An empirically-based model of the upstream heliopause and outer heliosheath - Current status

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Abstract. We describe a simplified model of the outer heliosheath upstream of the heliopause in an attempt to extract the heliosheath properties from the IBEX-Lo neutral He observations. The distribution of incident He on the sky shows a primary beam surrounded by an irregular cloud of secondary particles. These secondaries are generated by charge-exchange interactions between the neutral primary beam, carrying the properties of the distant interstellar medium, and the nearby interstellar plasma that is deflected around the obstacle posed by the heliosphere. We construct an analytical model for the plasma flow around an arbitrarily-shaped obstacle and compute the resulting distribution of neutral He at IBEX, to compare with the observed He fluxes. Here, we report on the current status of this modelling effort.

1. Introduction
The IBEX spacecraft was launched in 2008 in an orbit around the Earth to measure neutral atoms from the surrounding interplanetary and interstellar medium [1]. Neutral particles, streaming unaffected by electromagnetic fields, can be collected to form remote images of the particle sources and provide information on the plasma processes at large distances from the observer. This capability is illustrated by Figure 1, which shows a sky-map of neutral Helium originating in the interstellar medium (ISM) as detected by the IBEX-Lo instrument [2]. The data shown here compiles the total sputter-corrected fluxes of He in the lowest three energy bins of IBEX-Lo (11 – 77 eV), as observed during “super good times” in the Spring ram-direction periods of 2009 - 2011 (see e.g. [3-5] for explanation of these terms). The data are shown in a Mercator projection that preserves the size of the 6˚ × 6˚ pixels in J2000 ecliptic coordinates.

In this paper, we focus on the He component of the interstellar neutral gas since it is the second-most abundant species in the ISM, and since the motion of He through the inner heliosheath and supersonic solar wind has only a simple effect on the intensities of these particles. The sky-map of Figure 1 shows the superposition of a primary beam of ISM particles and an irregular cloud of secondary He resulting from the charge-exchange interaction, He⁺ + He → He + He⁺ [6], in the outer heliosheath beyond the heliopause. The distribution of this flux on the sky carries information on the global structure of the heliosphere. We are interested in extracting this information from the observations, and this paper will describe our attempts to construct a simple, empirically-based, model of the upstream heliopause and outer heliosheath consistent with these data.

2. Simple Model of the Upstream Heliosheath
2.1. Overview

The ISM at large distance from the Sun is a partially ionized plasma, flowing uniformly at ~ 26 km/s, with a temperature of ~ 8000 K [4, 7]. We assume that, far from the Sun, both the neutral and ionized components of this gas are in equilibrium. For the He component, this means that although charge-exchange is taking place as elsewhere, the relative densities and bulk properties of each component are not changing. However, as a parcel of ISM moves closer to the Sun, the presence of the heliosphere begins to affect the magnetized plasma, which deflects to stream around this obstacle in the flow. In this essentially collisionless system, the neutral particles continue to travel along their original paths. A non-zero relative bulk speed develops between the He+ plasma and the neutral He gas, and now the charge-exchange interactions begin to affect the properties of these components. When an atom in the He primary beam charge-exchanges with a deflected He+ ion, the new neutral particle possesses the flow properties of the deflected plasma. Some of these secondary He atoms are detected at IBEX, and the distribution of these fluxes is connected to the flow characteristics of the deflected plasma and the global shape of the heliopause.

We seek a simple model of this interaction in order to deduce this heliospheric shape. To include all the relevant physics in a heliospheric model, one requires a global simulation that computes the MHD flow field of the magnetized interstellar plasma, coupled with kinetic computations describing the neutral particle flow, as well as an accurate representation of the internal pressures due to the shocked solar wind and inner heliosheath whose pressure balance with the external plasma and field defines the heliopause [8-10]. Such simulations take weeks to run for each choice of physical parameters, and so cannot be easily adjusted to fit observations. The simple model presented here approximates the physical situation in several ways, while retaining the essential properties that determine the flux of He at IBEX. This model will not be completely rigorous or self-consistent, but it will allow consideration of a wide variety of heliospheric shapes for comparison to the observations.

