momentum by heliospheric ENAs: the ENAs born in the supersonic solar wind and the heliosheath would penetrate and "contaminate" the pristine LISM at distances up to 300–400 AU [*Gruntman*, 1982, 2004; *Baranov and Malama*, 1993; *Zank*, 1999; *Izmodenov et al.*, 2001a]. In the terrestrial magnetosphere, the similar processes are responsible for energetic particle transport from the ring current to the thermosphere [*Dessler et al.*, 1961; *Tinsley*, 1981].

[14] Most of the heliospheric ENAs are born in charge exchange between hot plasma ions and background interstellar neutral gas in the heliospheric sheath (Figure 1) and their energies are below a few keV. When charge exchange occurs, the resulting ENA instantaneously becomes independent from the surrounding plasma and the influences of the magnetic field. The energetic neutral particle moves along a ballistic trajectory away from the point of charge exchange governed only by the initial velocity and forces of the Sun's gravitational attraction and radiation pressure. As ENAs travel through space, they may be lost by ionization (electron and ion collisions and photoionization), which can be reliably quantified. Some ENAs would move toward the Sun and reach the inner heliosphere, contributing to the population of atomic hydrogen in the Sun's vicinity.

[15] Other sources of ENAs in the heliosphere include a neutral component in the solar wind [*Fahr*, 1968b; *Gruntman*, 1982, 1994] and energetic neutrals produced in charge exchange of heliospheric energetic ions, such as suprathermal ions, anomalous cosmic rays, solar energetic protons, and protons associated with the corotating interaction regions [*Hsieh et al.*, 1992; *Roelof*, 1992; *Hsieh and Gruntman*, 1993]. Heliospheric ENAs at high energies, 55–80 keV, have been detected by the neutral channel of the HSTOF sensor of the CELIAS instrument on SOHO [*Hilchenbach et al.*, 1998]. These high-energy heliospheric ENAs can be disregarded because their number densities are several orders of magnitude lower than those of the low-energy ENAs and of interstellar hydrogen anywhere in the heliosphere.

[16] The concept of the heliospheric ENA production, propagation, and loss is well understood [*Gruntman*, 1992, 1997]. Briefly, the directional differential ENA flux $j_{\mathrm{ENA},i}$ ($\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{erg}^{-1}$) of a given species i from a given direction $\vec{s}$ is a line of sight integral

$$j_{ENA,i}(\vec{s},E) = \int_{\vec{s}} j_i(\vec{s},E) \sum_k [\sigma_{ik}(E) n_k(\vec{s})] P(\vec{s},E) ds, \qquad (1)$$

where $j_i(\vec{s}, E)$ is the local directional differential flux of parent ions, $n_k(\vec{s})$ is the local number density of neutral species k of the background gas, and $\sigma_{ik}(E)$ is the energy-dependent charge-exchange cross section between ions of species i and neutrals of species k. The survival probability, $P(\vec{s}, E)$, of ENAs allowing for particle extinction on their way from their point of birth to the point of interest is

$$P(\vec{s},E) = \exp\left[-\int \beta(t)\, dt\right],$$

where $\beta(t)$ is the ENA total loss rate from charge exchange, electron impacts, and photoionization. The details of the calculations of ENA fluxes and number densities can be found in the works of *Gruntman* [1992, 1997], *Hsieh et al.* [1992], *Roelof* [1992], *Hsieh and Gruntman* [1993], *Fahr and Lay* [2000], and *Gruntman et al.* [2001].

3. Model

[17] We demonstrate the importance of the mass transport by heliospheric ENAs using axisymmetric flow fields (velocity, temperature, number density) of the LISM and solar wind plasmas and the heliospheric interface structure predicted by a two-shock gasdynamical Baranov model [*Baranov and Malama*, 1993, 1995]. The two-shock model assumes that both the interstellar plasma flow and the solar wind plasma flow are supersonic (Figure 1). The plasmas are described as single fluids, while the neutral gas is described kinetically. The plasma-gas charge exchange coupling is treated self-consistently, and cosmic rays, energetic particles, and magnetic field are disregarded.

