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SOLAR SYSTEM FRONTIER:
EXPLORING THE HELIOSPHERIC INTERFACE FROM 1 AU

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ABSTRACT
The region where the expanding solar wind meets the surrounding galactic medium remains poorly explored. The structure of and the physical processes at this solar system frontier – the heliospheric interface – are of fundamental importance for understanding the interaction of our star, the Sun, with the galactic medium. This region also needs to be charted for optimizing our first foray into interstellar space by the Interstellar Probe mission and for supporting the truly interstellar exploration of the future. The present concepts of the heliospheric interface are based on scarce and mostly indirect experimental data and limited by the technical difficulties and budgetary realities of sending space probes to this distant region. In addition, the sheer size of the essentially asymmetric heliosphere calls for remote techniques to probe its global three-dimensional properties. We describe two experimental approaches for probing the solar system frontier from 1 AU. Imaging in fluxes of energetic neutral atoms (ENAs) will determine the nature of the termination shock and the properties of the solar plasma in the heliospheric sheath. Then, imaging of the heliosphere in extreme ultraviolet (EUV) will map the heliopause. NASA recently selected a new dedicated space mission to image the heliosphere in ENA fluxes. The efforts in EUV mapping of the heliopause presently focus on development of the mission concept and enabling instrumentation.

Keywords: Heliosphere, heliopause, interstellar medium, ENA, EUV.

INTRODUCTION
The interaction of the expanding solar wind plasma with the surrounding galactic medium – Local Interstellar Medium (LISM) – creates the heliosphere.[1-4] The heliosphere is a complex phenomenon where the solar wind and interstellar plasmas, interstellar gas, magnetic field, and energetic particles all play important roles.[5-8] The region where the solar wind meets the galactic medium remains poorly explored. The structure of and the physical processes at this solar system frontier – the heliospheric interface – are of fundamental importance for understanding the interaction of our star, the Sun, with the galactic medium. This region also needs to be charted for optimizing our first foray into interstellar space by the Interstellar Probe mission and for supporting the truly interstellar exploration and interstellar travel of the future.

A possible two-shock Sun-LISM interaction scenario[5] illustrates the main features of the heliosphere (Fig. 1). The interstellar wind approaches the heliosphere with a supersonic velocity and forms a bow shock. The dynamic pressure of the expanding, highly supersonic solar wind decreases with the heliocentric distance. At a certain distance from the Sun, this pressure would equal the external LISM pressure of the interstellar wind and magnetic field. The solar wind expansion transitions to a subsonic flow at the termination shock. There the kinetic energy of the supersonic flow is largely converted into thermal energy in the subsonic plasma beyond the shock. The subsonic postshock solar wind plasma (Fig. 1, left) flows in the heliospheric sheath around the termination shock and down the heliospheric tail, where it eventually mixes with the interstellar galactic plasma at distances >5000 AU.[9] The galactic plasma (Fig. 1, right) flows around the heliopause, the boundary separating solar galactic plasmas; interstellar neutral atoms penetrate the heliosphere, some reaching the Sun's vicinity at 1 AU.

