Access to the heliospheric boundary: EUV-echoes from the heliopause

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Abstract. We argue that the heliopause, a boundary that separates the solar wind and the plasma of the Local Interstellar Medium (LISM), can be explored remotely, from 1 AU, by detecting solar extreme-ultraviolet (EUV) radiation reflected by the heliospheric interface region. The measurements of the solar EUV radiation echoes from the heliopause would map the heliopause and provide important insight into the LISM parameters. Heliopause mapping can be done in the oxygen O^+ resonance line (83.4 nm). We show that the expected heliopause brightness is higher than the expected major source of the background line radiation, viz. the glow of the solar wind O^+ pickup ions and discuss a way to remotely establish the ionization state of the LISM and to probe the LISM interstellar magnetic field.

Global heliosphere

The interaction of our star, the sun, with the surrounding interstellar medium leads to the build up of the heliosphere, i.e. the region where the sun controls the state and behavior of the environment [Dessler, 1967; Axford, 1990; Fahr and Fichtner, 1991]. Our understanding of this complex interaction (fig. 1) that involves the solar wind and interstellar plasmas, interstellar gas, magnetic fields, and cosmic rays is gradually improving. Some parameters of the local interstellar medium (LISM) have been experimentally established and recent advances in modeling of the global heliosphere provide insight into the processes at the heliospheric boundary. Direct experimental data on the heliospheric interface region are extremely scarce and ambiguous. We argue that the heliopause, a boundary that separates the solar wind and the plasma of the LISM, can be explored remotely, from 1 AU by an observer outside of the geocorona.

It is believed that in several years Voyager 1 will plunge into the solar wind termination shock (TS, fig. 1) terminating the highly supersonic solar wind flow. The spacecraft, now at 67 AU, will thus establish the distance to the termination shock in the upwind direction, estimated to be somewhere between 75 and 100 AU. Although Voyager is anticipated to provide first in situ measurements of the postshock plasma, the spacecraft will still be 50-80 AU from the heliopause. We know very little about the heliopause and the direct experimental data are next to non existing [Suess, 1990]. The only measurements that may be directly related to the heliopause are those of the 2-3 kHz radio emissions detected by Voyager [Gurnett and Kurth, 1996].

The sheer size of the heliosphere calls for development of remote experimental techniques to study the heliospheric boundary. The heliosphere is believed to be asymmetric and changing its size and shape during the 11-year solar cycle. Therefore only remote observations, preferably from 1 AU, can provide a global view of the 3-dimensional heliosphere on a continuous basis.

How can one remotely observe the heliospheric interface region? One possible technique advocated for some time [Gruntman, 1992a, 1997; Hsieh et al., 1992; Roelof, 1992; Hsieh and Gruntman, 1993] is to detect energetic neutral atoms (ENAs) that originate at the solar wind termination shock. The postshock solar wind plasma is heated by transformation of the kinetic energy of the solar wind bulk motion into thermal energy in the shock transition. Energetic protons of the hot plasma would charge exchange on neutral interstellar atoms producing ENAs that can reach 1 AU. It was argued that ENA imaging of the heliosphere would establish the nature of the termination shock (gasdynamical vs. energetic ion modulated) and the shock shape and distance from the sun.

Here we propose a different remote technique based on detecting extreme ultraviolet (EUV) solar radiation reflected by ions of the heliospheric interface region. The LISM plasma beyond the heliopause is much denser than the solar wind plasma in the heliospheric interface, and interstellar singly-charged ions like He^+, O^+, Ne^+, etc. would resonantly scatter the corresponding solar EUV-line emissions as a special signature. The measurements of the solar radiation echoes from the heliopause would map the heliopause and provide an important insight into the LISM ionization state and interstellar
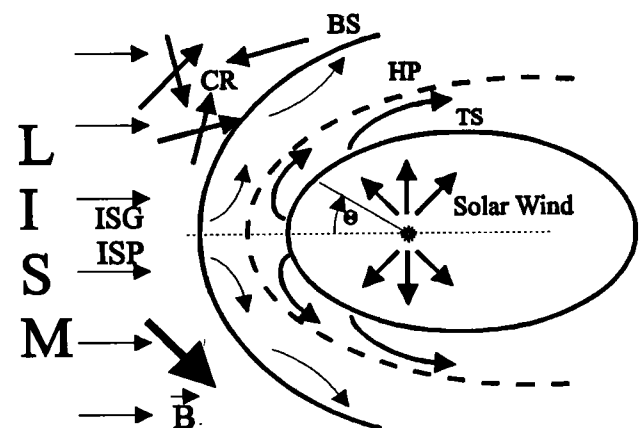