[18] We note that what happens exactly at the solar wind termination and how the energy of the solar wind plasma is partitioned in the heliospheric sheath among various plasma constituents are not exactly known. Inconsistent interpretations of the recent observations in the distant heliosphere by Voyager 1 [*Krimigis et al.*, 2003; *McDonald et al.*, 2003] have clearly revealed the limitations of our present concepts and models of the solar wind termination.

[19] The laws of conservation, however, suggest in a fundamental, model-independent way that heliospheric ENAs would reach the inner heliosphere. The supersonic

expansion of the solar wind has to slow down and transform into a subsonic flow because of the finite pressure of the interstellar medium surrounding the solar system. This slowing down, through a shock transition or otherwise, would result in two effects. First, some of the kinetic energy of the supersonic solar wind would transform into energy of the thermal motion of plasma particles and/or into energization of some type(s) of charged particles. Some plasma protons would thus reach, after charge exchange in the heliospheric sheath, the inner heliosphere as ENAs. Second, the slowing down of the solar wind would shift (in the velocity space) the distribution of the solar wind pick up protons, and some of these protons would reach, after charge exchange, the inner heliosphere as ENAs. This unavoidable presence of heliospheric ENAs in the inner heliosphere consequently enables the probing of the nature of the physical processes at and beyond the termination shock through ENA global imaging [*Gruntman*, 1992, 1997; *Gruntman et al.*, 2001; *McComas et al.*, 2003]. As we will see, the mass transport by heliospheric ENAs to the inner heliosphere significantly contributes to hydrogen number densities in the Sun's vicinity, which opens a way of constraining our global heliospheric models through analysis of the pickup proton abundances in the solar wind at 1 AU and from mapping the solar wind flow pattern in EUV.

[20] We assume in this work the following pristine (at infinity) LISM parameters: velocity 25 km s^{-1}, temperature 5672 K, electron (proton) number density n_e = 0.07 cm^{-3}, neutral hydrogen number density n_H = 0.14 cm^{-3}. The solar wind is spherically symmetric with the speed 450 km/s and number density 7.0 cm^{-3} at 1 AU. The calculated termination shock, heliopause, and bow shock are shown in Figure 2. The computation region extends from 400 AU in the upwind direction to 700 AU in the downwind direction and 1400 AU in the sidewind direction. The ENA production rates are numerically calculated using formula (1).

[21] We consider here a simplified model of ENA transport to the inner heliosphere. In particular, (1) we disregard losses of ENAs while propagating inside the heliospheric sheath and (2) ENA losses in the solar wind are calculated under assumption of the constant velocity of ENAs.

[22] The former model simplification results in a small, by 5–10 %, overestimation of the contributions of the ENA fluxes arriving from the upwind and sidewind (with respect to the interstellar wind) directions. While the model does not account for much larger ENA losses in the heliospheric tail, the contributions of ENAs arriving from the downwind hemisphere are significantly underestimated because the computational zone stretches only to 700 AU in this direction. Therefore the presented estimates of mass transport are the lower limit of the contribution of heliospheric ENAs to neutral hydrogen in the inner heliosphere.

[23] The latter model simplification means that no forces act on the ENAs. This simplification introduces only a small error. Relatively slow ENAs with $V < 120$ km/s ($E < 75$ eV) experience solar radiation pressure approximately counterbalancing solar gravitational attraction. ENAs with higher velocities (energies) are Doppler-shifted from the solar Lyman-α line and consequently accelerated by the solar gravitation. This effect is however small because of the relatively large original velocities of ENAs. Therefore this

