GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 20, 1993, doi:10.1029/2002GL015829, 2002

The outer source of pickup ions and anomalous cosmic rays

N. A. Schwadron
Southwest Research Institute, San Antonio, Texas, USA

M. Combi
Department of Atmospheric, Oceanic and Space Science, The University of Michigan, Ann Arbor, USA

W. Huebner and D. J. McComas
Southwest Research Institute, San Antonio, Texas, USA

Received 7 July 2002; revised 30 August 2002; accepted 31 August 2002; published 30 October 2002.

[1] The traditionally accepted source of Anomalous Cosmic Rays (ACRs) is neutral atoms penetrating the heliosphere from the local interstellar cloud (LIC). The ACR composition should be depleted in easily ionized atoms such as C, Si, and Fe. However, significant fluxes of these ions are observed in ACRs and their source has not been previously identified. We show that there is an "outer source" of pickup ions, and hence ACRs, caused by sputtered atoms (subsequently ionized and picked up by the solar wind) from small grains generated via collisions of objects in the Edgeworth-Kuiper Belt. The outer source accounts for the abundance and composition of the additional population of ACRs. The discovery that ACRs are generated from material in the Edgeworth-Kuiper Belt provides an exciting new tool for understanding the mass distribution and composition of the Edgeworth-Kuiper Belt, and for probing the plasma-dust interactions in stellar environments. *INDEX TERMS:* 2152 Interplanetary Physics: Pickup ions; 2104 Interplanetary Physics: Cosmic rays; 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 6213 Planetology: Solar System Objects: Dust. **Citation:** Schwadron, N. A., M. Combi, W. Huebner, and D. J. McComas, The outer source of pickup ions and anomalous cosmic rays, *Geophys. Res. Lett.*, *29*(20), 1993, doi:10.1029/2002GL015829, 2002.

1. Introduction

1.1. The Need for an ACR Source Within the Heliosphere

[2] The same acceleration processes that form ACRs within our heliosphere operate on galactic (and inter-galactic) scales and produce cosmic rays with enormous energies (up to current detection limits). Since cosmic ray sources are poorly understood, insights gleaned from locally produced ACRs apply to a much broader problem.

[3] The traditionally accepted source of ACRs is neutral atoms from the interstellar medium [*Fisk et al.*, 1974]. The neutrals drift freely into the heliosphere and subsequently undergo ionization, pickup and acceleration (schematically illustrated in yellow in Figure 1) which transforms them from low energy neutrals into high energy ACRs. Easily ionized elements such as C, Si, and Fe are naturally depleted in ACRs since they are not neutral in the interstellar medium and therefore cannot penetrate the heliosphere.

[4] The transformations of the interstellar neutrals inside the heliosphere begin with their ionization. The newly made ions are picked up and carried out by the solar wind as they gyrate about magnetic field lines frozen into the solar wind. The pickup process itself endows these ions with random speeds that are up to twice that of the solar wind and thereby predisposes them to subsequent acceleration at interplanetary shocks or due to wave-particle interactions. When the pickup ions encounter the termination shock of the solar wind, they are injected into diffusive shock acceleration (shown in Figure 1 by energy-gaining ion bounces) to high (GeV) ACR energies [*Pesses et al.*, 1981].

[5] Recent observations from the Voyager and Wind spacecraft have resolved ACR components comprised of easily ionized elements (such as Si, C, Mg, S, and Fe) [*Reames*, 1999; *Cummings et al*, 2002]. An interstellar source for these "additional" ACRs, other than a possible interstellar contribution to C, can be ruled out [*Cummings et al.*, 2002]. The source for these ACRs must reside within the heliosphere.