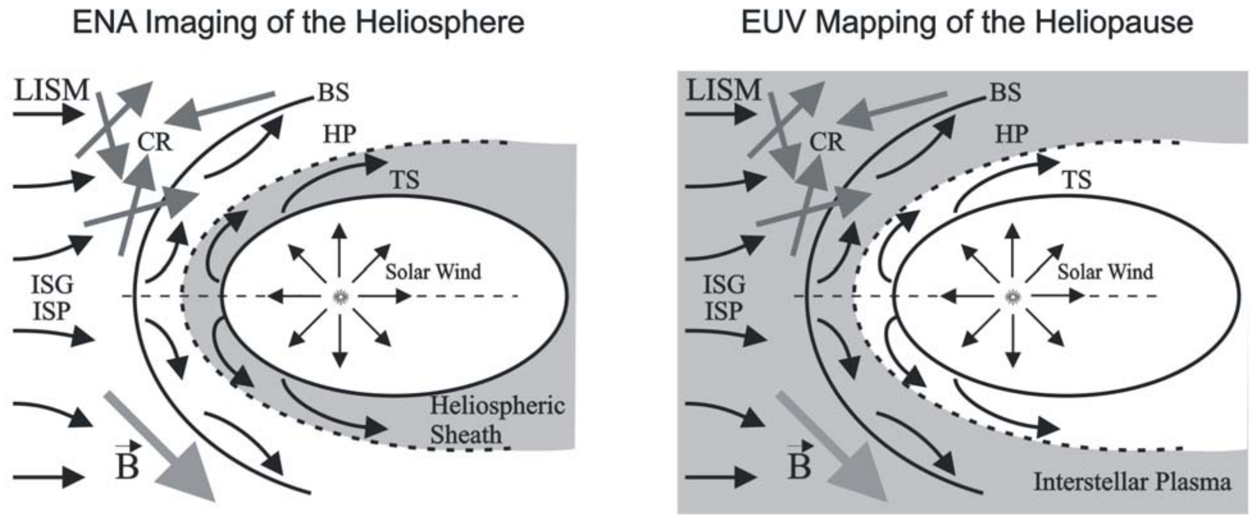

Figure 1. Two-shock model of the interaction of the solar wind with the local interstellar medium. LISM – local interstellar medium; TS – termination shock; HP – heliopause; BS – bow shock; CR – cosmic rays; ISP(G) – interstellar plasma (gas); B – magnetic field. Left: the heliospheric sheath – the region (gray) between the termination shock and the heliopause – contains the postshock subsonic solar wind plasma and pickup protons. The ions produce energetic neutral atoms (ENA) and the heliospheric sheath will be remotely probed by imaging in ENA fluxes. Right: interstellar plasma (gray) flows around the heliopause; the heliopause will be mapped and the plasma flow beyond probed by imaging in EUV.

The present concepts of the heliospheric interface are based on scarce and mostly indirect experimental data and limited by the technical difficulties and budgetary realities of sending space probes to this distant region. The termination shock and the heliopause are believed to be somewhere at 100 and 150 AU from the Sun, respectively, in the upwind direction. Inconsistent interpretations of the recent observations[10,11] by Voyager 1 at 80-95 AU have clearly revealed the limitations of our present concepts and models of the solar wind termination. Voyager's radioisotope thermoelectric generators can support spacecraft operations till 2020, when it reaches 150 AU.

Three fundamental factors make the heliosphere essentially asymmetric: (1) the motion of the sun with respect to the surrounding interstellar medium, the interstellar wind; (2) asymmetry of the solar wind flow in heliolatitude;[12] and (3) interstellar magnetic field of the unknown magnitude and direction. If Voyager 1 crosses the termination shock and reaches the heliopause, the shape of the heliosphere and directional variations of the nature of the heliospheric sheath and processes therein will still remain unknown. Only remote techniques, supported by the "ground-truth" in-situ measurements by Voyager and future Interstellar Probe spacecraft, will enable a comprehensive exploration and "putting on the maps" the solar system galactic frontier. The sheer size of the essentially asymmetric heliosphere calls for remote techniques to probe its global three-dimensional properties.

Several experimental techniques indirectly probed the heliospheric interface region: measurements of interplanetary glow at 121.6 and 58.4 nm, pickup ions in the solar wind, cosmic rays, and anomalous cosmic rays; direct detection of interstellar helium atoms; and spectroscopic observations of nearby stars and interstellar medium. All these phenomena either depend in a weak way on the properties of the three-dimensional heliospheric interface or are sensitive to the interface structure in the upwind (interstellar wind) direction only. The available experimental data are indirect and require use of complex modeling, with many fundamental assumptions not verified experimentally, for inferring the processes at the solar system frontier.