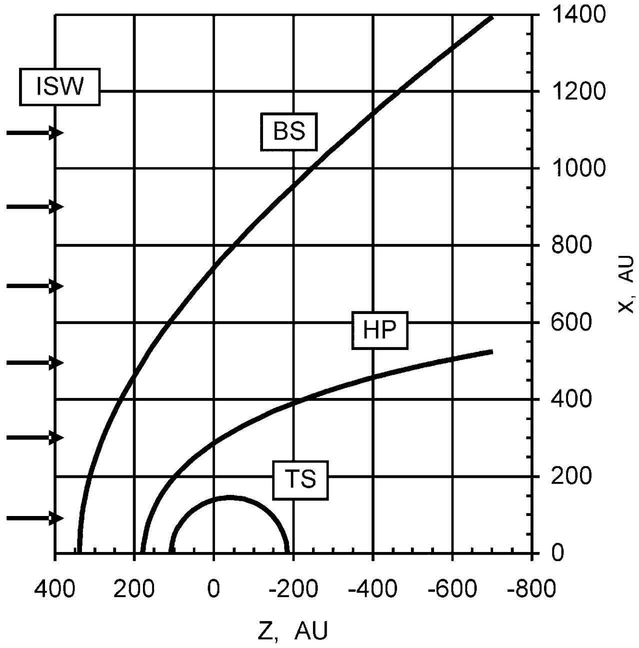

Figure 2. The axis-symmetric heliospheric structure used in this work (based on calculations by *Baranov and Malama* [1993]). The interstellar wind (ISW) approaches from the left along the Z axis. BS is bow shock, HP is heliopause, and TS is termination shock. The Sun is at the (0, 0) point.

simplification is perfectly adequate for the purposes of the present work.

[24] We compare the number densities of heliospheric ENAs at <1 AU with those of interstellar hydrogen. Distribution of interstellar hydrogen in the inner heliosphere is calculated using the hot model [e.g., *Fahr*, 1974; *Holzer*, 1977; *Meier*, 1977]. Although this computationally convenient model does not include important plasma-gas coupling in the heliospheric interface, it is adequate for the purposes of this work, if one accounts for the effect of the heliospheric interface by "adjusting" the velocity and temperature of the inflowing interstellar gas [*Gruntman*, 1994]. The adjusted parameters are inferred from the Lyman-α glow observations at 1 AU [e.g., *Lallement et al.*, 1993; *Costa et al.*, 1999]. The following adjusted interstellar hydrogen parameters are used in this work: number density 0.14 cm^{-3}, temperature 12,000 K, bulk velocity 20 km s^{-1}, radiation-to-gravitation force ratio μ = 0.95, and ionization rate 6.0×10^{-7} s^{-1} at 1 AU. The ionization rate is inversely proportional to the square of the distance from the Sun and independent of ecliptic latitude and longitude.

4. Interplanetary Hydrogen Number Densities at <1 AU

[25] Figures 3 and 4 show the calculated number densities of heliospheric ENAs and interstellar hydrogen for the upwind and downwind directions, respectively. A model used in this work is symmetric about the interstellar wind velocity vector that lies approximately in the ecliptic plane. Therefore the number density would depend on the heliocentric distance and angle θ counted from the upwind

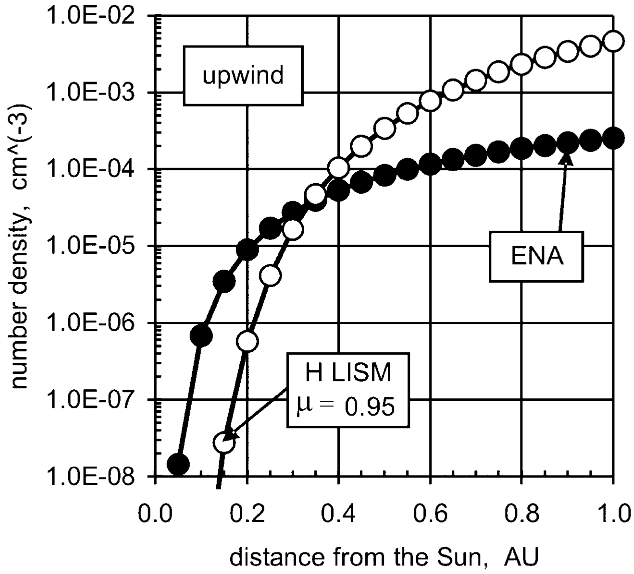

Figure 3. Radial dependence of number densities of interstellar atomic hydrogen and heliospheric ENAs for the upwind direction.

direction (Figure 1); no dependence on the position with respect to the ecliptic plane is thus expected.