2. Possible Heliospheric Sources

[6] Table 2 identifies a number of potential sources. Most of these provide negligible source rates and are dismissed. One possible source, the "inner source," is generated by the neutralization of solar wind by grains very near the Sun, at $\sim$10 solar radii [*Schwadron et al.*, 2000]. Ionization of these neutrals results in the production of pickup ions that have been identified by Ulysses observations [*Geiss et al*, 1995; *Gloeckler et al*, 2000; *Schwadron et al.*, 2000]. The composition of the inner source resembles that of the solar wind [*Gloeckler et al.*, 2000], and in particular, is rich in easily ionized elements (such as C, Si, and Fe). The source is peaked very near the Sun (at $\sim$10 solar radii) and distributions of inner source pickup ions are cooled adiabatically by the radially expanding solar wind [*Schwadron et al.*, 2000].

[7] The hypothesis that the additional population of ACRs is formed from the inner source requires pre-acceleration within the heliosphere, starting well inside of 1 AU. In principle, this is possible in *slow solar wind* (at low latitudes over most of the solar cycle), in which interstellar pickup ions are known to be accelerated ubiquitously [*Gloeckler et al.*, 1994; *Schwadron et al.*, 1996; *Gloeckler et al.*, 2000; *Fisk et al.*, 2000c]. The hypothesis of substantial inner source pre-acceleration is also supported by pickup He^+ simulations [e.g., *Chalov et al.*, 1965]. However, inner source observations in slow solar wind show

