flow conditions for three species during the current extended solar minimum. Any temporal variations of these conditions are of a much longer time scale than the observation period presented here. These observations provide constraints on the interstellar flow parameters and the interaction of the interstellar flow with the heliospheric boundary. Together with future observations during different solar activity, they also constrain the ionization rates of these species and the solar radiation pressure for H.

References and Notes

Imaging the Interaction of the Heliosphere with the Interstellar Medium from Saturn with Cassini
S. M. Krimigis,1,2,* D. G. Mitchell,3 E. C. Roelof,4 K. C. Hsieh,3 D. J. McComas4,5

We report an all-sky image of energetic neutral atoms (ENAs) >6 kilo–electron volts produced by energetic protons occupying the region (heliosheath) between the boundary of the extended solar atmosphere and the local interstellar medium (LISM). The map obtained by the Ion and Neutral Camera (INCA) onboard Cassini reveals a broad belt of energetic protons whose nonthermal pressure is comparable to that of the local interstellar magnetic field. The belt, centered at ~260° ecliptic longitude extending from north to south and looping back through ~80°, appears to be ordered by the local interstellar magnetic field. The shape revealed by the ENA image does not conform to current models, wherein the heliosphere resembles a cometlike figure aligned in the direction of Sun’s travel through the LISM.

The quest for the dimensions and shape of the bubble of plasma called the heliosphere, created by the continuously flowing solar wind as the Sun travels through the LISM, is older than the space age (1). Estimates of the distance to the boundary in the general direction of the solar apex have ranged from a few astronomical units (1 AU equals the distance between Earth and Sun, 150 million km) to tens of AU (2–4). Voyager 1 and 2 (V1 and V2) crossed the termination shock (TS) at distances of 94 and 84 AU in 2004 and 2007 at +35° and −26° ecliptic latitudes, respectively [e.g., (5–7)], implying that the radial dimensions of the TS are different in time and/or location. More surprisingly, the shocked thermal plasma in the heliosheath remained supersonic because only 20% of the upstream energy density went into heating the downstream thermal plasma, while most of the rest went into heating pickup ions (PUI), including a substantial part (≥15%) going into protons >28 keV (6, 7). PUI are interstellar neutrals that are ionized in the solar wind and picked up and accelerated to energies >1 keV by the flow (8).

The prevailing models of the shape of the heliosphere suggest a comet-like interaction (Fig. 1) with a possible bow shock and/or heliopause, heliosheath, and TS, all foreshortened in the direction of motion of the solar system through the LISM (3, 9). Energetic singly charged particles in the heliosheath will charge-exchange with interstellar neutral hydrogen and enter the heliosphere as ENAs unimpeded by the interplanetary magnetic field [e.g., (10, 11)].

Launch of the ENA imager on the Cassini-Huygens mission to Saturn occurred in October 1997. The Cassini spacecraft spent nearly 7 years in interplanetary cruise with sporadic data coverage before insertion into orbit at Saturn on 1 July 2004. Because the principal objective of the Ion and Neutral Camera (INCA) instrument (12) (fig. S1) is to image the energetic plasma ions trapped in Saturn’s magnetosphere through ENAs, it took several years to obtain a nearly full image of the heliosphere in directions away from Saturn, with a minor gap in the direction of the Sun. In October 2008, Interstellar Boundary Explorer (IBEX) was launched with ENA cameras specifically designed to map the heliospheric boundary at lower (<6 keV) energies (13, 14).

Fig. 1. Conventional concept of the heliosheath [(adapted from (3)]: The Sun is at the center, the region of the supersonic solar wind being asymmetric and compressed in the direction facing the interstellar wind flow (nose). Beyond the TS, the solar wind is expected to become subsonic and flow into the wake of the solar system, forming a cometlike tail.

*To whom correspondence should be addressed. E-mail: tom.krimigis@jhuapl.edu
the range $-30^\circ$ to $-150^\circ$ and then loops back to recross the equator again at longitudes $-50^\circ$ to $-110^\circ$, albeit at a lower intensity. Also, there are statistically significant enhancements in the intensity as the belt loops toward both north and south ecliptic poles. It is similar to, but broader than, the ribbon seen at lower ($<6$-keV) energies in the IBEX images (14). However, there is no maximum in the direction of the local interstellar flow (nose) at about $-100^\circ$, as anticipated from the model shown in Fig. 1. The lower intensities in the direction of the anticorrelated tail at $-90^\circ$ longitude are less organized. The intensities in the directions of V1 and V2 are slightly lower than those at the belt maximum.