[26] One can see (Figures 3 and 4) that the importance of the contribution of the heliospheric ENAs to the number density of hydrogen increases with the approach to the Sun. For given solar and interstellar conditions, interstellar hydrogen dominates at heliocentric distances >0.3 AU in the upwind direction and at >0.8 AU in the downwind direction. The pickup protons abundances in the solar wind is an accumulated effect of the wind propagation from the Sun to an observation point. In the upwind direction at 1 AU, the fractions of pickup protons due to interstellar hydrogen and heliospheric ENAs would be 92% and 8%, respectively. In the downwind direction, the relative contributions would be reversed: 91% due to heliospheric ENAs and only 9% due to interstellar hydrogen. It is clear that the heliospheric ENAs are a major contributor to the atomic hydrogen population within 1 AU and, correspondingly, to fluxes of pickup protons at 1 AU. The region within 1 AU would also contribute to solar wind charge exchange produced emissions in EUV, especially for lines of sight crossing the downwind region.

[27] Our preliminary estimates also show that the heliospheric ENAs with energies $E < 200$ eV would be responsible for most of ENA mass transfer to the Sun's vicinity. Such ENAs are much faster than the inflowing interstellar hydrogen atoms, which explains why the relative contribution of ENAs to the neutral hydrogen number density significantly increases inside the ionization cavity. On the other hand, the velocity of these relatively low-energy ENAs is much smaller than that of the solar wind. Therefore heliospheric ENAs would not produce exceedingly "hot" pickup protons and thus be consistent with the observed pickup proton velocity distribution functions.

[28] The fluxes of heliospheric ENAs and the resulting mass transport would depend on interstellar and solar conditions and on the way the energy is partitioned among plasma components in the heliospheric sheath. *Izmodenov et al.* [2001b] investigated the effect of varying ionization states of the interstellar medium surrounding the Sun. In addition, ENA fluxes are "filtered" in energy-dependent way while traversing the heliospheric sheath plasma. We also note that a number of researchers presently favor much higher values of the solar radiation pressure on atomic hydrogen then we used in our estimates. For example, *Bzowski* [2001] argues that the ratio of radiation-to-gravitation force μ varies from 1.0 to 1.5 during the solar cycle, based on the solar Lyman-alpha studies by *Tobiska et al.* [1997]. For these much higher values of radiation pressure (compared with $\mu = 0.95$ used in the present work) the relative importance of heliospheric ENAs would be substantially greater and they may become a dominant population even in the upwind direction, especially during the solar maximum conditions.

[29] The contribution of heliospheric ENAs to the atomic hydrogen population in the inner heliosphere would depend on partition of the solar wind energy among various plasma components in the heliospheric sheath. The efficiency of production of ENAs capable of reaching the inner heliosphere depends on the effective temperature of the proton component and local plasma velocity. *Gruntman et al.* [2001] showed how different assumptions of the processes at the termination shock would result in strikingly different directional properties of ENA fluxes (i.e., global ENA images). Energetic neutrals produced in charge exchange of pickup protons in the heliospheric sheath [e.g., *Chalov and Fahr*, 2003; *Chalov et al.*, 2003] may provide an important contribution to mass transport under certain conditions. The dependence of mass transport on the details of the interaction in the heliospheric interface region may thus open a way of constraining our global heliospheric models through examination of pickup protons and solar wind EUV emissions obtained at 1 AU.