0094-8276/02/2002GL015829

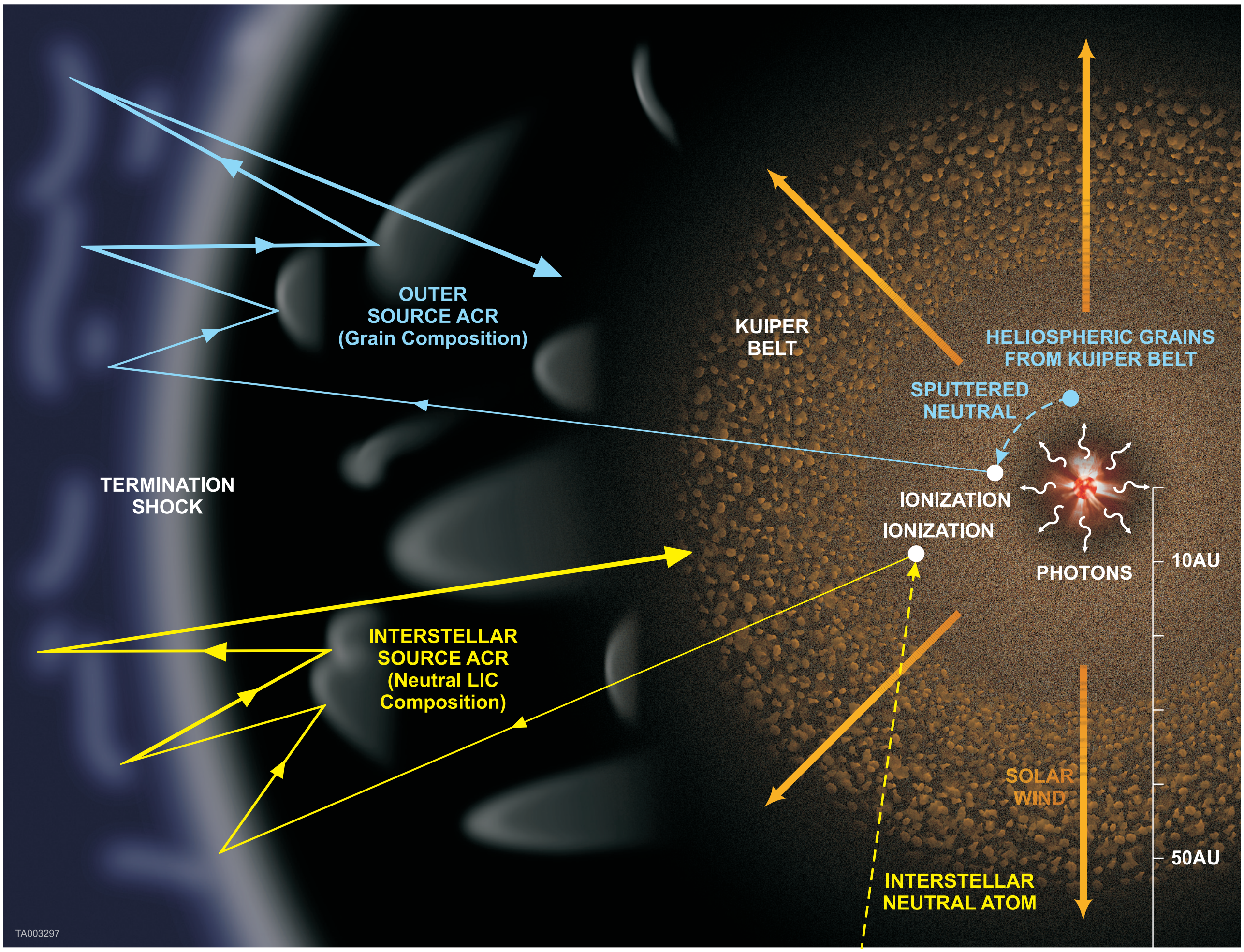

Figure 1. An illustration of ACR production. Yellow curves apply to the known interstellar source ACRs (adapted from *Jokipii and McDonald* [1995]), while blue curves apply to the outer source, first described here.

clearly the pronounced effects of adiabatic cooling [*Schwadron et al.*, 1999] and charge-state observations of energetic particles near 1 AU indicate no evidence for acceleration of the inner source [*Mazur et al.*, 2002]. In the fast solar wind (at high latitudes over most of the solar cycle) the case is even worse, since even interstellar pickup ions are not observed to undergo significant statistical acceleration there. This makes it unlikely that inner source pickup ions would be efficiently injected into an acceleration process at the termination shock and contribute substantially to ACRs.

[8] Another heliospheric source are the long-period comets. However, the abundances from this source would be strongly enriched in C, which is not the case, and the source strength is high only inside of 1.5 AU. As in the case of the inner source ions, it is likely that these particles are significantly cooled by the time they reach the termination shock and are not efficiently injected into an acceleration process there. It appears that the additional population of ACRs requires a large source of pickup ions inside the heliosphere that is produced well away from the Sun.

3. The Outer Source

[9] This brings us to the new idea of an "outer source" (illustrated by blue in Figure 1). There are many objects in the outer heliosphere that sputter and sublimate their material: Kuiper belt objects and grains, Jupiter family comets, Oort cloud comets, and Neptune Trojans [*Weissman and Levison*, 1997]. The Kuiper belt is unique because it contains many objects and continually produces small grains via collisions [*Stern*, 1995], causing a large filling factor. The grains spiral inward toward the Sun (the slight inward drift is caused by the Poynting-Robertson effect). Sputtering and sublimation produces atoms, molecules, and molecular ions. Atomic products become pickup ions after ionization. Molecular products undergo dissociation and ionization to form pickup ions and pickup molecules [e.g., *Fahr et al.*, 1981; *Schwadron and Geiss*, 2000]. The composition of the outer source is derived from the Kuiper belt grains.

Table 1. Predicted and Observed Abundances of ACRs Relative to Oxygen

Element	$Y_{X,\ dust}$, %	Sputtering [X/O], %	Observed[a] [X/O], %	Observed[b] [X/O], %
C	6	0.4	0.49 ± 0.05	<1
Mg	1	0.06	0.037 ± 0.013	0.12 ± 0.03
Si	1.3	0.08	0.12 ± 0.02	0.17 ± 0.03
S	0.3	0.02	0.039 ± 0.013	0.06 ± 0.02
Fe	1.5	0.1		<0.09

[a] *Cummings et al.* [2002].
[b] *Reames* [1999].

