JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, A05105, doi:10.1029/2004JA010847, 2005

Stability of the inner source pickup ions over the solar cycle

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Received 18 October 2004; revised 28 February 2005; accepted 24 March 2005; published 27 May 2005.

[1] Inner source pickup ions (PUIs) were discovered and are observed by Ulysses. They are thought to be generated by solar wind interaction with dust grains near the Sun. From previous work, four constraints were derived on inner source PUIs from observations near solar minimum: (1) the composition resembles the solar wind; (2) the distribution functions show strong adiabatic cooling, consistent with a source peaked near 10–30 R_S; (3) the production rates of inner source C^+ and O^+ are about 2×10^6 g/s each; (4) the individual inner source counts are randomly distributed in time. We compare inner source observations over three distinct 2-month periods in 1994, 1995, and 2001, when Ulysses was at high latitudes and about 2 AU from the Sun. Our observations not only substantiate the four constraints above but, in addition, reveal that the inner source appears stable over at least half a solar cycle and the inner source PUI flux is correlated with solar wind flux. A number of scenarios have been proposed to explain the origin of the inner source PUI. None of the proposed inner sources are consistent with our five observational constraints, suggesting that we do not yet understand the true source of these pickup ions.

Citation: Allegrini, F., N. A. Schwadron, D. J. McComas, G. Gloeckler, and J. Geiss (2005), Stability of the inner source pickup ions over the solar cycle, *J. Geophys. Res.*, *110*, A05105, doi:10.1029/2004JA010847.

1. Introduction

[2] There are two main extended sources of pickup ions (PUIs) in the inner heliosphere: the interstellar source [e.g., *Möbius et al.*, 1985; *Gloeckler et al.*, 1993; *Geiss et al.*, 1994] and the inner source [*Geiss et al.*, 1995; *Gloeckler et al.*, 2000; *Schwadron et al.*, 2000], which is believed to be due to solar wind interaction with heliospheric dust grains. On the basis of observed distribution functions [*Gloeckler and Geiss*, 1998] and modeling, the inner source PUIs are found to dominate interstellar PUIs close to the Sun, typically inside of 1 AU, and have peak source rates between 10 and 30 R_S [*Schwadron et al.*, 1999; *Schwadron et al.*, 2000]. The inner source PUIs were first identified by *Geiss et al.* [1995] through measurements of singly charged carbon with the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses. *Geiss et al.* [1996] derived from observations production rates of inner source C^+ and O^+ of 2×10^6 g/s each. The composition of the inner source PUIs is remarkably similar to that of the solar wind [*Gloeckler et al.*, 2000]. In particular, the [Ne/O] abundance of the inner source is somewhat enhanced relative to solar wind, which shows that the inner source cannot be directly produced from cometary or grain material since they are so strongly depleted in volatile elements like Ne.

[3] There are currently a number of different proposed scenarios for the production of inner source PUIs:

[4] 1. Scenario one is solar wind recycling. On the basis of the inner source composition, *Gloeckler et al.* [2000] and *Schwadron et al.* [2000] proposed that the inner source is produced due to neutralization of solar wind by grains. They considered a storage-release mechanism for the inner source: a solar wind ion is embedded in and subsequently released by a grain. The released neutral atom is readily ionized by UV radiation or charge exchange with the solar wind ions and picked up by the solar wind.

[5] 2. Scenario two is solar wind neutralization. *Wimmer-Schweingruber and Bochsler* [2003] argued that there are about 10^3 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. Therefore they suggested that the inner source derives not from large (approximately μm) grains but from very small nanometer-sized and the edges of larger grains that act as thin foils. These grains predominantly neutralize intercepted solar wind ions, without significant production of sputtered products. *Habbal et al.* [2003] found evidence

