Dust in the wind: The dust geometric cross section at 1 AU based on neutral solar wind observations

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Abstract. We report observations of the neutral component of the solar wind from the Low Energy Neutral Atom (LENA) imager on the NASA IMAGE spacecraft from year 2001. There is a pronounced annual modulation of the neutral solar wind, and the flux outside of the upstream region is used to place an upper limit on the dust geometric cross section in the sunward direction at 1 AU of $\Gamma^{1AU} < 6\text{x}10^{-19}$ cm^{-1}. This value agrees with inferences made from the zodiacal light.

INTRODUCTION

Because solar wind charge-state distributions are "frozen in" close to the Sun, they reflect high (ionization) temperatures ($> 10^6$ K) [1]. Consequently, a negligible fraction of the solar wind is expected to be neutral based on equilibrium charge state distributions. Yet, the solar wind is not completely ionized. Our observations at 1 AU indicate that a substantial ($\sim 10^{-5} - 10^{-3}$ fractionally) neutral component of the solar wind enters the Earth's magnetosphere at all times. This neutral solar wind forms between the Sun and the orbit of the Earth from solar wind ions exchanging charge with matter in this region.

There are three major sources of neutral solar wind: the Earth's geocorona, interstellar neutrals, and dust in the inner solar system. The Earth's geocorona extends far beyond the magnetopause and drops off rapidly with distance from the Earth [2]. So when the solar wind dynamic pressure increases dramatically, large fluxes of solar wind neutrals are created due to solar wind charge exchange with neutral hydrogen atoms surrounding the Earth but outside of the magnetopause. This mechanism for forming neutral solar wind was first discussed by *Dessler et al.* [3] in 1961 who considered it a potential source of background for observations of the energetic neutral atom flux resulting from proton ring current decay induced by charge exchange with hydrogen atoms.

Neutral solar wind may also form by solar wind protons exchanging charge with interstellar neutrals, a gas of mostly hydrogen and helium atoms streaming through the heliosphere at about 25 km/s coming from a point such that the Earth is upstream of the Sun in the neutral flow in early June each year (Specifically, the downstream flow direction is at a heliographic longitude of 74° so that the Earth is upstream on June 2 each year [4]). Because the interstellar neutral hydrogen becomes depleted due to photoionization and charge exchange with the solar wind, a one to three order of magnitude annual variation is expected in the neutral solar wind flux observed at the Earth as it moves from upstream, where the interstellar and solar wind neutral hydrogen fluxes are high, to downstream, where they are low [5]. *Fahr* [6] and *Hundhausen et al.* [7] both pointed out in 1968 that solar wind protons would charge exchange with neutral hydrogen near the Sun and produce a neutral solar wind.

Dust in the inner solar system is a source of neutrals for solar wind charge exchange close to the Sun [8]. The best-known effect of this dust is the zodiacal light, discovered and correctly identified by Cassini in 1683 as being due to sunlight scattered off small particles orbiting the Sun. The size range of these particles is from below one to more than 100 μm. The dust in the inner solar system, at least, is thought to originate primarily from comets and asteroids [9]. There are two possible mechanisms for dust to generate neutral solar wind shown in Figure 1. In the top panel, solar wind ions saturate the dust particles which later release neutral atoms that subsequently charge exchange with solar wind protons creating a neutral solar wind [10]. In the bottom panel, solar wind ions traverse small dust particles and

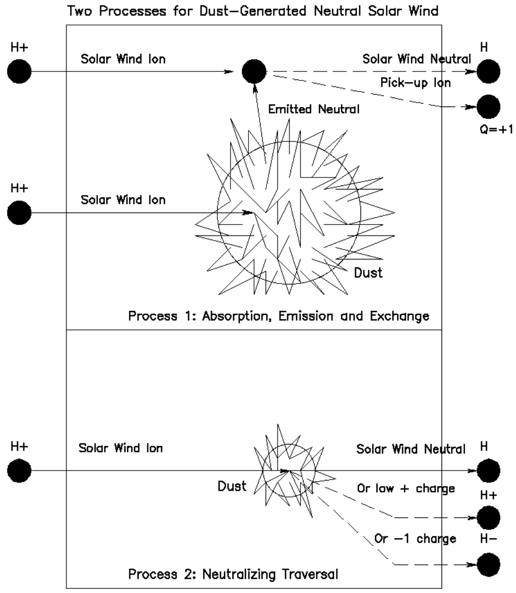

FIGURE 1. Dust creates solar wind neutrals either through a process of absorption, re-emission, and charge exchange or through a solar wind ion penetrating the dust grain and emerging on the other side in a neutral state.

emerge neutral or in low charge states [11][1].

NSW OBSERVATIONS DURING 2001

The neutral solar wind (NSW) was observed for the first time by the Low Energy Neutral Atom (LENA) Imager on the polar orbiter, IMAGE [13, 14].