Table 2. Possible Sources Within the Heliosphere

Source	Mechanism	Abundance	Location, AU	C, g/s	O, g/s	Issue	Significant source?
Interstellar gas	Ionization	Low-FIP depleted	>3	$0.5 - 2 \times 10^6$	3×10^9		Y
Solar wind	Coronal heating	Near solar	0.005	1×10^{10}	2×10^{10}	strongly cooled	N
Io [*Geiss et al*, 1994]	Fast O atoms	O	5.2		$<3 \times 10^5$	negligible	N
Mars [*Lundin et al.*, 1990]	O^+ release	O	1.5		1000	negligible	N
Jupiter family comets	Sublimation	H,O,C,N	<3	2×10^4	6×10^5	negligible	N
"	"	"	>3	$>2 \times 10^3$	2×10^5	negligible	N
Long period comets	"	"	<3	1×10^6	1×10^7	strongly cooled and too abundant in C	N
"	"	"	>3	1×10^5	1×10^6	negligible	N
Inner source [*Schwadron et al.*, 2000]	Solar wind neutralization by grains	Solar wind	$0.05 - 0.1$	1.5×10^6	2×10^6	strongly cooled	N
Outer source	Sputtering	Grain	$10 - 50$	1.3×10^6	$<1 \times 10^7$		Y

[10] Since scattering due to gravitational interaction with planets removes most grains that drift inside of 10 AU [*Liou and Zook*, 1996], the source is generated between ~10 and ~50 AU, much farther from the Sun than the inner source. At these distances, shocks from stream-stream interactions (co-rotating interaction regions) are strong and pre-acceleration is easily achieved.

[11] To derive the gas production rate from the outer source, we will consider the fate of small 1 μm grains. Grains somewhat smaller are carried out of the Kuiper Belt due to radiation pressure. Grains larger than 1 μm are less abundant. On a timescale of several million years, a 1 μm grain at 40 AU will drift into the Sun due to the Poynting-Robertson effect. As they spiral in, grains may be perturbed by gravitational interaction with planets (most notably with Saturn and Jupiter) leading either to grain capture, or to the disruption of the grain orbit and its subsequent heliospheric escape. *Liou and Zook* [1996] estimate that 80% of these grains are lost due to gravitational interaction with the planets. Beyond 10 AU however, less than 5% of the grains are lost due to interaction with Neptune. Hence, the small grain population exists between ~10 and ~50 AU.

[12] The mass loss rate of small grains from the Kuiper Belt is given by $\dot{M} = 5 \times 10^7$ g/s [*Landgraf et al.*, 2002]. The net production rate of small grains is then, $\dot{N} = 3\dot{M}/(4\pi a^3 \rho)$, where the size of the grains is $a = 1$ μm and the grain mass density is $\rho = 1$ g/cm^3 since they are mostly ice. The main loss mechanism from the Kuiper belt is the Poynting-Robertson effect, which introduces a weak inward radial drift with speed $v_1 r_1/r$ where $v_1 = 680$ cm/s, $r_1 = 1$ AU, and r the heliocentric radius. The grain number density is then $n_g(r) = \dot{N}/[4\pi \sin(\delta\theta) v_1 r_1 r]$ where the latitudinal half-width of the Kuiper belt is $\delta\theta = 8°$.

[13] Grains are sputtered by the solar wind and they sublimate their ices as they drift in through the heliosphere. These processes produce neutral atoms that become pickup ions after ionization. We may calculate a net sputtering yield (in particles per volume and time), $Q = 4\pi a^2 (\Delta a/\Delta t)\, \rho n_g(r)/(\langle A\rangle m_p)$, where the sputtering erosion rate is $\Delta a/\Delta t$, and the average (elemental) atomic mass is $\langle A\rangle \approx 8$. Measurements of lunar soils indicate that the sputtering erosion rate near 1 AU is $\Delta a_1/\Delta t$ = angstrom/yr [*Borg et al.*, 1980]. The grain erosion rate throughout the heliosphere is given by $\Delta a/\Delta t = (\Delta a_1/\Delta t)\ (r_1/r)^2$. We approximate the source rate, $Q_X = Y_{\text{dust,X}} \cdot Q$, for a specific element, X, with knowledge of the net elemental abundance, $Y_{\text{dust,X}}$, within the sputtered grain (this approximation is not valid for purely icy grains).