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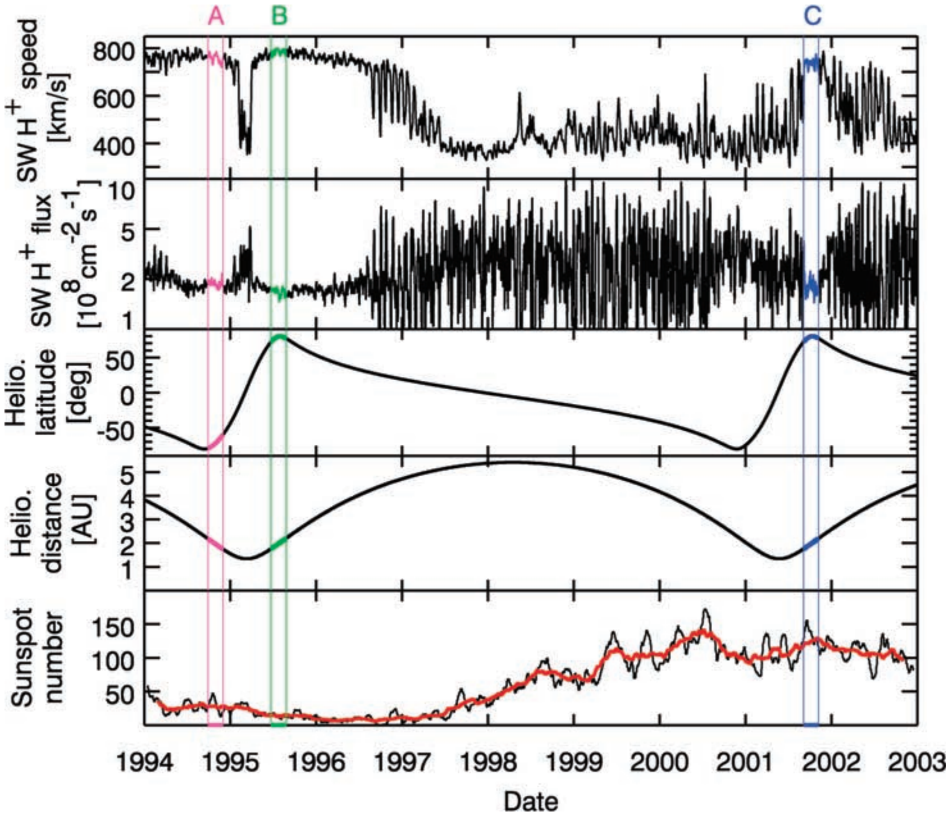

Figure 1. Solar wind proton speed and flux measured by SWOOPS in the top two parts, and Ulysses heliographic latitude and distance to the sun in the third and fourth parts. The bottom part represents the sunspot number (in black) with a smoothed average (in red). The three selected periods are delimited by the vertical lines. Two of them (in 1994 and 1995) are close to solar minimum and the last one (in 2001) is close to solar maximum.

in polarimetric observations in the line of Fe XIII for a large population of silicon nanometer dust grains in the inner corona. However, similar observations by *Singh et al.* [2004] did not confirm fluorescent emission from nanoparticle dust grains in the coronal hole region in the inner corona. They suggest that this is due to the absence of silicon nanoparticles or to their detection limit.

[6] 3. Scenario three is products of sungrazing comets. *Bzowski and Krolikowska* [2005] proposed that at least part of the inner source PUIs might be the material released by sungrazing comets. This scenario requires that the PUIs are produced locally and during limited time intervals.

[7] 4. Scenario four is dust-dust collisions. *Mann and Czechowski* [2005] recently proposed another scenario where dust–dust collisions feed ions into the interplanetary medium and produce a significant number of the heavy inner source pickup ions. In their model they say that the calculations show that collisional vaporization can produce the heavy pickup ion fluxes of the inner source.

[8] *Mann et al.* [2000] modeled a large dust cloud near the Sun made up of grains larger than ~10 μm, which are confined to a disk with a typical thickness of tens of degrees; small, several μm grains fill in a broader disk-like volume that is tilted off the ecliptic plane by a variable angle depending on the solar activity cycle; submicrometer-sized grains form a nearly spherical halo around the Sun with a radius of more than 10 R_S. The flux of tiny grains in the size range 0.5–2 μm area was found to vary with the solar activity phase. The amplitude of fluctuations may reach one order of magnitude for moderate latitudes and may be even higher at the poles. *Ragot and Kahler* [2003, 2004] suggested that grains smaller than 0.1 μm may be trapped in CMEs as their gyroradii are much smaller than the size of the CME. During solar maximum the rate of CMEs increases. If very small grains have higher charge-to-mass ratio and therefore are more strongly affected by Lorentz forces, there must be strong differences in the distribution of tiny (<1 μm) grains between solar minimum and maximum. This means that the hypothesis that a large population of very small grains (<0.1 μm) generates the inner source pickup ions (scenario two) requires differences in the inner source from solar minimum to solar maximum.