Figure 2 shows the neutral solar wind flux as observed by LENA during the year 2001 [15]. The observations were taken during the hour around apogee ($\sim$ 8 R_E) on each orbit (about every 14 hours) and cover slightly more than half the year (days 43-143 and 230-330) because LENA has the Sun in its $\sim$90° field-of-view only about half the time.

The data illustrate the three different sources of neutral solar wind: The spike on day 90 (31 March 2001) is due to solar wind charge exchange with the Earth's geocorona during a period when the solar wind ram pressure was unusually high and the terrestrial magnetopause was highly compressed [16]. The broad peak beginning about day 120 and lasting until about day 250 occurs when the Earth is upstream of the Sun in the interstellar neutral

[1] This is analogous to the behavior of ions penetrating the thin carbon foils used in time-of-flight instrumentation. More energetic ($\sim$50 keV) neutrals resulting from ions penetrating dust in Saturn's rings have been considered by Mauk et al. [12]

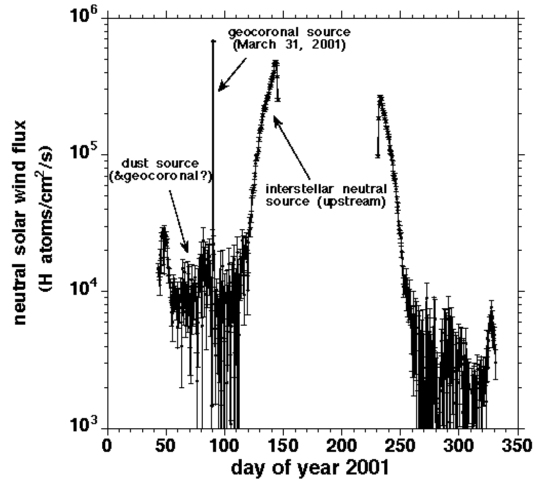

FIGURE 2. Neutral solar wind fluxes observed at IMAGE apogee during year 2001 illustrate the three major sources of neutral solar wind. Error bars indicate statistical uncertanties.

flow and a larger fraction of the interstellar neutrals penetrate to inside of 1 AU and charge exchange with the solar wind. It should be noted, however, that this peak may not be due to direct charge exchange with the $\sim$25 km/s interstellar neutrals but rather with a higher energy component that began as interstellars, e.g. neutralized pick up ions [17]. Finally the more uniform background flux between about $2x10^3$ and $2x10^4$/cm^2/s is due primarily to solar wind charge exchange with dust or dust-generated neutral atoms with probably a geocoronal contribution, as well. However, note that the uniform background does appear to have systematic variations in it of about a factor of two near the center and edges which are consistent with the degree of variability observed during calibration in the polar angle response. In addition, the LENA efficiency may have trended downward in the latter part of 2001, perhaps the result of sputtering agents on the tungsten surface becoming depleted.

THE DUST GEOMETRIC CROSS SECTION AT 1 AU

We consider a quantity called the dust geometric cross section (Γ), which is the dust density times the effective cross section of a dust particle. This may be thought of as the total cross-sectional area per unit volume or, equivalently, the probability per unit length, for small distances, a solar wind proton will interact with the dust, either by being absorbed, as in process 1, or traversing the dust, as in process 2 (see Fig. 1). The rate, then, at which a solar wind proton will be absorbed by dust is the

TABLE 1. Inferences of the dust geometric cross section at 1 AU based on various measurement techniques

Observation Method	Γ^{1AU} **(cm^{-1})**	**reference**
Zodiacal light observations	$10^{-21} - 2.0\text{x}10^{-19}$	[10]
Rocket and satellite data	$3.8\text{x}10^{-18}$	[10]
Thermal emission of the F corona	$8.0\text{x}10^{-18}$	[10]
He^{+} in the solar wind	$6.5\text{x}10^{-17}$	[10]
Balmer emissions	$3.8\text{x}10^{-17}$	[10]
Micro-craters and in-situ	$4.6\text{x}10^{-21}$	[9]
Inner source pickup ions	$> 1.3\text{x}10^{-17}$	[18]
Neutral solar wind observations	$< 6\text{x}10^{-19}$	this work

solar wind speed times Γ. Multiplying by the solar wind number density gives the volumetric rate of solar wind interaction with the dust: $n_{sw}v_{sw}\Gamma = \Phi_{sw}\Gamma$, where Φ_{sw} is the solar wind flux $\sim 3\text{x}10^8/\text{cm}^2/\text{s}$.

We take the dust density to decrease with distance from the Sun as $1/\text{r}$ [19, 20] (which is a theoretically based slope although *Helios* observations place the fall-off close to this at $1/\text{r}^{1.3}$ [8]) and the solar wind density to decrease as $1/\text{r}^2$. We can then relate the volumetric rate of solar wind absorption to 1 AU quantities

$$\Phi_{sw}\Gamma = \Phi_{sw}^{1AU}\Gamma^{1AU}(r_0/r)^3, \qquad (1)$$

where r_0 is 1 AU.