For this comparison, we will initially consider a subset of the data, chosen to exhibit the largest variations and asymmetries. The two cutlines shown in Figure 1 are set normal to each other, intersecting at the flux maximum. The lines are oriented such that one line points in the direction of the maximum secondary flux. This line roughly corresponds to the offset of the “warm breeze”

Figure 1. Sky map of neutral He, taken by IBEX-Lo during the super good times of 2009 – 2011, in Mercator projection. Fluxes are the sum of the lowest three energy steps (11 – 77 eV), and have been sputter-corrected. Straight lines in white are the cutlines defined in the text from which we take the data used for comparison with the model.
Figure 2. Interpolated fluxes on the two cutlines through the sky map shown in Figure 1, as functions of the angular position from the maximum where the lines cross. (left panel) The “along” line travels from the lower left to the upper right (South-Port to North-Starboard) in the figure. (right panel) The “across” line travels from lower right to upper left (South-Starboard to North-Port).

characterization of Kubiak et al. [11], so it also lies essentially parallel to the direction of the interstellar magnetic field as defined by the center of the IBEX ribbon [12, 13]. Consequently, we refer to the observations on this line as the “along” fluxes, and call the values on the other line the “across” fluxes. The fluxes along these cutlines are shown in Figure 2. The specific ecliptic coordinates of the cutlines in longitude $\phi$ and latitude $\alpha$ are

along line: $\phi = -121.3^\circ - \theta \cos(0.6747)$, $\alpha = 4^\circ + \theta \sin(0.6747)$

across line: $\phi = -121.3^\circ - \theta \cos(0.896)$, $\alpha = 4^\circ + \theta \sin(0.896)$  

where $\theta$ is the angular distance away from the maximum flux position along each line.

2.2. Upstream Flow Field

The basic idea behind our simple model is to recognize that the interstellar plasma and magnetic field flowing around the heliopause is responding to the shape of that surface, while also acting to determine that shape. Rather than trying to compute that shape as a result of the complicated internal and external pressures, we simply treat this undetermined shape as an obstacle in the flow field of the ISM. We then ask what flow field would be consistent with a given obstacle shape, compute the charge-exchange fluxes that would be seen at IBEX from that flow field, and attempt to adjust the obstacle shape to give good agreement with the IBEX observations. The construction of this model is still a work in progress, and this paper will describe the current state of our work.

In order to define a flow field without resorting to a global MHD simulation, we approximate the effect of the magnetized interstellar plasma as that of a gas with an effective isotropic pressure equal to the sum of the true thermal pressure and the isotropic magnetic pressure. By allowing the shape of our model obstacle to be non-axisymmetric and distorted with respect to the flow, we are already including some of the effects of the magnetic tension force, which we otherwise neglect in our description of the plasma flow.

Having made this assumption, and recognizing that the flow at large distances is uniform and curl-free, we can then represent the upstream plasma number flux in steady state as the gradient of a potential function, $nv = \nabla \phi$. It then follows from the conservation of number flux, $\nabla \cdot (nv) = 0$, that this potential is a solution of Laplace’s equation, $\nabla^2 \phi = 0$. We note that we are here neglecting the possible presence of an upstream bow shock or bow wave [14].

This simplification allows the specification of an essentially infinite variety of obstacle shapes and analytical solutions to the upstream flow fields around them. To demonstrate this, we start with Parker’s heliospheric model [15-18] as illustrated in Figure 3. The streamlines shown in this figure are obtained by superimposing the potential function due to a uniform flow from the right and that from a
point source placed at the origin. The red curve indicates the axisymmetric surface that separates the two flows, which can serve as the representation of a simple heliopause. This shape is well studied in hydrodynamics [19], and is typically called a “Rankine half-body”. The superposition of sources is a standard technique for solving linear differential equations, such as Laplace’s equation. The analytical character of the flow field is a simple consequence of the fact that when the sources and boundaries of a system can be expressed along single-coordinate surface in spherical coordinates, Laplace’s equation is separable in three dimensions and admits analytical solutions.