[9] The purpose of this paper is to explore the stability of the inner source through the solar cycle and to test the different proposed scenarios for the production of the inner source PUIs against the known constraints. We derive from in situ observations an important new constraint for the inner source that suggests its long-term stability. We also show that the inner source PUI flux seems to be correlated with solar wind flux.

2. Observations

[10] The pickup ion data were obtained with the Solar Wind Ion Composition Spectrometer (SWICS) [*Gloeckler et al.*, 1992], and the solar wind speed and density were

Table 1. Time Periods Analyzed With Ulysses Average Heliocentric Latitude and Distance[a]

Time Periods	Duration, day	⟨Helio lat⟩, deg	⟨Range⟩, AU	Solar Cycle
A, 27 Sep to 30 Nov 1994	64	−71.2	1.97	Min
B, 22 June to 26 Aug 1995	65	78.0	1.98	Min
C, 3 Sep to 6 Nov 2001	64	78.0	1.98	Max

[a]The time periods A and B are during solar minimum and C during solar minimum. The three periods have very similar heliographic latitudes and distances.

obtained with the SWOOPS (Solar Wind Observations Over the Poles of the Sun) instrument [*Bame et al.*, 1992] on the Ulysses spacecraft. We selected three time periods when Ulysses was at high latitude, two of them during solar minimum and one during solar maximum as indicated by color-coded vertical lines in Figure 1. The top two parts of Figure 1 show the solar wind proton speed and the solar wind proton flux normalized to 1 AU. The third and fourth parts show the heliographic latitude and the heliographic distance of Ulysses. The bottom part shows the smoothed sunspot number from the beginning of 1994 to the end of 2002. Table 1 gives the average latitude and range for the three periods. The average heliocentric latitude was the same for the two periods in the northern hemisphere (B and C) and somewhat close for the period in the southern hemisphere (A). The average heliocentric distance is the same for all three periods. Periods B and C are very similar in terms of heliographic latitude and range. The three regions correspond to fast solar wind (>600 km/s) and similar solar wind flux as illustrated in the top two parts of Figure 1. The choice of these periods allows us to remove any latitudinal or heliocentric distance effects as well as differences in solar wind. Thus the comparison between B and C is a comparison between solar minimum (B) and solar maximum (C).

[11] Figure 2 represents the distribution functions in the spacecraft reference frame for the inner source pickup carbon (Figure 2a) and oxygen (Figure 2b) ions for the three time periods during high-latitude scans of Ulysses. The distributions are plotted versus the speed of the ions (v') relative to the solar wind speed (u). The distribution functions all peak at the solar wind speed ($w = v'/u \approx 1$) showing that the pickup ions have been dramatically cooled from where they have been generated (near the Sun) to where they have been observed (∼2 AU) by SWICS. A distribution function of PUIs generated upstream of and close to the spacecraft would appear more flat from 0 to 2 times the solar wind speed ($0 < w < 2$) as observed for interstellar pickup ions [e.g., *Gloeckler et al.*, 2001]. Deriving the fluxes from the distribution functions of Figure 2, we find a production rate of 5×10^5 g/s for C^+ and 7×10^5 g/s for O^+. These values are lower than given in the work of *Geiss et al.* [1996]. The difference might be due to the fact that their values were calculated for near the ecliptic and ours are for high latitudes.