[14] We estimate the contribution of these outer source pickup ions to ACRs by considering the outer source rates relative to better known interstellar source rates. Interstellar oxygen provides a good reference. Its mass-per-charge is large and therefore should have an efficiency of injection into shock acceleration at the termination shock that is similar to the outer source pickup ions [*Cummings et al.*, 2002]. In what follows we determine the abundance of outer source ACRs relative to ACR oxygen by taking the ratio of the pickup ion fluxes (outer source to oxygen) near the termination shock, where the fluxes are integrated over the source rates beyond a distance R_p = 10 AU. Inside of the distance R_p, we argue that adiabatic cooling is strong enough to significantly reduce the injection efficiency into shock acceleration at the termination shock (beyond ~4 AU, shocks in the heliosphere are quite strong and are known sites of strong pre-acceleration.).

[15] The flux of outer source pickup ions available for acceleration near the termination shock is given by, $F_{\text{sputt,X}} = Y_{\text{dust,X}} \frac{3\dot{M}(\Delta a_1/\Delta t)}{4\pi \sin(\delta\theta)\langle A\rangle m_p a r_1 v_1} \left(\frac{r_1}{R_t}\right)^2 \ln\left(\frac{R_{\text{KB}}}{R_p}\right)$ where R_t is the heliocentric radius of the termination shock and R_{KB} is the average radial position of the Kuiper Belt. Given R_t = 90 AU, R_{KB} = 40 AU, we find $F_{\text{sputt,X}} = 0.4 \cdot Y_{\text{dust,X}}$ cm^{-2} s^{-1}.

[16] The interstellar O^+ pickup ion flux at the termination shock is given by $F_{\text{interstellar, O+}} = \beta n_{\text{LISM}}(R_t - R_p)\, r_1^2 / R_t^2 = 6.3$ cm^{-2} s^{-1} where $\beta = 8.5 \times 10^{-7}$ s^{-1} is the total ionization rate at 1 AU for oxygen and the density of O in the local interstellar medium (LISM) is $n_{\text{LISM}} = 5 \times 10^{-5}$ cm^{-3} [*Cummings et al.*, 2002].

[17] The abundances listed in Table 1 were adapted from *Huebner* [2002]. Listed in the second column are abundances of cometary dust. The third column gives predicted abundances of ACRs relative to interstellar oxygen exclusively for sputtering of grains[1]. In the final two columns are

[1]We make two assumptions: first, the efficiency of injection into diffusive shock acceleration at the termination shock is constant for these heavy ions [*Cummings and Stone*, 1996]. Lighter elements such as He and H have larger injection efficiencies, as predicted by [*Chalov and Fahr*, 1996]; second, only pickup ions near the ecliptic plane are accelerated to ACR energies. This is plausible over most of the solar cycle (a solar minimum configuration) since pre-acceleration occurs preferentially near the ecliptic plane where there is slow solar wind accompanied by ubiquitous statistical acceleration and strong shocks from co-rotating interaction regions.

the observed ACR abundances given by *Cummings et al.* [2002] and *Reames* [1999].

[18] Sublimation must also occur. Unlike sputtering however, sublimation becomes very rapid once grains achieve a temperature that is sufficiently high. This results in the total evaporation of a given form of ice carried by the grain once it drifts inside of a specific heliocentric radius. The flux of particles near the termination shock caused by sublimation is readily computed based on the total amount of material in the form of a given ice carried by the grain, $F_{\mathrm{subl,X}} = Y_{\mathrm{ice,X}} \frac{\dot{M}}{4\pi \sin(\delta\theta)\langle A\rangle m_p R_t^2} = 1.2 \cdot Y_{\mathrm{ice,X}}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. Taking an abundance of 6% for carbon containing ice (mostly CO and CO_2) [*Huebner*, 2002], we would predict an ACR C/O abundance of 1.3% which is much larger than the observational value. We also predict an ACR S/O abundance of 0.07% based on sublimation of H-C-N-S compounds. This value is also too high compared to ACR observations.