There are a limited number of other coordinate systems for which Laplace’s equation is separable in 3D [20], and we consider two further cases, both derived from the 2D elliptical coordinate systems shown in Figure 4. Elliptical coordinates are constructed from nested ellipses defining one coordinate, \(0 \leq \xi \leq \infty\), and the normal set of hyperbolae defining the other coordinate. If we rotate the elliptical coordinate system about the vertical axis, as indicated in Figure 4a, we obtain the prolate spheroidal coordinate system, which can be used to describe a line source at \(\xi = 0\). Placing a line source at an angle to a uniform flow gives the streamlines illustrated in Figure 5, where the blue curve separating the two flows gives an example of a non-axisymmetric heliopause. Another example is given in Figure 6, which shows three views of the boundary between a tilted line source and a uniform flow.

Rotating the elliptical coordinates about the horizontal axis, as in Figure 4b, gives oblate spheroidal coordinates and describes the flow field from a disc source at \(\xi = 0\). Figure 7 shows three views of a surface separating a tilted disc source from a uniform flow. Since Laplace’s equation is linear, the flow fields of any number of point, line, and disc sources of any size, strength and orientation may be superimposed on a uniform flow from infinity to give analytical flow fields representing heliopause surfaces of essentially any plausible shape. We will use this capability to test the distributions of secondary He produced by different outer heliosheath plasma flow fields around a variety of heliopause shapes.

Figure 3. Streamlines for a Rankine half-body, an axisymmetric structure formed by the superposition of a point source and a uniform flow. The red curve separates the flows from the two sources, which can serve as a model heliopause.

Figure 4. Three-dimensional coordinate systems derived from the 2D elliptical coordinates. (Left panel) Rotation about the vertical axis results in the prolate ellipsoidal coordinate system, containing a line source at the origin. (Right panel) Rotation about the horizontal axis results in the oblate ellipsoidal coordinate system, containing a disc source at the origin. Source objects are shown in red.
2.3. Plasma Properties

For a given obstacle shape and corresponding flow field, we then describe the plasma properties upstream of the obstacle resulting from a typical undisturbed ISM at infinity. We assume that the partially ionized plasma is composed of protons and He$^+$ ions, with a neutralizing population of electrons, along with neutral populations of H and He atoms. All the components of this plasma are in equilibrium with each other at large distance from the Sun, and their distributions are taken to be Maxwellian there. The proton number density at infinity is taken to be $n_p = 0.04 \text{ cm}^{-3}$, the He$^+$ ions have a number density of $0.1 n_p$, and the bulk speed of all the co-moving particles is $V_o = 26 \text{ km s}^{-1}$. The kinetic plasma temperature there is taken to be $T_o = 8000 \, ^\circ\text{K}$, but we will treat the inflowing plasma as having an isotropic pressure with an effective sound speed equal to the MHD fast speed $c_f = \sqrt{c_s^2 + V_A^2}$, such that $kT_o/m = 3/5 c_f^2$, where $c_s$ is the true kinetic sound speed, $V_A$ is the Alfvén speed, $k$ is Boltzmann’s constant, and $m$ is the mass/particle in the plasma. An undisturbed interstellar magnetic field intensity of 4.4 $\mu$G gives an Alfvén speed of 40.6 km s$^{-1}$, so the fast speed at infinity is taken to be 41.6 km s$^{-1}$.

A given set of sources in the otherwise uniform flow yields the potential $\phi(x)$, which provides the number flux as a function of position, $n_p v = \nabla \phi$. We assume that this interstellar plasma behaves adiabatically as it approaches the heliosphere. Taking the effective sound speed as $c_f$, the adiabatic equation of state can be manipulated to give $n_p c_f^{-3} = N = \text{constant}$. Similarly, Bernoulli’s law yields $c_f^2 + v^2/3 = C = \text{constant}$. If we define $W = n_p^2 v^2/3$, these equations can be combined to give the quartic

![Figure 5](image1.png)

**Figure 5.** Plane slice through the non-axisymmetric superposition of a line source (red) and a uniform flow. The blue curve locates the separating surface, acting as a model heliopause in this system.