Two main concepts have emerged to remotely sense the heliospheric interface; they rely on emissions originating at the solar system frontier and reaching the observer at 1 AU with little disturbance. First, heliosphere imaging in fluxes of energetic neutral atoms (ENAs) will probe the plasma properties in the heliospheric sheath between the termination shock and the heliopause (Fig 1, left). A concept of ENA imaging of the heliospheric interface originated in early 1980s.[13-14] Today, the concept[15] and instrumentation[16,17] are mature and NASA selected in January 2005 a dedicated mission, Interstellar Boundary Explorer (IBEX),[18] to perform heliosphere ENA imaging. The second concept to map the heliopause and explore the flow of interstellar plasma around the solar system (Fig.1, right) was formulated in 1990s.[19-22] Heliopause mapping in extreme ultraviolet (EUV) requires advancing of the instrumentation state-of-the-art by a factor of 100, which is presently being pursued.[21-23]

1. HELIOSPHERE IMAGING IN FLUXES OF ENERGETIC NEUTRAL ATOMS

What happens exactly at the solar wind termination and how the energy of the solar wind plasma is partitioned in the heliospheric sheath among various plasma components are not known. The laws of conservation suggest in a fundamental, model-independent way that heliospheric ENAs would reach the inner heliosphere. The supersonic expansion of the solar wind has to slow down and transform into a subsonic flow because of the finite pressure of the interstellar medium surrounding the solar system. This slowing down, through a shock transition or otherwise, would result in two effects. First, some of the kinetic energy of the supersonic solar wind would transform into energy of the thermal motion of plasma particles and/or into energization of some type(s) of charged particles. Some plasma protons would thus reach, after charge exchange in the heliospheric sheath, the inner heliosphere as ENAs. Second, the slowing down of the solar wind would shift (in the velocity space) the distribution of the solar wind pick up protons, and some of these protons would reach, after charge exchange, the inner heliosphere as ENAs. This unavoidable presence of heliospheric ENAs in the inner heliosphere consequently enables the probing of the nature of the physical processes at and beyond the termination shock through ENA global imaging.[15,16,18,24]

The concept of heliospheric ENAs can be traced back to 1960s (see review[16]). The presence of atomic hydrogen in interplanetary space was first derived in 1963 from sounding rocket measurements of Doppler-broadened hydrogen at 121.6 nm. The emerging concept of the heliosphere[25] was extended in 1963 by the suggestion that about half of the solar wind protons would reenter the solar cavity in the form of hydrogen ENAs (with 3/4 of the initial solar wind velocity) as a result of processes at and beyond the solar wind termination region.[26] It was established later the observed optical signature of hydrogen was produced by resonant scattering of the solar radiation by interstellar gas directly entering the solar system. The postulated "returning" neutral solar wind flux[26] is significantly smaller and highly anisotropic.[24] This pronounced anisotropy[24] actually pointed to ENA imaging as a technique highly-sensitive to the details of the interaction and processes at the solar system frontier.

ENAs with energies between 200 eV and a few keV are of most interest for heliosphere imaging.[15,16] Global ENA images in this energy range promise to reveal the strength of the termination shock and discover what happens with the solar wind pickup protons (10-20% of the solar wind near the heliospheric interface) at the termination shock and beyond in the heliospheric sheath.[15] The all-sky (4π) ENA images are expected to be strikingly different depending on what exactly happens at the solar wind termination. Figure 2 shows two such images for two physically different possibilities of a strong gasdynamical shock and a weak shock with pickup protons preserving their velocity distribution function.[15]