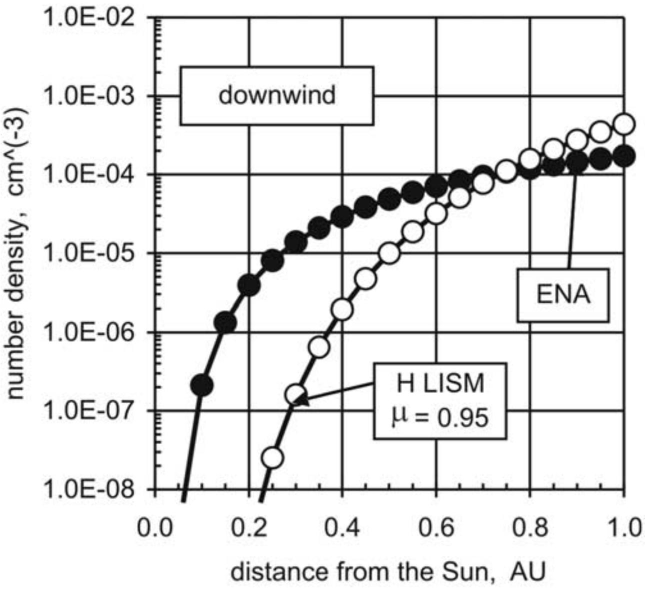

Figure 4. Radial dependence of number densities of interstellar atomic hydrogen and heliospheric ENAs for the downwind direction.

[30] We show in this work for the first time that the heliospheric ENAs originating in the heliospheric sheath between the termination shock and the heliopause and reaching the inner heliosphere provide an important and heretofore unaccounted source of atomic hydrogen in the Sun's vicinity. Our calculations consider only one possible global heliosphere model, where plasmas are described as single fluids. We show that for this model the mass transport to the inner heliosphere by ENAs is important and dominates the population of atomic hydrogen in the downwind direction under typical solar and interstellar conditions.

[31] **Acknowledgments.** This work is partially supported by NASA.
[32] Shadia Rifai Habbal thanks Herbert O. Funsten and Vladimir B. Baranov for their assistance in evaluating this paper.

