GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 2, 1077, doi:10.1029/2002GL015218, 2003

On the origin of inner-source pickup ions

Robert F. Wimmer-Schweingruber[1] and Peter Bochsler

Physikalisches Institut, Universität Bern, Switzerland

Received 27 March 2002; revised 3 May 2002; accepted 16 May 2002; published 28 January 2003.

[1] In situ measurements of pickup ions (PUI) exhibit a component that has nearly thermalized with the solar wind. This implies an origin close to the Sun and is generally ascribed to interaction of the solar wind with interplanetary dust particles (IDPs). We propose a scenario for the origin of inner-source PUIs in which a population of very small IDPs serves as the neutralizing agent for solar wind ions. The size of these IDPs is less than or comparable to the penetration range, of solar wind ions in IDP material. The interaction of the solar wind with such particles results in a net charge exchange in which solar wind ions exit the IDPs as predominantly neutral or singly-charged ions. When the neutralized solar wind is reionized, it is picked up and can then be measured as a PUI. *INDEX TERMS:* 2152 Interplanetary Physics: Pickup ions; 6025 Planetology: Comets and Small Bodies: Interactions with solar wind plasma and fields; 6015 Planetology: Comets and Small Bodies: Dust. **Citation:** Wimmer-Schweingruber, R. F., and P. Bochsler, On the origin of inner-source pickup ions, *Geophys. Res. Lett.*, *30*(2), 1077, doi:10.1029/2002GL015218, 2003.

1. Introduction

[2] Observations of singly-charged carbon ions in the outer heliosphere by the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses by *Geiss et al.* [1994] marked the discovery of an "inner source" of pickup ions (PUIs). The ions were believed to be due to the loss of the volatile elements C and O from interstellar dust particles between 2–3 astronomical units (AU). Subsequent work by *Gloeckler et al.* [2000], *Schwadron et al.* [2000], and *Schwadron and Geiss* [2000] identified an inner source of PUIs in the inner heliosphere, located between 10–50 solar radii from the Sun. The present paper deals with this latter "inner source" for heliospheric PUIs.

[3] Normal heavy solar wind ions are multiply charged. Pickup ions are almost entirely singly charged and have non-thermal velocity distribution functions. In this work we will consider only singly charged PUIs. Investigations of inner-source PUIs have lead to two remarkable discoveries. Their composition is to a good approximation solar, for instance, the Ne/Mg abundance ratio is about that of the average solar wind. Second, the flux of inner-source PUIs is amazingly high compared to the solar wind flux. Based on the flux of inner-source O^+, the neutralizing cross section per unit volume can be estimated to be $\Gamma \geq 1.3 \cdot 10^{-17}$ cm^{-1}, which is almost two orders of magnitude larger than other typical values [*Schwadron et al.*, 2000]. The origin of inner-source PUIs has been attributed to interplanetary dust particles (IDPs) which have been saturated with solar wind. In that view, dust particles trap and release solar wind particles [e.g. *Gloeckler et al.*, 2000]. The net result is a neutralization of the solar wind. In this Letter we propose an alternative scenario for the origin of inner-source PUIs, which can account for the above-mentioned two observational facts as well as predict an as yet unreported systematic dependence of the Ne/Mg abundance ratio with solar wind speed.

2. Dust in the Inner Heliosphere

[4] In the context of this work, we need to address the question of whether an IDP can trap sufficient heavy solar wind ions during its lifetime to release predominantly solar wind atoms when grain surface layers are sputtered. Grain lifetimes are limited by various processes, which also determine the dynamics of dust in the inner heliosphere, e.g. gravitation, radiation pressure, sputtering, collisions, and electrostatic grain charging. Not all effects are of equal importance at all locations in the heliosphere and some are inherently difficult to quantify. In this work, we completely neglect the effects of electrostatic charging. Recent observations of small dust particles released by sun-grazing comets [*Sekanina*, 2000] showed no evidence at all for this process to be of any relevance.