[12] The purpose of the curves in Figure 2 is only to guide the eye. These curves are taken from a model for the production and transport of the inner source pickup ions [*Schwadron et al.*, 2000]. They are unaltered in shape and amplitude. The variations between the three time periods are comparable to the error bar size, suggesting that there is no significant difference between the three time periods. Hence there is no significant difference in the flux of inner source PUIs between the northern and the southern hemisphere or between solar minimum and solar maximum. The average solar wind flux is also similar for the three periods: $(2.0 \pm 0.3) \times 10^8$ cm^{-2} s^{-1} for period A, $(1.8 \pm 0.3) \times 10^8$ cm^{-2} s^{-1} for period B, and $(2.2 \pm 1.3) \times 10^8$ cm^{-2} s^{-1} for period C. The uncertainties are the sigma of the averaged data points. The periods in 1994 (A) and 1995 (B) are close to solar minimum, and the period in 2001 (C) is close to solar maximum, as shown in Figure 1. Therefore the inner source pickup ions show remarkable stability for the periods considered. Since the conditions (latitude, distance, solar wind speed, and flux) for these periods are very similar, it is reasonable to deduce the stability of the inner source PUIs over half the solar cycle.

[13] In Figure 3, we show the mass-per-charge histogram cumulated for the three periods. We restricted the velocity range to $0.95 < w < 1.05$ (around the peak) in order to

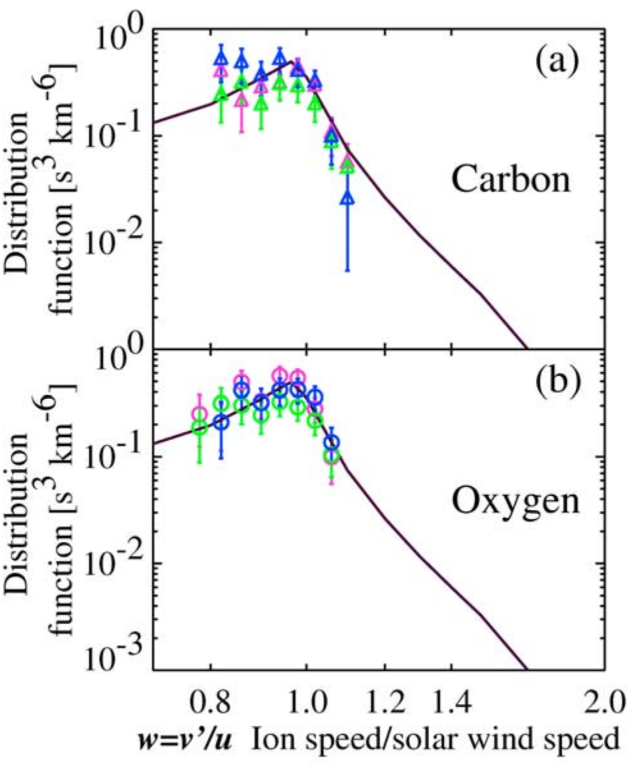

Figure 2. Distribution functions of inner source PUIs for the three periods of Figure 1 and Table 1. The triangles (upper part) correspond to inner source pickup carbon and the circles (lower part) to oxygen. The colors indicate the periods labeled A, B, and C, respectively, in Figure 1. The curves, which are taken from the model in the work of *Schwadron et al.* [2000], are shown only to guide the eye. They are not fit to the data. Instead, they are set at the same value for comparison between the periods. The inner source pickup ions show remarkable stability for the periods considered.

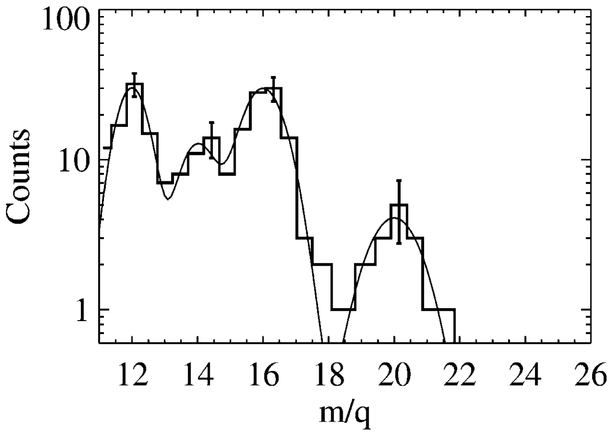

Figure 3. Mass-per-charge histogram cumulated for the three periods A, B, and C. Peaks of C^+ (m/q = 12), N^+ (m/q = 14), O^+ (m/q = 16), and Ne^+ (m/q = 20) are clearly visible. The relative abundances are given in Table 2 and compared to previous results. There is generally good agreement with previous measurements. The inner source PUIs show a composition similar to solar wind composition.