References

Axford, W. I. (1972), The interaction of the solar wind with the interstellar medium, in *Solar Wind*, edited by C. P. Sonnett, P. J. Coleman Jr., and J. M. Wilcox, *NASA Spec. Publ., NASA SP-308*, 609–660.
Banks, P. M. (1971), Interplanetary hydrogen and helium from cosmic dust and the solar wind, *J. Geophys. Res.*, *76*, 3441–4348.
Baranov, V. B., and Y. G. Malama (1993), The model of the solar wind interaction with the local interstellar medium: Numerical solution of self-consistent problem, *J. Geophys. Res.*, *98*(A9), 15,157–15,163.
Baranov, V. B., and Y. G. Malama (1995), Effect of local interstellar medium hydrogen fractional ionization on the distant solar wind and interface region, *J. Geophys. Res.*, *100*(A8), 14,755–14,761.
Bertaux, J.-L. (1984), Helium and hydrogen of the local interstellar medium observed in the vicinity of the Sun, *IAU Colloquium 81*, edited by Y. Kondo, S. C. Bruhweiler, and B. D. Savage, *NASA Conf. Publ., NASA CP 2345*, 3–23.
Bertaux, J.-L., et al. (1995), SWAN: A study of solar wind anisotropies on SOHO Lyman alpha sky mapping, *Sol. Phys.*, *162*, 403–439.
Bzowski, M. (2001), Time dependent radiation pressure and time dependent, 2D ionization rate for heliospheric modeling, in *The Outer Heliosphere: The Next Frontier*, edited by K. Scherer et al., pp. 69–72, Elsevier, New York.
Chalov, S. V., and H. J. Fahr (2003), Energetic particles from the outer heliosphere appearing as a secondary pick-up ion component, *Astron. Astrophys.*, *401*, L1–L4.
Chalov, S. V., H. J. Fahr, and V. V. Izmodenov (2003), Evolution of pickup proton spectra in the inner heliosheath and their diagnostics by energetic neutral atom fluxes, *J. Geophys. Res.*, *108*(A6), 1266, doi:10.1029/2002JA009492.
Costa, J., R. Lallement, E. Quémerais, J.-L. Bertaux, E. Kyrölä, and W. Schmidt (1999), Heliospheric interstellar H temperature from SOHO/SWAN H cell data, *Astron. Astrophys.*, *349*, 660–672.
Davis, L., Jr. (1955), Interplanetary magnetic field and cosmic rays, *Phys. Rev.*, *100*, 1440–1444.
Dessler, A. J. (1967), Solar wind and interplanetary magnetic field, *Rev. Geophys*, *5*, 1–41.
Dessler, A. J., W. B. Hanson, and E. N. Parker (1961), Formation of the geomagnetic storm main-phase ring current, *J. Geophys. Res.*, *66*, 3631–3637.
Fahr, H. J. (1968a), On the influence of neutral interstellar matter on the upper atmosphere, *Astrophys. Space Sci.*, *2*, 474–495.
Fahr, H. J. (1968b), Neutral corpuscular energy flux by charge-transfer collisions in the vicinity of the sun, *Astrophys. Space Sci.*, *2*, 496–503.
Fahr, H. J. (1973), Non-thermal solar wind heating by suprathermal ions, *Solar Phys.*, *30*, 193–206.
Fahr, H. J. (1974), The extraterrestrial UV-background and the nearby interstellar medium, *Space Sci. Rev.*, *15*, 483–540.
Fahr, H. J., and G. Lay (2000), Remote diagnostic of the heliospheric termination shock using neutralized post-shock pick-up ions as messengers, *Astron. Astrophys.*, *356*, 327–334.
Fahr, H. J., H. W. Ripken, and G. Lay (1981), Plasma-dust interaction in the solar vicinity and their observational consequences, *Astron. Astrophys.*, *102*, 359–370.
Geiss, J., G. Gloeckler, U. Mall, R. von Steiger, A. B. Galvin, and K. W. Ogilvie (1994), Interstellar oxygen, nitrogen, and neon on the heliosphere, *Astron. Astrophys.*, *282*, 924–933.
Geiss, J., G. Gloeckler, L. A. Fisk, and R. von Steiger (1995), C+ pickup ions in the heliosphere and their origin, *J. Geophys. Res.*, *100*, 23,373–23,377.
Gloeckler, G. (1996), The abundance of atomic 1H, 4He and 3He in the local interstellar cloud from pickup ion observations with SWICS on Ulysses, *Space Sci. Rev.*, *78*, 335–346.
Gloeckler, G., and J. Geiss (1998), Interstellar and inner source pickup ions observed with SWICS on Ulysses, *Space Sci. Rev.*, *86*, 127–159.
Gloeckler, G., and J. Geiss (2001), Heliospheric and interstellar phenomena deduced from pickup ion observations, *Space Sci. Rev.*, *97*, 169–181.
Gloeckler, G., J. Geiss, H. Balsiger, L. A. Fisk, A. B. Galvin, F. M. Ipavich, K. W. Ogilvie, R. von Steiger, and B. Wilken (1993), Detection of interstellar pickup hydrogen in the solar system, *Science*, *261*, 70–73.