![Figure 6](image2.png)

**Figure 6.** Three views of a model heliopause resulting from a tilted line source in a uniform flow, as seen from upstream of the surface.
Both constants, $C$ and $N$, are given by the ISM conditions far from the Sun, and $W$ is known from the particular flow field, so the effective temperature is then determined from the appropriate solution of equation (2). For $0 < W/N^2 < 27 C^4/256$, equation (2) has two real roots and the larger root is the physical one related to $c_f^2 = C$ when $v = 0$. As the plasma speeds up around the flanks of the obstacle, $W/N^2$ reaches $27 C^4/256$ where the two roots coalesce, and the flow speed reaches the effective sound speed $v = c_f$. Beyond this point, equation (2) has no real solutions and the simple model constructed here is no longer valid.

The charge-exchange process that produces the He secondaries depends on the properties of the He\(^+\) component of the upstream plasma, so these properties must be extracted from the model results. The density fraction of He\(^+\) does not change, but the kinetic temperature of the ions is still an unknown fraction of the effective plasma temperature from the model. Here, we define a “partition function” $\zeta$ to relate the actual kinetic temperature of He\(^+\) proportional to $c_s^2$, to the effective model temperature proportional to $c_f^2$, $\zeta = (c_s/c_f)^2$. The simplest assumption would be to take $\zeta = \text{constant}$, but we know that the plasma is more compressible than the magnetic field so this would be a poor choice. Instead, we take a hint from the global simulation of Izmodenov & Alexashov [10], who plot the plasma density and pressures (kinetic and magnetic) along the stagnation line in their Figures 4a and 4b. We assume that the partition is a function of plasma density, and estimate from these figures the change in $\zeta$ between the two positions, far upstream and at the heliopause stagnation point. A linear dependence between these points, along with the statement that $\zeta = 0$ at zero density, gives the model partition function as

$$\zeta(n_p) = \begin{cases} 19.78n_p - 0.826 & n_p \geq 0.044 \\ n_p & n_p < 0.044 \end{cases}$$

where the total ion density here is measured in cm\(^{-3}\).
2.4. Trajectories of He Incident at IBEX-Lo

The sky-map in Figure 1 is composed of $6' \times 6'$ pixels labeled according to the orientation of the IBEX-Lo instrument. The IBEX spacecraft spins about an axis nominally pointing toward the Sun, and the measurements are made in the spin plane perpendicular to the spin axis. For a given day-of-year, the spin plane nominally scans a strip of sky centered on a given ecliptic longitude, and fluxes are compiled as a function of spin angle corresponding to ecliptic latitude. Pixel position on the map simply refers to the direction of the instrument aperture when those specific fluxes were measured.

However, the measured atoms arrive at IBEX by traveling along Keplerian trajectories in the Sun’s gravitational field. Thus, an incident atom has passed through regions of interstellar and interplanetary space on a curved path quite different from a traditional “line of sight”. Furthermore, atoms arriving within a given pixel designation but at different speeds will have encountered different regions of space during their passage. Since we are dealing with energy-integrated measurements, the fluxes in the map are a superposition of many trajectories, each encountering different conditions and subject to different charge-exchange interactions.

To compute the model fluxes corresponding to a given pixel, we follow a straightforward, though cumbersome, procedure. We take IBEX to sit at 1 AU, at a given position in the Earth’s orbit, with a given spin angle, and track the incident atoms backwards along their Keplerian trajectories [21-23]. We include the effects of both elliptical (closed) and hyperbolic (open) atom trajectories. Starting with an atom speed large enough to reach the heliopause, we first transform that incident velocity into the inertial frame of the Sun. In the inertial frame, both the particle total energy/mass, $E_o = w^2/2 - k_g/r$, and the angular momentum/mass, $\ell = r w \phi$, are constants along the trajectory, where $w$ is the particle speed in the inertial frame and $k_g$ is the gravitational potential of the Sun at 1 AU. We then compute the He flux fraction from that trajectory by evaluating the charge-exchange gains and losses due to the model plasma properties along that path in the outer heliosheath, allowing for the contribution of primary interstellar He on the open trajectories [6]. Specifically, we solve the difference equation

$$\Delta n_{He} = \left[ \beta_{prod} - \beta_{loss} n_{He} \right] \frac{\Delta s}{V_{traj}}$$