[5] The most important processes for this work are the interplay of gravitational and radiation-pressure forces, sputtering, and/or collisions. IDPs scatter and absorb solar radiation and thus experience a net force due to radiation pressure. This effectively reduces the gravitational acceleration $GM/r^2 \rightarrow (1-\beta)\, GM/r^2$, and exerts a drag that leads to orbital decay of the IDPs. This latter effect is termed the Poynting-Robertson effect [e.g., *Burns et al.*, 1979]. Poynting-Robertson lifetimes, τ_{PR}, are grain-size dependent and have been amply discussed in the literature [e.g., *Burns et al.*, 1979], $\tau_{PR} \approx 400$ R^2/β in years, where R is heliocentric distance in AU and β is the ratio of the radiation pressure force and gravitation. For very small, sub-micron-sized particles, $\beta \sim 0.1$. A plot of β for "astronomical silicate" [*Draine*, 1985] is shown in Figure 1 and has been calculated using Mie theory for spherical grains [*Bohren and Huffman*, 1983].

[6] Lifetime limitations due to collisions are hard to quantify because of the badly known spatial density of sub-micron-sized particles in the inner heliosphere. It is the aim of this paper to address this issue. Sputtering removes the outermost layers of a grain via excitation processes of surface molecules or atoms. Sputtering agents can be solar radiation, the solar wind, or solar energetic particles. Their fluxes all scale as $(R_0/R)^2$. Therefore, we only need to consider one heliocentric distance to answer the question whether a grain can trap sufficient solar wind heavy ions when its surface is constantly being sputtered by solar radiation. Values for the sputtering rate, S, are hard to quantify, we assume a value of S_0 = 1 Å $year^{-1}$ to be

[1] Now at Institut für experimentelle und angewandte Physik, Christian-Albrechts-Universität zu Kiel, Germany.

0094-8276/03/2002GL015218

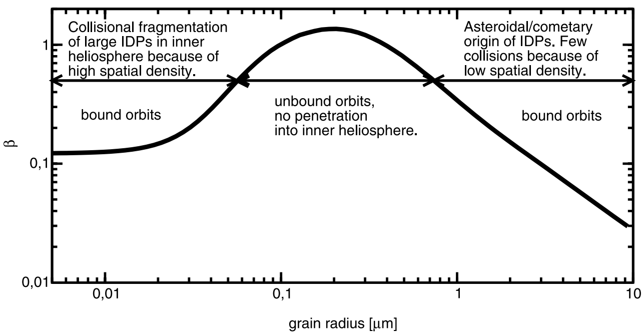

Figure 1. Ratio of radiation pressure force to gravitational force for spheres of astronomical silicate. Only IDPs with $\beta < 1/2$ can remain bound on circular orbits, resulting in a "hole" in their size distribution.

typical at 1 AU. This is comparable with measurements of erosion rates of lunar soils, when erosion by micrometeorites is taken into account [*Borg et al.*, 1980].

[7] The solar wind Si flux at 1 AU, Φ_0, is $\Phi_0 = n_{Si} \cdot v_{SW} \approx 3\ 10^{-4}\ \mu\mathrm{m}^{-2}\ \mathrm{s}^{-1}$, and hence about $\Phi_0 \approx \pi\ 10^4\ s^2$ solar wind Si particles are trapped in the sub-surface layers (at approximately the solar wind penetration range, λ, typically a few 100 Å deep) of a grain of radius s (in units μm) in one year. In the same period of time, about 1 Å is removed from the grain surface because of sputtering. This corresponds to a volume $V_{sp} = 4\pi\ s^2\ S_0 \times 1$ year $\approx 4\pi\ s^2\ 10^{-16}\ \mathrm{cm}^3$. Using a typical IDP density $\rho = 2.5\ \mathrm{g/cm}^3$ [e.g., *Gustafson*, 1994] and a mean molecular weight of SiO_2 of 60 g/mol, we obtain the number of atoms or molecules sputtered per year, $N_{sp} = \rho V_{sp}/(60\ \mathrm{g/mol}) * N_A \approx \pi\ s^2\ 10^7$. Thus we have $\pi\ 10^4\ s^2$ trapped solar wind Si and $\pi\ 10^7\ s^2$ sputtered IDP Si atoms leading to a ratio of sputtered to trapped atoms $\sim 10^3$. The outermost 1 layer of the grain contains solar wind atoms that were implanted $\sim \lambda/S_0$ years earlier. There are about 10^3 times more original grain atoms in the outermost Å than implanted solar wind atoms, and hence many more grain atoms are sputtered than old implanted solar wind atoms. Because IDPs get much hotter than the condensation temperature of the highly volatile Ne, grains contain no indigenous Ne, but only implanted solar wind Ne. Hence we expect Ne to be depleted by a factor 10^3 compared to an important constituent of grains, e.g. Si or Mg. This would lead to a Ne/Mg ratio in pickup ions about 10^3 times lower than in the solar wind. Hence, the observation that pickup Ne/Mg and Ne/Si are approximately the same as in the solar wind demonstrates that these ions are not sputtered grain material. Thus it appears that another mechanism is somehow neutralizing the solar wind, resulting in a solar-wind-like composition of inner-source PUIs. In this work we propose that sub-micron-sized IDPs in the innermost heliosphere (typically at 0.1 AU) are this neutralizing agent by charge exchanging with the solar wind.