Plotted in galactic coordinates (Fig. 2B), the belt of higher intensities now lies within $\pm60^\circ$ of the galactic equator, being tilted $-30^\circ$ toward north and south at positive and negative longitudes, respectively. The two intensity minima discussed earlier are now identified with the galactic north and south poles, although their boundaries are also tilted $-30^\circ$ to the galactic equator. Although most x-ray, ultraviolet, and extreme ultraviolet radiation sources reside close to the galactic plane, a detailed study of the most intense ultraviolet radiation sources resides close to the belt maximum. The intensities are less organized. The intensities in the belt loops toward both north and south ecliptic poles. It is similar to, but broader than, the ribbon seen at lower (<6-keV) energies in the IBEX images (14). However, there is no maximum in the direction of the local interstellar flow (nose) at about $-100^\circ$, as anticipated from the model shown in Fig. 1. The lower intensities in the direction of the anticorrelated tail at $-90^\circ$ longitude are less organized. The intensities in the directions of V1 and V2 are slightly lower than those at the belt maximum.

We evaluated the role that the nonthermal energetic ion pressure in the heliosheath (estimated from the observed ENAs) plays in the dynamics of the interaction with the LISM. The intensity ($\text{JA}$) measured by INCA for ENAs with velocity ($v$) is given by the line-of-sight (LOS) integral beyond the TS ($r_0$) through the heliosheath of the product of interstellar H-atom density ($n_H$) and the energetic intensity ($\text{JA}$) multiplied by the charge-exchange cross section ($\sigma^{(10)}$)

$$j_{\text{JA}}(v,t + r_0/v) = \sigma^{(10)} \int_{r_0}^{\infty} d\nu n_H(r - v\nu)j_{\text{JA}}(r - v\nu,t)$$

$$t \geq 0$$

We could rewrite the integral as

$$j_{\text{JA}} = \left(\sigma^{(10)} n_0 / j_0\right) L_{\text{ion}}$$

where $n_0 / j_0$ is the average value of the product of the density and intensity ($n_0 / j_0$) over some radial interval ($r_0$ to $r_0 + L_{\text{ion}}$), presumably beyond the TS that contains the bulk of the energetic ion population. This allows us to convert the measured $j_{\text{JA}}$ into a proton intensity averaged over a radial interval $L_{\text{ion}}$ beyond the TS.

$$j_0 = j_{\text{JA}} / \left(\sigma^{(10)} n_0 / j_0\right)$$

Figure 2C shows ENA spectra at key locations identified in Fig. 2, A and B. Proton spectra (Eq. 3) are derived by normalizing the intensity of the highest ENA energy channel (~45 keV) to the overlapping Voyager 1 proton channel (~46 keV), making in situ measurements in the heliosheath at 110 AU. We find that $j_0 = 80 j_{\text{JA}}$ at V1. By assuming that $n_H \sim 0.1$ cm$^{-3}$ and using the known value of $\sigma^{(10)} (\sim 2.32 \times 10^{-16}$ cm$^2$) at that energy, we find that $L_{\text{ion}} \sim 36$ AU or $n_H L_{\text{ion}} \sim 3.6$ AU cm$^{-3}$ for any other choice of $n_H$. The value for $L_{\text{ion}}$ may well be different at other locations along the belt, and various assumptions on averaging can change it by up to $-40\%$; we adopt a representative value of 50 AU. The ENA spectra have a power-law slope of $-E^{-4}$, whereas the resulting ion spectrum is substantially less steep because of the energy dependence of the cross sections, and it joins smoothly with the V1 slope of $-E^{-1.5}$ at $>40$ keV. The ENA spectrum overall has the same slope, irrespective of locations marked on the map shown in Fig. 2A. A calculation of the spectral index over every pixel in the entire map gives the same slope throughout to within $5\%$.

Having converted the ENA intensities into equivalent ion intensities beyond the TS, we computed the partial plasma pressure at $>6$ keV, a range where many of the PUIs associated with the TS and heliosheath are expected to reside. The partial pressure $\Delta P$ is given by

$$\Delta P = (4\pi / 3) n_0 \Delta E$$

where $n_0$ is proton density and $\Delta E$ is the energy width of each INCA channel. This becomes

$$\Delta P(p\text{Pa}) = (7.47 \times 10^4) v (\text{km s}^{-1}) \times j_{\text{JA}} \Delta E (\text{cm}^2\text{sr s}^{-1}) / \sigma^{(10)} n_0 L_{\text{ion}}$$