Figure 1. A possible model (two-shock model) of the interaction of the solar wind with the local interstellar medium. LISM - local interstellar medium: TS - termination shock; HP - heliopause; BS - bow shock; CR - cosmic rays; ISP(G) - interstellar plasma (gas); B - magnetic field. Angle θ is counted from the upwind direction.

magnetic field direction. We argue that heliopause EUV mapping can be done in the oxygen O^+ resonance line (83.4 nm) and, to the best of our knowledge, it has never been discussed in the past.

Heliopause mapping in EUV

Heliopause EUV mapping critically depends on the brightness of the corresponding solar line, the interstellar ion abundance, and the background radiation. Partially ionized interstellar gas has a temperature of 7000-8000 K in the LISM. The interstellar gas is not in thermodynamical equilibrium and the ionization state of its constituents is not accurately known. The gas consists of hydrogen (~90%), helium (~10%) and minor constituents. Interstellar neutrals are unsuitable for heliopause mapping because they penetrate deep into the heliosphere and most of the detectable glow would originate close to the sun (< 20 AU).

Interstellar oxygen O^+ ions are ideally suited for the heliopause mapping in the resonance 83.4 nm line for the following reasons:
1. Oxygen is the most abundant species of the interstellar gas minor constituents.
2. LISM oxygen is predominantly singly-charged and its ionization degree is nearly identical to that of LISM hydrogen [e.g., *Fahr et al., 1995*]; the ionization state of hydrogen is of prime importance in defining the size and shape of the heliosphere.
3. Background galactic radiation is minimal at 83.4 nm because the hydrogen atom photoionization cross section is close to maximum at this wavelength.

The ions of the most abundant interstellar gas component, hydrogen, cannot be imaged optically. The sun is a source of a bright HeII resonant line (30.4 nm), and one could thus image the interstellar He^+ ion population. The heliosphere imaging in 30.4 nm could be an excellent complement to the proposed imaging in 83.4 nm but its feasibility is uncertain. In particular the line background due to galactic emissions [*Paresce and Jakobsen*, 1980] and due to solar wind alpha-particle charge exchange on interplanetary hydrogen [*Paresce et al.*, 1992; *Gruntman*, 1992b] requires detailed evaluation. The glow of the solar wind He^+ pickup ions is probably not an obstacle because of the mounting evidence of the relatively high ionization degree of interstellar helium [*Dupuis et al.*, 1995; *Frisch and Slavin*, 1996].

The geocoronal line emissions in λ = 83.4 nm [*Chakrabarti et al.*, 1984] and 30.4 nm [*Chakrabarti et al.*, 1982] are much stronger than the expected heliospheric interface emissions. Therefore the heliospheric interface EUV imaging experiment can only be done from a spacecraft well outside the geocorona.

The interstellar wind plasma flow carries O^+ ions that cannot cross the heliopause and has to move along its outer surface. So one can imagine the sun surrounded by the LISM O^+ ion "wall" beyond the cavity limited by the heliopause boundary. The individual O^+ ions would scatter solar radiation with different individual scattering rates determined by their Doppler shifts from the line center. One can thus introduce an effective g-factor, or an effective scattering rate, for a given O^+ ion population allowing for the ion thermal motion and bulk velocity with respect to the sun.