3. Charge Exchange in IDPs

[8] When a multiply-charged solar wind ion approaches, penetrates, and leaves the IDP, its final charge-state distribution is a function of residual projectile energy after passage through the grain. Charge exchange of solar wind with IDPs has not been studied in quantitative detail. However, the charge-state distribution of solar-wind ions after passage through thin (few $\mu\mathrm{g/cm}^{-2}$) carbon foils are well studied [e.g., *Bürgi et al.*, 1993; *Kallenbach et al.*, 1993; *Gonin et al.*, 1994]. Without more pertinent data currently available, we will apply the carbon-foil results to ions passing through IDPs. While the exact numbers will need to be taken with a grain of salt, elemental abundance ratios are much less affected by the target material. Prototypical spherical IDPs are sketched in Figure 2 where we have also defined various quantities of interest. The cross section for passage of an ion through a distance l of IDP material is $d\sigma = 2\pi\xi\ d\xi$, where $\xi = \sqrt{s^2 - (l/2)^2}$. We thus have the cross section for passage through l, $d\sigma = -\pi/2l\ dl$ which is independent of s as long as $l < s$. With this knowledge we can compute the charge-state distribution of various solar-wind ions after they have passed through a population of IDPs. Such populations are commonly described using a power-law distribution in grain size, s, $dN/ds \sim s^{-\gamma}$, where the exponent, γ, is often given as $\gamma \sim 3.3-3.7$ [e.g., *Leinert and Grün*, 1990]. Other prescriptions use piece-wise power laws, notably the reference population model of *Divine* [1993]. For reasons that will become apparent shortly, we use $dN/ds \sim s^{-\gamma}$ with $\gamma \sim 3.6$ to describe the size distribution of very small IDPs. The resulting charge-state distributions for Ne and Mg are plotted in Figure 3. Neon is shown as thick lines, Mg in thin lines, the different charge states are shown with different line styles (solid: neutral, dashed: singly charged, dash-dotted: doubly charged). The striking difference between Ne and Mg is the important contribution of Mg^{++} while Ne^{++} is all but absent. This difference will manifest itself in in situ measurements of inner-source PUIs. To a first approximation, the neutralized solar wind ions are rapidly re-ionized by solar radiation and, just as the singly ionized ions, picked up by the swept-by interplanetary magnetic field. Because current instrumentation only measures the composition of singly-ionized heavy PUIs, the strong energy dependence of Mg^{++} should result in an observable energy dependence of the apparent Ne/Mg elemental abundance ratio. We have summed the neutral and singly charged fractions of Ne and Mg in Figure 3 and plotted the resulting elemental abundance ratio Ne/Mg in Figure 4 for two indices γ. Such a

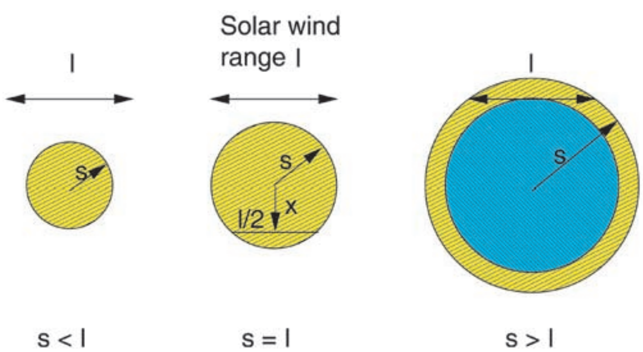

Figure 2. IDP sizes and solar wind penetration range. The ratio of trapping and neutralizing cross sections σ_t and σ_n depends strongly on the size of the IDP. Hence the expectation values for these cross sections are a strong function of the size distribution of IDPs in the inner heliosphere.