suppress the background and where any other contribution is small. We used a mass-per-charge scale based on the one calibrated by *Ipavich et al.* [1982], and the counts have been corrected for efficiencies. We did not apply any correction for interstellar N, O, and Ne. However, the contribution of interstellar PUI for O, for example, is only ~2–3 % at 1.4 AU and ~10–15 % at 2.8 AU [see, e.g., *Gloeckler and Geiss*, 1998]. We fit a Gaussian to the peaks at m/q = 12, 14, 16, and 20. The ratios of the Gaussian maxima relative to oxygen are compared to previous measurements in Table 2. There is generally good agreement with previous measurements. However, carbon and neon have lower abundances, which are closer to solar wind abundances. A possible explanation for the high Ne^+/C^+ and Ne^+/O^+ is given in the work of *Gloeckler et al.* [2000] in the perspective of scenario 1. Ne will not form molecules when it is released, contrary to C and O that could. A portion of the molecules will become ionized molecules and would be picked up. If the lifetime of the ionized molecules is sufficiently large, they would reach SWICS as ionized molecules and could escape detection.

[14] Figure 4 shows two mass-per-charge histograms in counts per day for the period C in 2001. The upper part refers to times when the solar wind flux (normalized to 1 AU) exceeded 2×10^8 cm^{-2} s^{-1} and the lower part for a flux lower than 2×10^8 cm^{-2} s^{-1}. There is a clear correlation between inner source PUI and solar wind flux. The ratio of the carbon peaks is 2.4 ± 0.9, and the ratio of oxygen peaks is 2.0 ± 0.8. The average solar wind flux in the high- and low-flux cases are $(2.7 \pm 0.8) \times 10^8$ cm^{-2} s^{-1} (one sigma) and $(1.60 \pm 0.25) \times 10^8$ cm^{-2} s^{-1}, respectively, which gives a ratio of 1.7 ± 0.8. The ratio of high to low fluxes for the inner source PUIs and the solar wind are consistent within the uncertainties. Therefore the inner source PUI flux seems to be correlated to the solar wind flux.

[15] In order to check whether the inner source is made up of a finite number of localized sources or is distributed, *Geiss et al.* [1996] studied the distribution of time intervals between registrations of individual pickup ions with m/q > 10 and for C^+ for a broad range of solar latitude and distance. They find that the counts are Poisson distributed and hence that there is no indication of a contribution from point sources. If the distribution of the time intervals between the registrations follows a Poisson distribution, then the number of registrations during a given time interval should also follow a Poisson distribution. This is illustrated in Figure 5 for C^+, N^+, O^+, and Ne^+ where we show the occurrences of counts per 3 days for the three combined periods. The curves on top of the histograms are Poisson distributions ($N(\mu) = N_0 e^{-\mu}\mu^c/c!$, where μ is the expectation value and c is the number of counts per 3 days). We used the averages of the histograms for the expectation values μ of the curves and the sum of the occurrences for N_0. We calculated the χ^2 with the number of degrees of freedom d indicated in each part. The χ^2 values obtained show that these distributions are compatible with Poisson distributions. Thus the inner source PUIs are consistent with randomly distributed as opposed to localized sources. Nevertheless, this conclusion must be taken with some caution. The inner source PUI fluxes are very small and the distributions are known to vary so that long time averages are required. Moreover, transport processes may lead to enough of a randomization so that it may look like a distributed source.

3. Discussion

[16] Our observations revealed an additional constraint on inner source pickup ions: the source appears stable over half a solar cycle. We now have a total of five important constraints that need to be satisfied in order to explain inner source pickup ions:

[17] 1. *Gloeckler et al.* [2000] find an inner source PUI composition similar to the solar wind composition. This work confirms this finding.