The flux of scattered photons (photon/cm^2 sr s) at 1 AU is an integral along the line of sight

$$F = \frac{1}{4\pi} \int_{1AU}^{\infty} g(R) N_{O^+}(R) dR$$

where $g(R)$ is the effective local scattering rate and $N_{O^+}(R)$ is the local O^+ number density. (The solar radiation $\sim R^{-2}$ dependence is included in $g(R)$.) For a simplified case of a vanishing O^+ ion

number density inside the heliopause and uniformly distributed interstellar plasma at rest beyond the heliopause, the brightness is inversely proportional to the distance to the heliopause in the direction of observation. Thus the proposed heliosphere imaging in the OII resonance line is a direct way to establish the size and shape of the heliopause.

There are two major sources of the background radiation in 83.4 nm, viz. diffuse galactic radiation [*Paresce and Jakobsen*, 1980; *Cheng and Bruhweiler*, 1990; *Vallerga*, 1996] and solar radiation resonantly scattered by the O^+ pickup ions in the solar wind. The heliopause EUV echoes are line emissions which simplifies their separation from the continuum background. Various observations indicate that the continuum background does not exceed 4×10^{-6} R/Å [*Cheng and Bruhweiler*, 1990; *Vallerga and Welsh*, 1995; *Vallerga*, 1996], while the galactic O^+ resonance line emisison is negligible [*Cheng and Bruhweiler*, 1990]; 1 R = 1 Rayleigh = $10^6/4\pi$ photon/cm^2 s sr.

Neutral interstellar atoms penetrate the heliosphere where they become ionized and carried to the termination shock as pickup ions [*Moebius et al.*, 1985]. These pickup ions are singly-charged and essentially characterized by a spherical shell velocity distribution function. The O^+ pickup ions would resonantly scatter solar radiation, producing "glow," when their resonance frequencies are within the solar emission lines. Solar radiation scattering by both the LISM plasma and the pickup ions would produce line-emission, and the relative intensities of these emissions are most important for the feasibility of heliopause mapping.

The heliopause, plasma flow, and pickup ion model

The flow field (velocity, temperature, number density) of the LISM and solar wind plasmas and the heliospheric interface structure were rigorously calculated for this work under the assumption of a two-shock model of the LISM interaction with the solar wind. (The calculations were performed by V. Baranov and V. Izmodenov of the Russian Academy of Sciences.) The two-shock model assumes that both the interstellar plasma and the solar wind plasma flows are supersonic, the interaction between ionized and neutral components is treated self-consistently, and cosmic rays and interstellar magnetic field are disregarded [*Baranov and Malama*, 1993].

The following LISM parameters (at infinity) were used: velocity 25 km/s, temperature 5672 K, electron (proton) number density $n_e = 0.07$ cm^{-3}, neutral hydrogen number density $n_H = 0.14$ cm^{-3}. The solar wind was assumed spherically symmetric with a velocity 450 km/s and number density 7 cm^{-3} at 1 AU. The plasma flow field and heliospheric interface are similar to what is shown in fig.1. LISM oxygen was assumed to be present in cosmic abundance, i.e. 7×10^{-4} by number of atoms relative to hydrogen. The total solar disk emission at 83.4 nm that includes O^+ triplet and O^{++} multiplet [*Meier*, 1990] was used for rigorous calculation of the local O^+ g-factors for given velocity distributions of the LISM plasma and pickup ions.