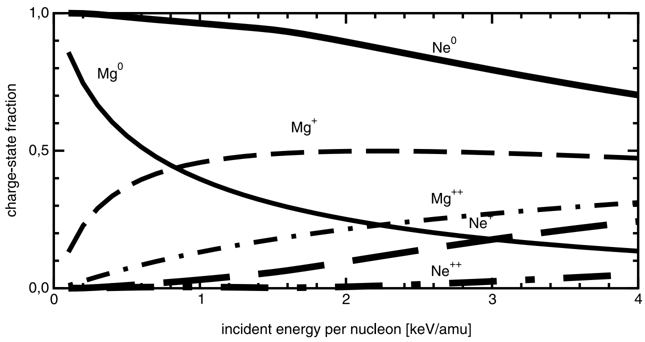

Figure 3. Charge-state distributions of Mg and Ne after passage through a model IDP population.Thin lines are Mg, thick lines for Ne. The charge states are indicated (solid line: neutral, dashed: singly charged, dash-dotted: doubly charged).

speed - or energy - dependence has indeed been observed in the Ne/Mg ratio [N. Schwadron, personal communication, 2001]. This simple picture is complicated somewhat by the non-instantaneous reionization of Ne^0, we find that a substantial fraction can escape from the vicinity of the Sun in atomic form. However, this is again offset by the additional ionization of $Mg^+ \rightarrow Mg^{++}$ which, based on comparison of ionization potentials, has an ionization time that is of the same magnitude as that for Ne^0. Regardless of these details, this discussion has shown that the PUI flux should be correlated with the emission of ionizing solar UV. This correlation could be tested for using e.g. data from the SOHO/CELIAS/SEM instrument [*Hovestadt et al.*, 1995].

4. Origin of Small IDPs in the Inner Heliosphere

[9] Current models [e.g., *Leinert and Grün*, 1990] of IDPs in the inner heliosphere do not include a significant population of very small IDPs, its constituent particles can not be measured with present dust instrumentation. IDPs are believed to originate mainly from asteroidal and cometary material. The radiation pressure force acting on these particles can expel some of them. One can easily find that for a near circular orbit (as is the case for most large IDPs) $\beta > 1/2$ suffices for the orbits to be unbound. In Figure 1 we have plotted β for spherical grains of "astronomical silicate" using the optical constants tabulated by *Draine* [1985]. Obviously, large particles, for which geometric optics gives a good approximation, are on bound orbits. Smaller particles can not remain on bound orbits and will eventually leave the solar system if their optical properties are not changed by other processes. Even smaller particles ($s < 0.07$ μm) again can remain on bound orbits, as has been pointed out earlier [*Gustafson*, 1994]. Mie scattering calculations show that such particles are inefficient absorbers (and scatterers) of solar radiation and one may readily convince oneself that they can survive conditions in the inner heliosphere, even as close as 0.1 AU from the Sun. They are also inefficiently heated by interaction with the solar wind and energetic particles because these traverse these grains depositing only a fraction of their kinetic energy. Cooling times [*Hoyle and Wickramasinghe*, 1991] are shorter than the typical collision time scale $(\Phi_{SW}\pi\ s^2)^{-1}$. Sputtering is also much less efficient for such small grains than for larger ones. Investigations of sputtering of thin carbon foils by heavy ions (N at 2 keV/amu) showed that one target carbon atom or ion is released for about 100 transmitted heavy ions [*Gonin*, 1995]. The reason for this inefficient sputtering is probably the very inefficient deposition of projectile energy in the target. With our assumed value for S_0 = 1Å per year, the sputtering lifetime of a s = 250 Å IDP would be 2.5 years at 0.1 AU from the Sun. Because the small IDPs do not absorb all the energy, this time scale can be increased by a substantial amount. Solar wind hydrogen looses only about 40% of its energy in a s = 250Å IDP and hence the sputtering lifetime is increased to at least 5 years. Sputtering by solar UV is negligible for such small particles because they are transparent. Because the relative importance of UV- and particle-induced sputtering is not known for the lunar soil grains that we used to infer S_0, we may consider the 5 years as a lower bound on the sputtering lifetime.

[10] If such particles originated in the asteroid belt, they could not reach 0.1 AU. A sun-grazing cometary origin can also be discounted because such particles would not remain on stable orbits.