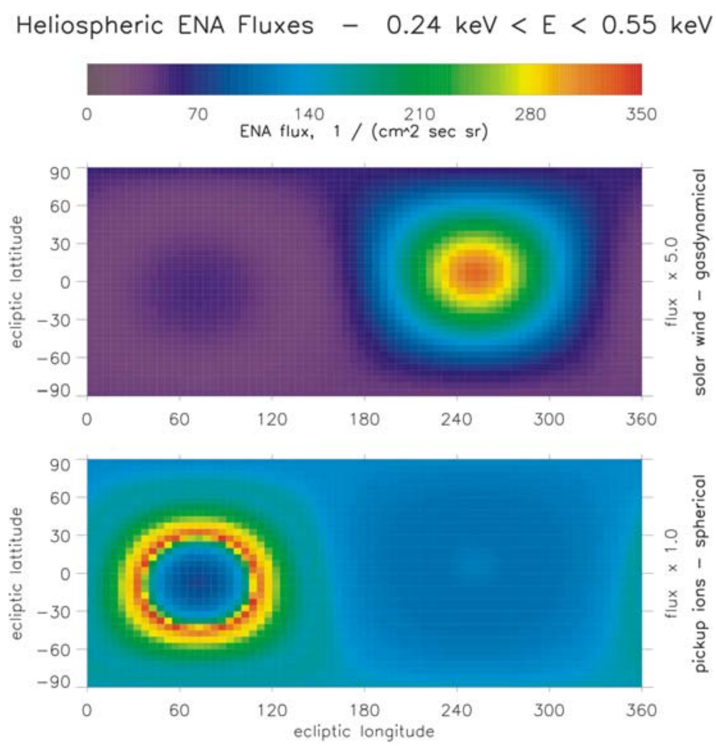

Figure 2. Simulated all-sky ENA images[15] in the 0.24-0.55 keV energy band for (top) a strong gasdynamical shock and (bottom) a spherical isotropic solar wind pickup proton population without thermalization and without cooling. Note that the fluxes are multiplied by 5.0 and 1.0 for the top and bottom panels, respectively, to fit into the same color scale.

Energetic neutral atoms with energies from a few hundred eV to several keV can be conveniently and reliably detected by secondary electron multipliers. The main obstacle for ENA detection is the background flux of photons in the heliosphere, predominantly at 121.6 nm. This flux ranges from 500 to 1000 R (1 R = 1 Rayleigh = $10^6/4\pi$ phot cm^{-2} sr^{-1} s^{-1}) and would cause detector count rate 5-8 orders of magnitude higher than the count rate due to ENAs. This measurement challenge led development of instrumentation concepts and enabling components in 1980s and 1990s (see review[16]). Many techniques have been developed including ultra-thin (2-3 nm) foils, time-of-flight spectrometry, coincidence technique, multi-electron electron emission, diffrac-