The solar wind pickup ion glow was calculated using neutral interstellar gas parameters adjusted to allow for disturbing effects of the heliospheric interface [*Gruntman*, 1994]. The neutral oxygen distribution inside the heliosphere was modelled on the basis of the so-called hot model [e.g., *Gruntman*, 1992b] with the following parameters: interstellar gas velocity 20 km/s, temperature 12000 K, and oxygen loss rate 5.8×10^{-7} s^{-1} at 1 AU;
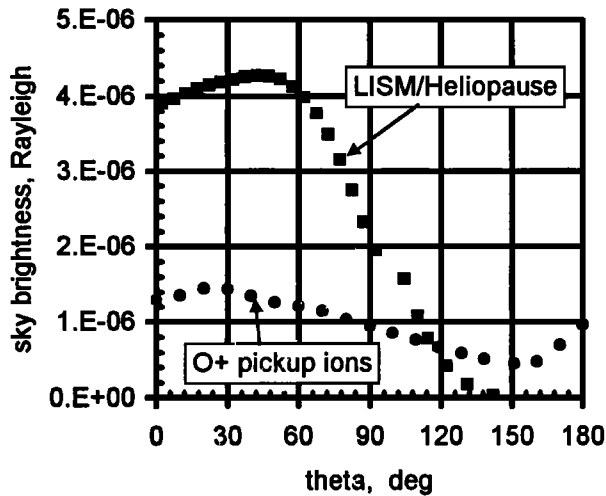
Figure 2. Sky brightness in the OII resonance line due to LISM plasma beyond the heliopause and due to solar wind pickup ions.

the filtering coefficient of oxygen was 0.75 [*Izmodenov et al.*, 1997].

Sky brightness

The calculated directional dependences of the sky brightness in the OII line due to the LISM plasma beyond the heliopause, F_{LISM}, and due to the solar wind oxygen pickup ions, F_{SW}, are shown in fig.2. The observation angle θ is counted fom the upwind direction (fig.1). The initial slight increase of the LISM plasma brightness with the angle θ is due to the Doppler effect as the velocity radial component diminishes in the plasma flowing around the heliopause. The brightness falls as the heliopause moves farther off from the sun and the Doppler effect reduces the g-factor. The scattered radiation is mostly concentrated between 83.25 and 83.45 nm, and there are some differences in spectral distributions for the LISM plasma and heliospheric pickup ions. The radiation scattered by the pickup ions, as seen at 1 AU, originates mostly at distances R < 5-10 AU from the Sun.

The brightness of the LISM plasma beyond the heliopause is roughly proportional to the number density of the interstellar gas ionized component, while the pickup ion brightness is roughly proportional to the number density of the interstellar gas neutral component. The dependences $F_{LISM}(\theta)$ and $F_{SW}(\theta)$ were obtained under the assumption of $n_e/n_H=1/2$. An increase in the LISM ionization degree would result in an increase of the F_{LISM}/F_{SW} ratio. Since the dependences $F_{LISM}(\theta)$ and $F_{SW}(\theta)$ are essentially different, the measurement of the angular dependence of the sky brightness is a direct way to establish the relative contributions of F_{LISM} and F_{SW} and thus the ionization state of the oxygen and correspondingly hydrogen components of the LISM.

The heliopause shape and the LISM plasma flow field are dependent on interstellar magnetic field. The tilt of the magnetic field vector with respect to the interstellar wind velocity vector would result in non-axis-symmetric shape of the heliopause. This asymmetry would be much stronger than the corresponding effect on the termination shock. Thus the proposed heliopause mapping will open the way for remote probing the LISM magnetic field direction.

For the LISM ionization degree, $n_e/n_H=1/2$, the expected heliopause brightness is higher than that of the pickup ion glow

(fig.2). An addition of the LISM magnetic field and cosmic ray pressure would result in a heliosphere size shrinking and hence in a further increase of the heliopause brightness F_{LISM}.

The heliopause EUV mapping together with the complementary termination shock ENA imaging are the powerful tools for remote study of the heliospheric boundary. Such imaging would take a full advantage of the anticipated Voyager 1 "ground truth" *in situ* measurements of the termination shock and beyond, which would allow "calibration" of remote observations in one point-direction. The instrumentation for ENA imaging is well developed [*Gruntman*, 1997]. The recently developed new EUV instruments have significantly advanced the sensitivity of the diffuse EUV radiation detection [*Bowyer et al.*, 1997]. The heliosphere EUV imaging experiment would require further three orders of magnitude improvement in the instrument sensitivities, which is a challenging but not impossible task.

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