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**Fig. 2.** (A) Image of heliospheric ENAs in the range of 5.2 to 13.5 keV (data from day 265, 2003, to day 184, 2009) plotted in ecliptic coordinates. The location of local interstellar flow (nose), its opposite (tail), solar apex (5A), and anti-solar apex (5A), as well as the positions of Voyager 1 and 2 in the heliosheath are marked; the local ISMF direction (16, 17) is indicated. Gray-shaded areas centered at about $-70^\circ$ longitude, $0^\circ$ latitude and at about $-120^\circ$ longitude, $-40^\circ$ latitude are regions of incomplete coverage in the directions of the Sun and Saturn, respectively. (B) The same data plotted in galactic coordinates. (C) ENA spectra of INCA data over the energy range 5.2 to 55 keV (lower grouping) and derived proton spectra (upper grouping) from selected locations shown in (A). Horizontal bars indicate the INCA energy channel limits for hydrogen ENAs.
with the pressure expressed in picopascals. Thus, our measurable quantity is the product \( n_0 u_{\text{spec}} A P \) for each channel; its sum over all INCA channels is shown in Fig. 3 in ecliptic coordinates (Mercator projection). Its distribution is similar to the ENA intensity profile shown in Fig. 2A, as would be expected. The total INCA partial pressure (assuming \( L_{\text{out}} \sim 50 \) AU) ranges from 0.02 to 0.09 pPa. The in situ measurements (40 keV to 4 MeV) from Voyager 1 near the brightest part of the belt add another \( \sim 0.02 \) pPa (6). When the IBEX-derived pressure (14) of protons 0.2 to 6 keV (0.2 pPa) is added in, the total nonthermal pressure above 0.2 keV becomes larger than 0.31 pPa, exceeding the hydrostatic pressure \( (B^2/2\mu_0) = 0.25 \) pPa for a 0.25-nT interstellar magnetic field (ISMF).

The ram pressure of the interstellar flow (with a proton density of 0.1 cm\(^{-3}\)) is 0.11 pPa. This is less than half of the pressure of the ISMF, which is why the signature of the ISMF shows up as the dominant one in the ENA images; the interstellar flow produces secondary effects in terms of dynamics compared with the nonthermal pressure of the energetic protons in the heliosheath interacting with the ISMF. This implies that the nonthermal pressure of >0.2-keV protons dominates the configuration of the heliopause through their interaction with the local ISMF.

There was an alternative model to the one shown in Fig. 1, where the termination-shocked plasma generates a partially closed diamagnetic “bubble” in which a strong local ISMF interacts directly and dynamically with the subsonic outflow (15). This model neglects the ram pressure of the interstellar plasma in favor of the thermal pressure of the heated plasma downstream of the heliospheric TS. The particle pressure interacts directly with the Maxwell stresses \( \mathbf{J} \times \mathbf{B} \) of the interstellar field to produce the diamagnetic bubble. We have modified this model by replacing the shock-heated thermal pressure at the TS with the ENA-inferred nonthermal proton pressure that fills the heliosheath from the TS to the heliopause, thus moving the interaction with the ISMF from the TS to the heliopause (Fig. 4). The directions to the belt correspond approximately to the locations where the ISMF is normal \( \mathbf{N} \) to the heliopause \( \mathbf{B} \times \mathbf{N} \equiv 0 \) (16). This simple concept of the dominant interaction provides an immediate quantitative explanation of the dominant topological feature (the ribbon or belt) in the ENA images obtained from both IBEX and INCA.

**Fig. 3.** Pressure contributed by protons beyond the TS computed from spectra deduced from the ENA observations in pPa \((1 \text{ pPa} = 10^{-11} \text{ dynes cm}^{-2})\). The thickness of the heliosheath is estimated to be \( \sim 50 \) AU.

**Fig. 4.** Annotated summary of basic findings from the ENA maps of the heliosheath; the dominant interaction between the nonthermal heliosheath pressure with the ISMF tends to produce a diamagnetic bubble, as envisioned by Parker (15), who neglected the effects of the ram pressure of the interstellar plasma. It is very different from the contemporary paradigm (Fig. 1).

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**References and Notes**

18. We are grateful to M. Kusterer, S. Turner, J. Aiello, and R. DeMajistre for assistance in the data reduction and analyses efforts of Cassini and the Magnetospheric Imaging Instrument in general and this work in particular. Discussions with R. B. Decker are most appreciated. The work at the Johns Hopkins University Applied Physics Laboratory was supported by NASA under contracts NASS-97271 and MX07A096G and by subcontract at University of Arizona; the work at the Southwest Research Institute was supported by the NASA IBEX contract.

Supporting Online Material

www.sciencemag.org/cgi/content/full/1181079/DC1

SOM Text

Fig. S1

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Published online 15 October 2009; accepted 5 October 2009

25 August 2009; accepted 5 October 2009

Include this information when citing this paper.