Gloeckler, G., L. A. Fisk, N. A. Schwadron, and T. H. Zurbuchen (2000), Elemental composition of the inner source pickup ions, *J. Geophys. Res.*, *105*, 7459–7463.
Gruntman, M. A. (1982), Effect of neutral component of solar wind on the interaction of the solar system with the interstellar gas flow, *Sov. Astron. Lett., Engl. Transl.*, *8*, 24–26.
Gruntman, M. A. (1992), Anisotropy of the energetic neutral atom flux in the heliosphere, *Planet. Space Sci.*, *40*, 439–445.
Gruntman, M. A. (1994), Neutral solar wind properties: Advance warning of major geomagnetic storms, *J. Geophys. Res.*, *99*, 19,213–19,227.
Gruntman, M. A. (1996), H2+ pickup ions in the solar wind: Outgassing of interplanetary dust, *J. Geophys. Res.*, *101*, 15,555–15,568.
Gruntman, M. (1997), Energetic neutral atom imaging of space plasmas, *Rev. Sci. Instrum.*, *68*, 3617–3656.
Gruntman, M. (2000), Solar wind bombardment of interplanetary dust: Search for evidence in SWAN/SOHO data, *Eos Trans. AGU*, *81*(19), Spring Meet. Suppl., S356.
Gruntman, M. (2001a), Imaging the three-dimensional solar wind, *J. Geophys. Res.*, *106*, 8205–8216.
Gruntman, M. (2001b), Mapping the heliopause in EUV, in *The Outer Heliosphere: The Next Frontiers*, *COSPAR Colloq. Ser.*, vol. 11, edited by K. Scherer, pp. 263–271, Elsevier, New York.
Gruntman, M. (2004), Instrumentation for interstellar exploration, *Adv. Space Res.*, *34*, 204–212.
Gruntman, M., E. C. Roelof, D. G. Mitchell, H. J. Fahr, H. O. Funsten, and D. J. McComas (2001), Energetic neutral atom imaging of the heliospheric boundary region, *J. Geophys. Res.*, *106*, 15,767–15,781.
Hilchenbach, M., et al. (1998), Detection of 55–80 keV hydrogen atoms of heliospheric origin by CELIAS/HSTOF on SOHO, *Astrophys. J.*, *503*, 916–922.
Holzer, T. E., and W. I. Axford (1970), Solar wind ion composition, *J. Geophys. Res.*, *75*, 6354–6359.
Holzer, T. E. (1977), Neutral hydrogen in interplanetary space, *Rev. Geophys.*, *15*, 467–490.
Hsieh, K. C., and M. A. Gruntman (1993), Viewing the outer heliosphere in energetic neutral atoms, *Adv. Space Res.*, *13*(6), 131–139.
Hsieh, K. C., K. L. Shih, J. R. Jokipii, and S. Grzedzielski (1992), Probing the heliosphere with energetic neutral atoms, *Astrophys. J.*, *393*, 756–763.
Izmodenov, V., and D. Alexashov (2003), A model for the tail region of the heliocentric interface, *Astron. Lett. Transl. Pis'ma Astron. Zh.*, *29*, 58–63.
Izmodenov, V. V., M. Gruntman, and Y. G. Malama (2001a), Interstellar hydrogen atom distribution function in the outer heliosphere, *J. Geophys. Res.*, *106*, 10,681–10,689.
Izmodenov, V., M. Gruntman, V. B. Baranov, and H. Fahr (2001b), Heliospheric ENA fluxes: How sensitive are they to the ionization sate of LIC?, *Space Sci. Rev.*, *97*(1/4), 413–416.
Jaeger, S., and H. J. Fahr (1998), The heliospheric plasma tail under influence of charge exchange processes with interstellar H-atoms, *Solar Phys.*, *178*, 631–656.
Krimigis, S. M., R. B. Decker, M. E. Hill, T. P. Armstrong, G. Gloeckler, D. C. Hamilton, L. J. Lanzreotti, and E. C. Roelof (2003), Voyager 1 exited the solar wind at a distance of ~85AU from the Sun, *Nature*, *426*, 45–48.
Lallement, R., J.-L. Bertaux, and J. T. Clarke (1993), Deceleration of interstellar hydrogen at the heliospheric interface, *Science*, *260*, 1095–1098.
McComas, D. J., et al. (2003), Interstellar pathfinder—A mission to the inner edge of the interstellar medium, in *Solar Wind Ten*, edited by M. Velli et al., *AIP Conf. Proc.*, *679*, 834–837.
McDonald, F. B., E. C. Stone, A. C. Cummings, B. Heikkila, N. Lal, and W. R. Webber (2003), Enhancements of energetic particles near the heliospheric termination shock, *Nature*, *426*, 48–51.
Meier, R. R. (1977), Some optical and kinetic properties of the nearby interstellar gas, *Astron. Astrophys.*, *55*, 211–219.
Moebius, E. (1990), The interaction of interstellar pickup ions with the solar wind—Probing the interstellar medium by in-situ measurements, in *Physics of the Outer Heliosphere*, edited by S. Grzedzielski and D. E. Page, pp. 345–354, Springer, New York.