In either of the two processes shown in Fig. 1, the rate of neutral solar wind creation in steady state will be roughly the rate of solar wind absorption given by (1). In the case of process 1, absorption, emission, and charge exchange, this neglects the probability that an emitted neutral will become photoionized, which occurs at a much lower rate than charge exchange [21]. In the case of process 2, neutralizing traversal, this neglects both the probability that an emitted neutral will be photoionized as well as the probability that it will emerge in a low positive charge state or with a charge -1. However, the ions that emerge as ions after traversing the dust may proceed to interact with a second dust particle and those emerging with charge -1 may be neutralized soon thereafter.

To a good approximation, then, (1) represents the source term for the dust-generated neutral solar wind and continuity dictates

$$\frac{\partial \rho_{NSW}^{dust}}{\partial t} + \nabla \cdot (\rho_{NSW}^{dust}\mathbf{v}_{sw}) = \Phi_{sw}^{1AU}\Gamma^{1AU}\left(\frac{r_0}{r}\right)^3, \qquad (2)$$

which in steady-state is

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\Phi_{NSW}^{dust}) = \Phi_{sw}^{1AU}\Gamma^{1AU}\left(\frac{r_0}{r}\right)^3. \qquad (3)$$

Integrating from $10R_\odot$, taken because from this point on the assumptions made about the solar wind density drop and constant velocity are valid, to 1 AU, we get

$$\Phi_{NSW}^{dust}(1\text{ AU}) = \Phi_{sw}^{1AU}\Gamma^{1AU} \cdot 4.6\text{x}10^{13}\text{ cm}. \qquad (4)$$

Taking a typical value for the dust-source neutral solar wind of 8300 $/\text{cm}^2/\text{s}$ from the 2001 neutral solar wind data shown in Fig. 2, and applying (4) we get

$$\Gamma^{1AU} = 6\text{x}10^{-19}\text{ cm} \qquad (5)$$

for the total dust geometric cross section at 1 AU. Since this assumes that the observed neutral solar wind flux is due solely to dust-generated neutrals, it should probably be viewed as an upper limit on Γ, although the assumptions discussed above in deriving (2) will tend to somewhat lower the estimate of Γ, mitigating the error introduced by the geocoronal contribution to the neutral solar wind flux.

DISCUSSION

This value, $\Gamma^{1AU} < 6\text{x}10^{-19}\text{ cm}^{-1}$, provides a useful upper limit because of the large uncertainty in measurements of dust in the inner solar system. As indicated in Table 1, measurements of the total geometric cross section at 1 AU vary from 10^{-21} through $6.5\text{x}10^{-17}\text{ cm}^{-1}$, about four to five orders of magnitude.

This upper limit is consistent with the zodiacal light observations, but is significantly lower than the other determinations and, interestingly, our upper limit is lower than the lower limit of *Schwadron et al.* [18]. Although it is unclear why this should be the case, the determinations depend critically on the measurement technique, perhaps because the various techniques are sensitive to dust in different size ranges.

This value is estimated at one phase in the solar cycle. The zodiacal light brightness does not appear to vary with solar cycle suggesting that the dust-generated neutral solar wind will not vary with solar cycle either [22]. However, even if the dust distribution is steady, the variability of the solar wind may cause some variation in the dust-generated neutral solar wind. Although this number contains a contribution from interstellar dust, this contribution is small in comparison to interplanetary dust, about 4% [23, 24], and exhibits a different spatial distribution, in particular, the presence of a downstream focussing cone [25].

One concern with this estimate involves the assumption that the contribution due to dust is close to azimuthally symmetric. The dust population may not be azimuthally symmetric or may deviate from a plane as was concluded by *Vrtilek and Hauser* [26]. However, there do not appear to be structures in zodiacal light measurements of the scale of $10^5 - 10^6$ km [20].

CONCLUSION

The properties of dust in the inner solar system and of the interaction of the solar wind with the interplanetary dust play a key role in understanding the origin of inner source pickup ions [27] and in determining the contribution of the interstellar neutral and geocoronal sources to the neutral solar wind. Solar wind-dust interaction was undoubtedly even more important during earlier, dusty periods in the solar system and may be of paramount importance near stars surrounded by very dense dust clouds [10].

Neutral solar wind observations provide a powerful and new probe of the cloud of interplanetary dust particles that pervades our solar system. This technique is not apparently sensitive to the size of interplanetary dust particles, requiring only that a solar wind ion interacts with a dust particle, which provides an advantage over other observational methods that are restricted to dust particles within certain size ranges [8].

ACKNOWLEDGMENTS

Special thanks to Melvyn Goldstein without whom this manuscript would not have materialized. Special thanks also to Ed Roelof, David McComas and Martin Hilchenbach for very helpful conversations during the meeting. This research is supported by the Explorer Program at NASA's GSFC under Mission Operations and Data Analysis UPN 370-28-20.

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