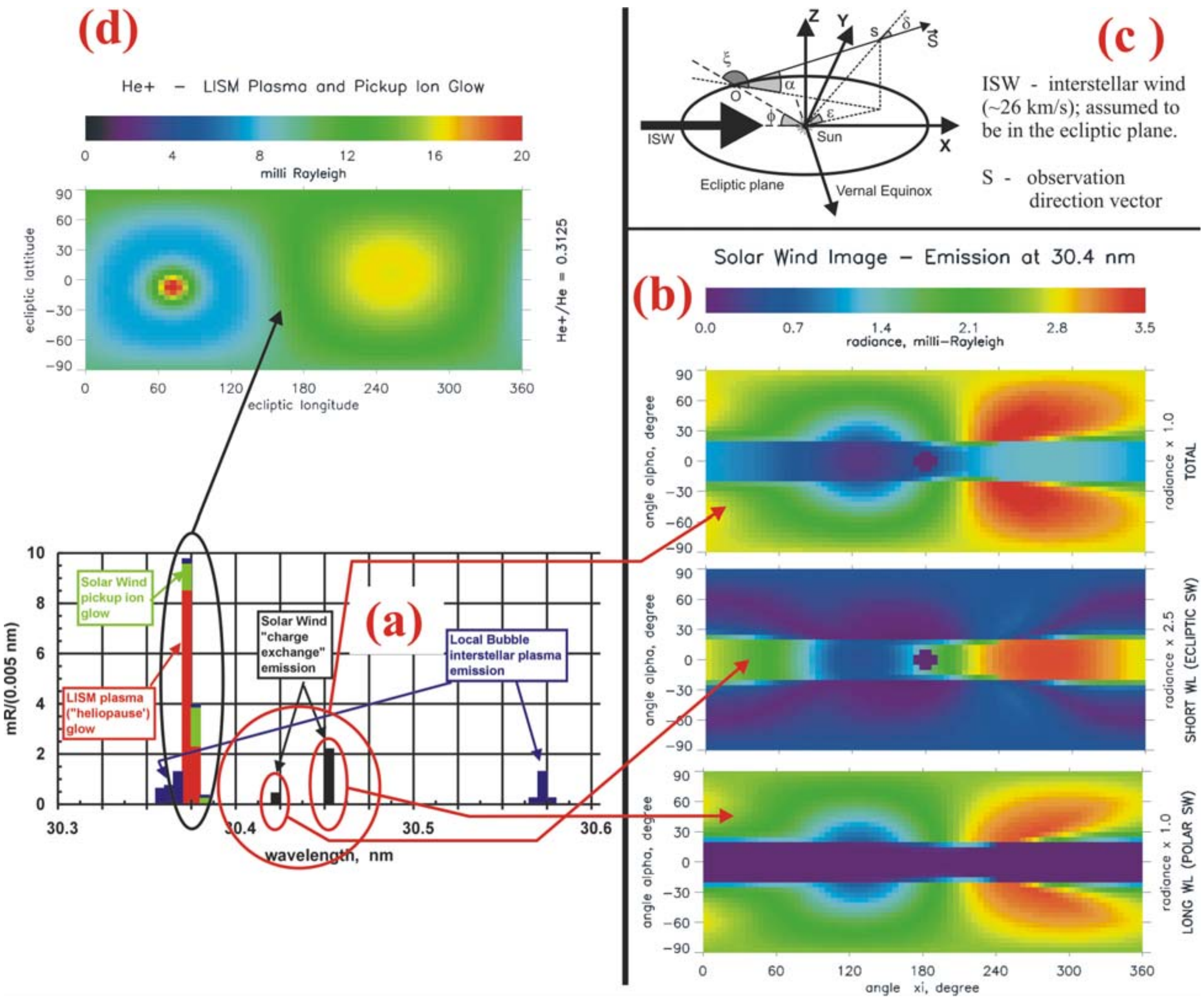

Figure 3. (a) Representative spectral radiance (at 1 AU) summed over 0.005-nm (0.05 A) bins for an observational direction partially in the slow and partially in the fast solar wind. The solar wind emission (black bars) shows two distinct Doppler-shifted peaks, produced by charge exchange in the slow and fast flows, respectively. Red bars are the glow of the LISM plasma beyond the heliopause. Green bars are the glow of helium pickup ions in the solar wind. Blue bars are the line emissions of hot plasma in the Local Bubble. (b) All-sky images in the solar wind 30.4-nm emission. Top: total red-shifted solar wind emissions. Sky maps in the spectral ranges corresponding to the 250-500 km/s ("short wl") and 550-900 km/s ("long wl") flows are shown in the middle and bottom panels, respectively. The solar wind is symmetric with respect to the ecliptic, with the slow (ecliptic) flow filling the region within ±20 deg from the ecliptic. The sun is in the center at (alpha = 0) and (xi=180 deg). The longitudinal asymmetry is explained by the atomic hydrogen distribution in the heliosphere. (c) The observer is positioned at 60-deg from the upwind (interstellar wind) direction in the ecliptic plane at 1 AU. (d) All-sky map (ecliptic coordinates) of the sky brightness at 30.4 nm due to the glow of the LISM plasma beyond the heliopause (peaks in the upwind direction: longitude 252 deg and latitude +7 deg) and pickup ions in the solar wind (peaks in the downwind direction).

100 higher in sensitivity and in spectral resolution than those of the state-of-the-art instruments. The new instrumental concept has been developed and its demonstration is being currently pursued.[23] The instrumental challenge is enormous, but it is not unlike the challenge faced in early 1980s in development of ENA instrumentation.[13,16]

CONCLUSIONS

Remote sensing of the solar system galactic frontier is of fundamental importance for understanding of the interaction of our star, the Sun, with the surrounding galactic medium and for supporting the truly interstellar exploration and interstellar travel of the future. The new NASA's IBEX mission will image the heliosphere in ENA fluxes and revolutionize our understanding of the termination shock and the processes beyond. Mapping of the heliopause in EUV will follow after the enabling instrumentation demonstrated.

ACKNOWLEDGMENTS

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