[18] 2. The distribution functions show a strong adiabatic cooling, consistent with a source distribution that peaks near 10–30 R_S [*Schwadron et al.*, 2000].

[19] 3. The inner source PUI production rates for C^+ and O^+ are about 2×10^6 g/s each [*Geiss et al.*, 1996].

[20] 4. The inner source is compatible with randomly distributed sources [*Geiss et al.*, 1996].

[21] 5. The inner source looks stable over the solar cycle (this work).

[22] The apparent correlation of inner source PUI flux with solar wind flux could constitute a sixth constraint. However, this correlation should be studied over a longer period of time.

Table 2. Element Abundance Ratios of the Inner Source PUIs Compared With Previous Results and to Solar Wind Abundances[a]

	Inner Source		Solar Wind
M/q (Element)	This Work	*Gloeckler et al.* [2000]	[*von Steiger et al.*, 2000]
m/q = 12 (C^+)	1.01 ± 0.12	1.46 ± 0.12	0.683 ± 0.040
m/q = 14 (N^+)	0.42 ± 0.07	0.40 ± 0.05	0.111 ± 0.022
m/q = 16 (O^+)	1.00 ± 0.10	1.00 ± 0.06	1 ± 0
m/q = 20 (Ne^+)	0.14 ± 0.03	0.32 ± 0.05	0.082 ± 0.013

[a]The inner source PUIs show a composition similar to solar wind composition.

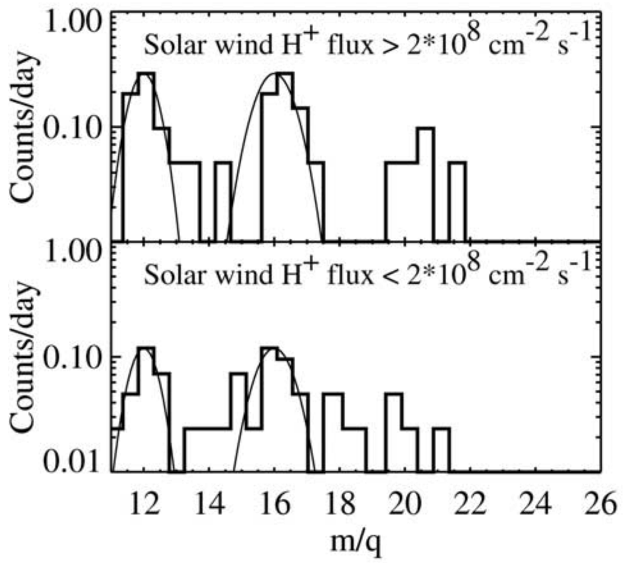

Figure 4. Mass-per-charge histograms in counts per day for the period C in 2001 when the solar wind proton flux is greater (upper part) and lower (lower part) than 2×10^8 cm^{-2} s^{-1}. The rate of PUIs production is clearly higher when the flux is higher. The inner source PUI flux seems to be correlated to the solar wind flux.

[23] In the introduction we mention four scenarios that have been proposed to explain the inner source pickup ions. Table 3 shows a matrix listing the scenarios and their relation to the five inner source constraints. The fact that inner source pickup ions have solar wind-like composition strongly constrains possible source mechanisms. In fact, it immediately rules out the scenarios where the pickup ions are produced by sungrazing comets or dust-dust collisions. Given this constraint, and especially the presence of a large abundance of Ne, this makes it difficult to reconcile the inner source with sputtering, vaporization and/or sublimation of material on the surface of asteroids, comets, and/or dust grains. Meteoroids and asteroids are strongly depleted in volatiles and, in particular, noble gases [see, e.g., *Lodders*, 2003]. In comets, volatiles are also depleted but to a lesser extent than in asteroids. Neon has not been detected in comets. An upper limit for the neon abundance was given by *Geiss et al.* [1999], who found a depletion by a factor of 100 in the material released in 1986 by comet Halley.