[19] It is apparent that the predicted abundances agree with observations if sputtering from grains is considered exclusively. If sublimation of H-C-N-S compounds, CO and CO_2 ices were also considered we would predict higher abundances for C and S. The apparent implication is that Kuiper-belt grains are depleted of these ices.

4. Discussion

[20] We have proposed that there exists a strong outer heliospheric source of pickup ions and that it explains the presence of easily ionized elements such as Fe, Si, and C in anomalous cosmic rays. The source is extracted from material in the Kuiper belt through a series of processes (shown schematically in blue in Figure 1): First, Kuiper belt objects are ground down to micron-sized grains through collisions; grains spiral in toward the Sun due to the Poynting-Robertson effect; neutral atoms are produced by sputtering and are converted into pickup ions when they become ionized; the pickup ions are transported by the solar wind to the termination shock and, as they are convected, are pre-accelerated due to interaction with shocks and due to wave-particle interactions; finally, they are injected into an acceleration process at the termination shock to achieve ACR energies. The predicted abundances are all within a factor of two of observed values, providing strong validation of this scenario.

[21] We have made predictions about the anomalous component based on known properties of grains. This line of argument may be inverted. Observations of ACRs constrain the abundances of Kuiper belt grains. The implications of the phenomenon are striking for it appears that grains may play a very important astrophysical role for producing cosmic rays, particularly in stellar systems where the dust content is large and in the primordial solar system. Since the inner edge of the outer source lies near 10 AU, there is now even more reason to send spacecraft beyond 10 AU to detect directly the outer source of pickup ions.

[22] Thus, we have discovered an important new source of pickup ions and anomalous cosmic rays in the heliosphere - the outer source.

[23] **Acknowledgments.** This work was supported by NSF grant ATM 0100659 and by Southwest Internal Research Grant R9302.01.001. MC was supported by NASA Planetary Atmospheres grant NAG5-8942.

References

Borg, J., J. Chaumont, Y. Langevin, M. Maurette, and C. Jouret, Solar wind radiation damage in lunar dust grains and the characteristics of the ancient solar wind, in *The Ancient Sun: Fossil Record in the Earth*, *Moon and Meteorites*, 431–461, 1980.

Chalov, S. V., and H. J. Fahr, Reflection of Pre-Accelerated Pick-up Ions at the Solar Wind Termination Shock: The Seed for Anomalous Cosmic Rays, *Solar Phys.*, *168*, 389–411, 1996.

Chalov, S. V., H. J. Fahr, V. V. Izmodenov, *Astron. Astrophys*, *304*, 609, 1965.

Cummings, A. C., and E. C. Stone, Composition of anomalous cosmic rays and implications for the heliosphere, *Space Sci. Rev.*, *78*, 129–136, 1996.

Cummings, A., E. Stone, and C. Steenberg, Composition of anomalous cosmic rays and other heliospheric ions, *Astrophys. J.*, in press, 2002.

Fahr, H. J., H. W. Ripken, and G. Lay, Plasma-dust interaction in the solar vicinity and their observational consequences, *Astron. Astrophys.*, *102*, 359, 1981.

Fisk, L. A., B. Kozlovsky, and R. Ramaty, An interpretation of the observed oxygen and nitrogen enhancements in low energy cosmic rays, *Astrophys. J.*, *190*, L35–L38, 1974.

Fisk, L. A., G. Gloeckler, T. H. Zurbuchen, and N. A. Schwadron, Ubiquitous statstical acceleration in solar wind, in *Acceleration and Transport of Energetic Particles Observed in the Heliosphere: ACE 2000 Symposium*, edited by R. A. Mewaldt et al., pp. 229–233, AIP, 2000.

Geiss, J., G. Gloeckler, and U. Mall, Origin of the O^+ pick-up ions in the heliosphere, *Astron. Astrophys.*, *289*, 933, 1994.