[11] We propose that the very small IDPs needed to explain inner-source PUI measurements originate in collisions of μm-sized IDPs which spiral into the inner heliosphere. Close to the Sun, relative motions of IDPs exceed several tens of km/s and collisions even with small (few 100 Å) particles result in catastrophic destruction of large particles. Laboratory studies of catastrophic collisions show that the fragments exhibit a power-law size distribution, $dN/ds \sim s^{-\gamma}$, with $\gamma \sim 3.6$ [e.g., *Fujiwara et al.*, 1977]. Knowing the mass of the largest collision fragment [see *Fujiwara et al.*, 1977] and the power-law index γ allows us to calculate the mass of the smallest fragments and the expectation value for the size of the fragments, $\langle s \rangle \sim 250$ Å, and for their number, $\langle N \rangle \sim 6\ 10^4$. The largest particle that is created in such a catastrophic disruption is still smaller than the maximum size for which IDPs are still stable on circular orbits against the Poynting-Robertson effect and much smaller than the size of the IDP. Hence the total energy of the largest projectile and the IDP is to a good approximation that of the IDP. The same holds for the momentum of the projectile-target system. Because the target IDP is on a near-circular, only slowly decaying orbit, it's orbital energy is negative and a substantial input of energy is needed to place it on an unbound orbit. The energy needed is considerably larger than that imparted to the target by the projectile. Hence we may assume that a

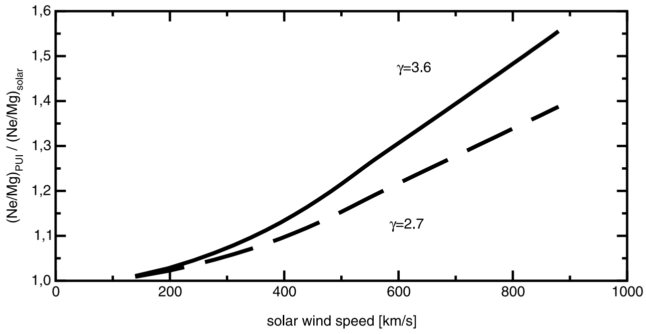

Figure 4. Predicted elemental abundance ratio for Ne/Mg as a function of solar wind speed.

substantial fraction of the collision fragments remains on heliocentric orbits in the inner heliosphere. Lifetimes against collisions at 1 AU of 1 μm IDPs are on the order of few 10^4 years [*Dohnanyi*, 1978]. At 0.1 AU, increased number density and collision velocities result in collisional lifetimes which are about two orders of magnitude shorter than typical Poynting-Robertson times. Thus the IDP population in the inner heliosphere is dominated by very small collision fragments, thin enough for the solar wind to penetrate through the particles and exit with a very different charge-state and energy distribution than the solar wind. Because the *Fujiwara et al.* [1977] value $\gamma \sim 3.6$ falls within the often quoted range for IDPs $3.3 < \gamma < 3.7$ we used it for our calculations of the charge-state distribution of Ne and Mg for Figure 3. We have also plotted results for a significantly different value, $\gamma = 2.7$, to illustrate the modest influence of this parameter.

5. Discussion and Conclusions

[12] The current explanation of the origin of inner-source pickup ions posits that solar wind that has been implanted in IDPs is set free from the IDP, ionized and picked up by the solar wind. We have challenged this view because more pickup ions should be produced by sputtering of IDP material than through this process. In this work, we propose a population of very small dust grains that originate in catastrophic collisional disruptions of μm-sized IDPs in the innermost heliosphere. The typically $\sim 610^4$ collision fragments are smaller than $\sim$600 Å, with an expectation value of $\sim$250 Å, and remain on bound orbits (see Figure 1) and are available as projectiles for further collisions with incoming IDPs. At 0.1 AU large IDPs are rapidly destroyed in catastrophic collisions giving rise to the proposed large population of very small IDPs. Estimates of the charge-exchange cross section by *Schwadron et al.* [2000] based on the flux of inner-source PUI O^+ resulted in a value that was nearly two orders of magnitude larger than currently accepted values. Our proposed population solves this dilemma because the charge-exchange cross section for many small particles is much larger than for few large particles. For the population of collision fragments, $\sigma \langle N \rangle \pi \langle s \rangle^2$ is 30–40 times larger than for the 1μm target particle. So far, such an inner dust population has not been and can not be observed with past and present-day instrumentation. As previously mentioned, such a population would also not contribute any appreciable amount to scattering in the zodiacal cloud, especially if the wave-length dependence of the refractive indices are taken into account [*Perrin and Lamy*, 1989].