[24] *Wimmer-Schweingruber and Bochsler* [2003] assume in their calculation a grain erosion rate of 1 Å/year at 1 AU and therefore conclude that grains cannot saturate with solar wind material. *Johnson and Baragiola* [1991] estimate the erosion rate of lunar grains in the range 0.1 to 0.2 Å/year. This is still not low enough to allow the grains to saturate with solar wind according to the same calculation. Nevertheless, given that the grains are very porous, the erosion rate might well be much lower than 0.1 Å/year. Moreover, if the sputtering rates were so high, we ask why we do not see more sputtering products in our observations. There is no evidence of grain composition (most likely rich in refractory elements and depleted in volatile elements) in the inner source PUIs. On the contrary, we observe an apparent enhancement of N^+ and Ne^+ with respect to carbon compared to solar wind. New laboratory measurements are needed to study erosion and sputtering of dust grains. Therefore the first scenario involving solar wind recycling may succeed, provided that the erosion rate of grains is small. The second scenario involving nanoscale grains definitely reproduces solar wind abundances, though it does not seem to explain the measured high Ne^+/C^+ and Ne^+/O^+ ratios.

[25] The second constraint is not as difficult to satisfy and does not conflict with any of the proposed scenarios. *Bzowski and Krolikowska* [2005] point out that the majority of the sungrazing comets belong to the Kreutz group and break up between ~4 and 40 R_S, which is close enough to the ~10 to 30 R_S range.

[26] The third constraint concerns the production rates of the observed inner source PUIs. *Schwadron et al.* [2000] modeled inner source pickup ions in the case of the first scenario involving solar wind recycling. Comparing their model results to observations, they discovered that the total geometric dust cross section required to reproduce the inner source PUI production rates would be $\Gamma > \sim 1.3 \times 10^{-17}$ cm^{-1}, which is several orders of magnitude larger than the total geometric cross section inferred from zodiacal light observations (*Grün et al.* [1985], in ecliptic $\Gamma \sim 4.6 \times 10^{-21}$ cm^{-1}; see, e.g., *Schwadron et al.* [2000] and references therein) or from calculations based on neutral solar wind observations (*Collier et al.* [2003], $\Gamma < 6 \times 10^{-19}$ cm^{-1}). Most of the zodiacal light is scattered by ~10 to ~100 μm-sized particles [*Grün et al.*, 1985]. Therefore the dust that causes zodiacal light is only a

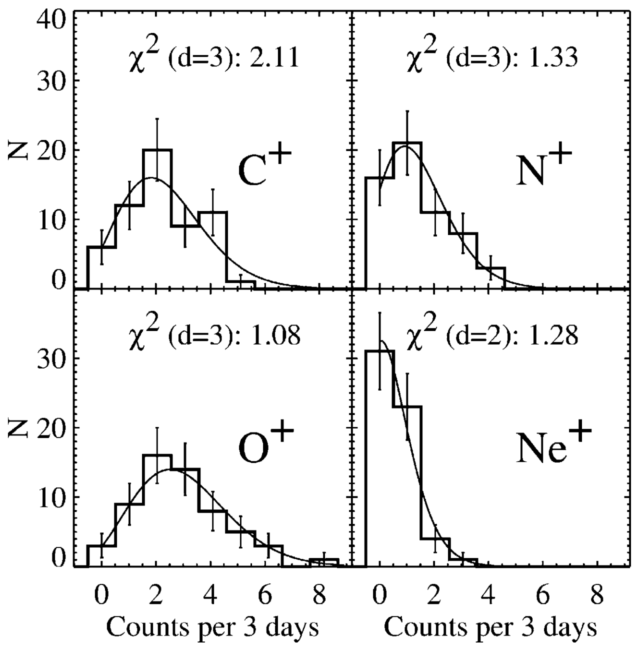

Figure 5. Occurrences N of counts per 3 days for C^+, N^+, O^+, and Ne^+ inner source PUIs. The curves are Poisson distributions with the respective expectation values equal to the average count rates. The validity of the hypothesis of a Poisson distribution is tested with a χ^2 calculation (d is the number of degrees of freedom). They show that the assumption of Poisson distributions is valid for the inner source PUIs.