Geiss, J., G. Gloeckler, L. A. Fisk, and R. von Steiger, C^+ pickup ions in the heliosphere and their origin, *J. Geophys. Res.*, *100*, 23,373, 1995.

Gloeckler, G., J. Geiss, E. C. Roelof, L. A. Fisk, F. M. Ipavich, K. W. Ogilvie, L. J. Lanzerotti, R. von Steiger, and B. Wilken, Acceleration of interstellar pickup ions in the disturbed solar wind observed on Ulysses, *J. Geophys. Res.*, *99*, 17,637, 1994.

Gloeckler, G., L. A. Fisk, J. Geiss, N. A. Schwadron, and T. H. Zurbuchen, Elemental composition of the inner source pickup ions, *J. Geophys. Res.*, *105*(A4), 7459, 2000.

Gloeckler, G., L. A. Fisk, T. H. Zurbuchen, N. A. Schwadron, Sources, Injection and Acceleration of Heliospheric Ion Populations, in *AIP Conf. Proc. 528: Acceleration and Transport of Energetic Particles Observed in the Heliosphere*, p. 221, 2000.

Huebner, W. F., Composition of comets: Observations and models, *Space Sci. Rev.*, in press, 2002.

Jokipii, J. R., and F. B. McDonald, Quest for the Limits of the Heliosphere, *Scientific American*, *272*, 58, 1995.

Landgraf, M., J.-C. Liou, H. A. Zook, and E. Grün, Origins of Solar System Dust beyond Jupiter, *Astrophys. J.*, *123*, 2857–2861, 2002.

Liou, J.-C., and H. A. Zook, Kuiper belt dust grains as a source of interplanetary dust particles, *Icarus*, *124*, 429–440, 1996.

Lundin, R., et al., ASPERA/PHOBOS measurements of the ion outflow from the Martian ionosphere, *Geophys. Res. Lett.*, *17*, 873–876, 1990.

Mazur, J., G. Mason, and R. Mewaldt, Charge states of energetic particles from corotating interaction regions as constraints on their source, *Astrophys. J.*, *566*, 555–561, 2002.

Pesses, M. E., J. R. Jokipii, and D. Eichler, Cosmic ray drift, shock wave acceleration, the anomalous component of cosmic rays, *Astrophys. J.*, *246*, L85, 1981.

Reames, D. V., Quiet-time spectra and abundances of energetic particles during the 1996 solar minimum, *Astrophys. J.*, *518*(1), 473–479, 1999.

Schwadron, N. A., and J. Geiss, On the processing and transport of inner source hydrogen, *J. Geophys. Res.*, *105*(A4), 7473, 2000.

Schwadron, N. A., L. A. Fisk, and G. Gloeckler, Statisitical acceleration of interstellar pick-up ions in co-rotating interaction regions, *Geophys. Res. Lett.*, *23*, 2871–2874, 1996.

Schwadron, N. A., G. Gloeckler, L. A. Fisk, J. Geiss, T. H. Zurbuchen, The Inner Source for Pickup Ions, in *AIP Conf, Proc. 471: Solar Wind Nine*, p. 487, 1999.

Schwadron, N. A., J. Geiss, L. A. Fisk, G. Gloeckler, T. H. Zurbuchen, and R. von Steiger, Inner source distributions: Theoretical interpretation, implications, and evidence for inner source protons, *J. Geophys. Res.*, *105*(A4), 7465, 2000.

Stern, S. A., Collisional time scales in the Kuiper disk and their implications, *American Astronomical Society*, *110*(2), 1995.

Weissman, P. R., and H. F. Levison, The population of the trans-Neptunian region: The Pluto-Charon environment, in *Pluto and Charon*, edited by S. A. Stern, and D. J. Tholen, p. 559, The University of Arizona Press, Tucson, AZ, 1997.

N. Schwadron, W. Huebner, and D. J. McComas, Southwest Research Institute, Post Office Drawer 28510, San Antonio, Texas, 78228-0510 USA.

M. Combi, Department of Atmospheric, Oceanic and Space Science, The University of Michigan, Ann Arbor, USA.