Moebius, E. (1996), The local interstellar medium viewed through pickup ions, recent results and future perspectives, *Space Sci. Rev.*, *78*, 375–386.

Moebius, E., D. Hovestadt, B. Klecker, M. Scholer, G. Gloeckler, and F. M. Ipavich (1985), Direct observation of He+ pickup ions of interstellar origin in the solar wind, *Nature*, *318*, 426–429.

Morton, D. C., and J. D. Purcell (1962), Observations of the extreme ultraviolet radiation in the night sky using an atomic hydrogen filter, *Planet. Space Sci.*, *9*, 455–458.

Parker, E. N. (1963), *Interplanetary Dynamical Processes*, Wiley-Interscience, Hoboken, N. J.

Patterson, T. N. L., F. S. Johnson, and W. B. Hanson (1963), The distribution of interplanetary hydrogen, *Planet. Space Sci.*, *11*, 767–778.

Roelof, E. C. (1992), Imaging heliospheric shocks using energetic neutral atoms, in *Solar Wind Seven*, edited by E. Marsch and R. Schwenn, pp. 385–394, Elsevier, New York.

Robertson, H. P. (1937), Dynamical effects of radiation in the solar system, *Mon. Not. R. Astron. Soc.*, *97*, 423–438.

Schwadron, N. A., and J. Geiss (2000), On the processing and transport of inner source hydrogen, *J. Geophys. Res.*, *105*, 7473–7481.

Schwadron, N. A., J. Geiss, L. A. Fisk, G. Gloeckler, T. H. Zurbuchen, and R. von Steiger (2000), Inner source distributions: Theoretical interpretation, implications, and evidence for inner source protons, *J. Geophys. Res.*, *105*, 7465–7472.

Schwadron, N. A., M. Combi, W. Huebner, and D. J. McComas (2002), The outer source of pickup ions and anomalous cosmic rays, *Geophys. Res. Lett.*, *29*(20), 1993, doi:10.1029/2002GL015829.

Thomas, G. E. (1978), The interstellar wind and its influence on the interplanetary environment, *Annu. Rev. Earth Planet. Sci.*, *6*, 173–204.

Tinsley, B. A. (1981), Neutral atom precipitation—A review, *J. Atmos. Terr. Phys.*, *43*, 617–632.

Tobiska, W. K., W. R. Pryor, and J. M. Ajello (1997), Solar hydrogen Lyman-alpha variation during solar cycles 21 and 22, *Geophys. Res. Lett.*, *24*, 1123–1126.

Vasyliunas, V. M., and G. L. Siscoe (1976), On the flux and the energy spectrum of interstellar ions in the solar system, *J. Geophys. Res.*, *81*, 1247–1252.

Wimmer-Schweingruber, R. F., and P. Bochsler (2003), On the origin of inner-source pickup ions, *Geophys. Res. Lett.*, *30*(2), 1077, doi:10.1029/2002GL015218.

Yatchmenoff, R. Y., and M. Gruntman (1998), Search for neutral hydrogen in the Sun's vicinity by SOHO/SWAN, *Eos Trans. AGU*, *79*(45), Fall Meet. Suppl., F699.

Zank, G. P. (1999), Interaction of the solar wind with the local interstellar medium: A theoretical perspective, *Space Sci. Rev.*, *89*, 1–275.

M. Gruntman, Aeronautics and Space Technology Division, Viterbi School of Engineering, University of Southern California, MC-1191, Los Angeles, CA 90089-1191, USA. (mikeg@spock.usc.edu)

V. Izmodenov, Department of Aeromechanics and Gas Dynamics, Faculty of Mechanics and Gas Dynamics, Lomonosov Moscow State University, Vorob'evy Gory, Main Building MSU, Moscow 119899, Russia.