[13] The possibility of a new population of very small IDPs in the innermost heliosphere has implications for at least two currently planned space missions, NASA's Solar Probe and ESA's Solar Orbiter. While the number density of such very small IDPs is much higher than what is presently predicted by standard models, the particles themselves are much smaller and hence much less dangerous to spacecraft venturing into this unexplored region of the heliosphere.

[14] **Acknowledgments.** We thank Nathan Schwadron and Peter Wurz for stimulating discussions. This work was supported by the Swiss National Science Foundation.

References

Bohren, C. F., and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, John Wiley & Sons, New York, USA, 1983.

Borg, J., J. Chaumont, C. Jouret, Y. Langevin, and M. Maurette, Solar wind radiation damage in lunar dust grains and the characteristics of the ancient solar wind, in *The Ancient Sun*, edited by R. O. Pepin, J. A. Eddy, and R. B. Merrill, Geochim. Cosmochim. Acta Suppl. 13, pp. 431–461, 1980.

Bürgi, A., et al., Charge exchange of low energy ions in thin carbon foils, II, Results for ions of B, F, Ne, Na, Si, S, Cl, Ar, K, and Fe, *J. Appl. Phys.*, *73*, 4130–4139, 1993.

Burns, J. A., P. H. Lamy, and S. Soter, Radiation forces on small particles in the solar system, *Icarus*, *40*, 1–48, 1979.

Dohnanyi, J. S., Particle Dynamics, in *Cosmic Dust*, edited by J. A. M. McDonnell, pp. 527–605, John Wiley, Chichester, UK, 1978.

Draine, B. T., Tabulated optical properties of graphite and silicate grains, *Astrophys. J. Suppl. Ser.*, *57*, 587–594, 1985.

Fujiwara, A., G. Kamimoto, and A. Tsukamoto, Destruction of basaltic bodies by high-velocity impact, *Icarus*, *31*, 277–288, 1977.

Geiss, J., G. Gloeckler, U. Mall, R. von Steiger, A. B. Galvin, and K. W. Ogilvie, Interstellar oxygen, nitrogen and neon in the heliosphere, *Astron. Astrophys.*, *282*, 924–933, 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*, 7459–7463, 2000.

Gonin, M., Ein semiempirisches Modell des Ladungsaustausches von niederenergetischen Ionen beim Durchgang durch dünne Folien, zur Eichung von isochronen Flugzeit-Massenspektrometern, Ph.D. thesis, Univ. of Bern, Bern, Switzerland, 1995.

Gonin, M., R. Kallenbach, and P. Bochsler, Charge exchange of atoms with high first ionization potentials in carbon foils at $E \leq 35$ keV/u, *Nucl. Instrum. Methods Phys. Res., Sect. B*, *94*, 15–21, 1994.

Gustafson, B. Å. S., Physics of zodiacal dust, *Annu. Rev. Earth Planet. Sci.*, *22*, 553–595, 1994.

Hovestadt, D., et al., CELIAS - charge, element and isotope analysis system for SOHO, *Solar Physics*, *162*, 441–481, 1995.

Hoyle, F., and N. C. Wickramasinghe, *The Theory of Cosmic Grains*, Kluwer, Dordrecht, The Netherlands, 1991.

Kallenbach, R., M. Gonin, A. Bürgi, and P. Bochsler, Charge exchange of hydrogen atoms in carbon foils, *Nucl. Instr. Meth. B*, *83*, 68–72, 1993.

Leinert, C., and E. Grün, Interplanetary dust, in *Physics of the Inner Heliosphere I*, edited by R. Schwenn and E. Marsch, pp. 207–275, Springer, Berlin, Germany, 1990.

Perrin, J.-M., and P. L. Lamy, The color of the zodiacal light and the size distribution and composition of interplanetary dust, *Astron. Astrophys.*, *226*, 288–296, 1989.

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

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

Sekanina, Z., Solar and heliospheric observatory sungrazing comets with prominent tails: Evidence on dust-production peculiarities, *Astrophys. J.*, *545*, L69–L72, 2000.

R. F. Wimmer-Schweingruber and P. Bochsler, Physikalisches Institut, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland. (wimmer@phim.unibe.ch)