Table 3. Summary Table Listing the Proposed Mechanisms and Their Relation to the Five Constraints

	Scenario One, Solar Wind Recycling	Scenario Two, Solar Wind Neutralization	Scenario Three, Products of Sungrazing Comets	Scenario Four, Dust-Dust Collisions
Solar wind composition	Possibly[a]	Yes[b]	No[c]	No[c]
Peak near the Sun (10–30 R_S)	Yes	Yes	Possibly	Possibly
Large pickup ion flux	Unlikely[d]	Possibly	Possibly	Possibly
Randomly distributed source	Yes	Yes	Unlikely	Yes[e]
Stability over solar cycle	Yes	Unlikely[f]	Yes	Possibly

[a]Success of this scenario requires a very low sputtering yield.
[b]Grains act as carbon foils to neutralize the solar wind.
[c]Depleted in Ne, rich in C, Si, Mg, Fe.
[d]Grains efficiently scatter light and would yield a cross section 2 decades higher than observed from zodiacal light.
[e]However, peaks at low latitude.
[f]Success of this scenario requires that CMEs do not trap nanometer-sized grains.

subset of the interplanetary dust cloud. Catastrophic collisions give rise to a size distribution weighted toward small grains that could account for the fairly large geometric dust cross section. Therefore the third constraint might be satisfied by scenario 2 because the total cross section for many small particles is much larger than for few large particles. However, note that the spatial density of submicron-sized dust particles is poorly known. *Bzowski and Krolikowska* [2005] suggest that a considerable portion of the inner source PUIs may arise from the sungrazing comets. Under some assumptions the fourth scenario involving dust-dust collisions is able to reproduce the inner source PUI production rates for the heavy ions [*Mann and Czechowski*, 2005].

[27] The fact that the number of inner source PUI counts follows a Poisson distribution may imply that the inner source is a randomly distributed source rather than a localized source. However, because of low statistics, localized sources are difficult to rule out. Although sungrazing comets can be ruled out as a direct and unique source of inner source PUIs because of the composition constraint, the dust released by sungrazing comets certainly contributes to the dust population near the Sun.

[28] The last of the five constraints, stability through half a solar cycle, is satisfied by all but the second scenario. As mentioned in the introduction, dust fluxes for grains in the size range 0.5–2 μm fluctuate with the solar activity cycle and in particular at high latitude. Moreover, tiny grains (<0.1 μm) might be trapped in CMEs. Therefore if the tiny grains contribute a significant amount to the inner source PUI production, we should observe differences between solar minimum and maximum, particularly at high latitudes.

[29] In summary, our observations show that the inner source pickup ions appear stable over half a solar cycle. The inner source also shows composition like the solar wind and produces a remarkably large pickup ion flux. These facts suggest inconsistencies with the current picture of heliospheric grains and their interactions with solar wind.

[30] The most likely scenario, consistent with the majority of the constraints discussed above, is that inner source pickup ions are generated near the Sun by the interaction of the solar wind with dust grains. Nevertheless, the detailed source process remains unclear. Are inner source PUIs produced from nanometer-sized or micrometer-sized grains? Table 3 lists candidate sources and their relation to the five inner source constraints. With our current knowledge of grain-particle interactions, none of the proposed sources appear to satisfy all the constraints.

[31] The difficulty in explaining the inner source underscores our need for new laboratory and in situ measurements to better understand the interaction of charged particles with dust grains. For example, ion sputtering and storage-release are processes that work simultaneously, but their time-dependence and relative efficiency are unclear. In situ measurements (dust and particles) close to the Sun (i.e., on the Solar Probe mission presently under study) would provide direct detection of the grain population that produces inner source PUIs.

[32] **Acknowledgments.** This work was supported by NSF grant 0100659 for research on implications of near solar source pickup ions, the NASA Ulysses program, and an Internal Research grant from the Southwest Research Institute. The authors would like to thank Dan Boice, Heather Elliott, Walter Huebner, Eberhard Möbius, Arik Posner, and Robert Wimmer-Schweingruber for their valuable comments on this topic.

[33] Shadia Rifai Habbal thanks Eberhard S. Moebius and another referee for their assistance in evaluating this paper.

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