along the trajectory, where the production rate $\beta_{prod}$ counts only those He atoms produced by charge-exchange from an He$^+$ ion already moving at the speed and direction appropriate to that trajectory at that position in space, and the loss rate $\beta_{loss}$ removes any atom already on the trajectory which charge-exchanges with the He$^+$ plasma. At this point in our modeling, we take the charge-exchange cross-section for the process $\text{He}^+ + \text{He} \rightarrow \text{He} + \text{He}^+$ to be constant at $\sigma = 2. \times 10^{-15}$ cm$^2$. For closed trajectories, we start at the model heliopause, moving outward toward aphelion, with a boundary condition on equation (4) that $n_{He} = 0$ at the starting point. This assumes that the measured atoms reaching 1 AU will have been produced somewhere during their first traversal of the outer heliosheath. The boundary condition for the open trajectories sets the initial density at 40,000 AU upstream equal to the phase-space density of the Maxwellian distribution of primary interstellar particles.

The incident speed at IBEX is then incremented, the solution of equation (4) is obtained for the next trajectory, and the total flux for that pixel is eventually obtained as

$$j(\phi,\alpha) = G \int \nu_0^3 d\nu_0 n_{He}(\nu_0) d\nu_0,$$

where $\nu_0$ is the incident speed, and $G$ is a proportionality constant equivalent to the instrument geometric factor.

The map intensity distribution is affected by photoionization due to solar UV. In addition to an overall reduction at 1 AU, this process depletes the slower atoms more than the faster ones. We assume that the photoionization rate at 1 AU is a constant, $\beta_{ph} = 10^{-7}$ s$^{-1}$, decreasing as $r^{-2}$ [24]. Each incident flux value, $n_{He}(\nu_0)$ is then reduced by the factor
Figure 8. Comparison of model results for the interstellar primary neutral beam with the IBEX-Lo observations (red diamonds) on the two cutlines, along (left panel) and across (right panel). The blue curves show the model predictions for two pointing directions of the spacecraft spin axis, toward the Sun (dashed line) and offset 2° to the West (solid line).

\[
\exp \left(-\beta \frac{r_0}{r^2} \int_1^{\infty} \frac{dr}{r^2 \sqrt{E_0 + k g / r}} \right)
\]

before adding to the integral (5).

Another effect is important when comparing models to the IBEX-Lo data. When spacecraft spin axis is pointed at the Sun, as is nominally described, the incident He atoms arrive at IBEX at the perihelion point of their trajectory. If the spin axis is shifted, the true particle trajectories will also be shifted, and the resulting fluxes will be different. It turns out that the spacecraft spin axis was often not pointed at the Sun during 2009 – 2011, but offset by several degrees at various times during the measurements shown in Figure 1 [22, 25]. The magnitude of this effect can be seen in Figure 8, which shows a comparison between the measured He fluxes given in Figure 2 (red diamonds) with two model curves representing the primary beam (that is, setting \( \sigma = 0 \) along the trajectories). The primary curves are normalized so their peak fluxes coincide with the peak of the data. The two panels correspond to the fluxes on the “along” and “across” cutlines of Figure 1, as functions of the angular distance along each cutline. The two curves in each panel show the modeled primary fluxes assuming no offset of the spin axis (dashed line) and a 2° offset of the axis to the West (solid line). The primary beam should dominate the measured fluxes above the 10% level, but discrepancies between either model and the data are evident.

It is apparently necessary to incorporate the actual position of the IBEX spin axis during the specific observation time of each pixel to truly model the measured fluxes. We are in the process of making these improvements to our models.

3. Current Status of the Model

The motivation for this modeling effort has always been to extract empirical information on the shape of the heliopause and plasma conditions of the outer heliosheath. We have explored the apparent effect of many trial obstacle shapes and flow patterns in our model. Generally, our findings seem to indicate that the heliopause is approximately symmetric about the \( B-V \) plane (see also [26]). At this time, we are still refining the model effects of spin axis positioning for the IBEX spacecraft. In the future, we will determine the type of obstacle shape that is most consistent with the observations. This information can be used to guide and validate the much more complicated global simulation efforts being undertaken by other groups.
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