Structure of the IBEX Ribbon from Distributed Sources

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Abstract. The Interstellar Boundary Explorer (IBEX) mission discovered the presence of a global structure in energetic neutral atom emissions from the outer heliosphere not predicted by any model — the IBEX “ribbon”. In the search for possible explanations, observations have pointed to a likely source from neutral atoms produced through charge-exchange with the outflowing solar wind. The secondary (neutral) solar wind then undergoes charge-exchange beyond the heliopause to produce the proton population that forms the ribbon. Here we study the plasma structure beyond the heliopause created from distributed secondary neutral atom sources. We provide a framework to analyze the IBEX ribbon taking into account distributed neutral atom sources within the local interstellar medium.

1. Introduction
The Interstellar Boundary Explorer (IBEX) was launched in 2008 to study the global heliosphere [1]. The subsequent discovery was made by IBEX of a narrow, almost circular structure of energetic neutral atoms from \( \sim 300 \) eV to 6 keV [1, 2], and extending in position from beneath the nose of the heliosphere toward the north polar region, then slightly above the tail and back down beneath the nose [2–5]. This structure is now referred to as the “IBEX ribbon”, and is believed to be centered approximately on the direction of the interstellar magnetic field [2, 5, 6].

There are a broad array of proposed sources for the IBEX ribbon [2, 7]. IBEX observations [2] increasingly point to a source mechanism for the IBEX ribbon from the secondary (neutral) solar wind, which travels out beyond the heliopause, charge-exchanges with protons within the very local interstellar medium (VLISM), and then through subsequent charge-exchange collisions becomes energetic neutral atoms that travel back toward the Sun where they can be detected by IBEX. This mechanism is fundamentally tied to the secondary solar wind and has been modeled in numerous studies [8–13].

Models of the IBEX ribbon involving the secondary solar wind are roughly organized into two variants: (1) ring-beam models in which secondary solar wind atoms populate a ring-beam about the interstellar magnetic field after ionization beyond the heliopause. Energetic Neutral Atoms (ENAs) are then created from the portion of the ring beam that projects neutral atoms
back toward the Sun, and therefore toward IBEX where they are detected [8–10, 12, 13]; (2) models involving the spatial retention of protons beyond the heliopause on magnetic field lines [11, 14, 15]. In the first of these variants of secondary solar wind models, very low scattering rates are required so that ring beams remain stable over multiple years [8, 11]. Conversely, for spatial retention models, we require ion scattering from magnetic field variations and Alfvén waves to retrain ions within the ribbon [11, 14, 15].

Here, we discuss the concept that the ribbon is composed of a superposition of spatial distributions integrated along the line-of-sight. In §2, we derive the kappa function that results from a superposition of randomly distributed sources. In §3, we fit observations using our derived kappa function and provide conclusions in §4.

2. Structure of the Ribbon from Distributed Sources

In the case of the retention region or ring beam distributions, the line-of-sight integrated observations of ENAs includes an array of plasma structures beyond the heliopause. The spatial distributions beyond the heliopause can be modeled either using a spatial retention region or in the limit of weak scattering. In these cases, we expect a peaked distribution close to the source with a spatial tail that decays exponentially, \( f \propto \exp(-\beta x) \). Here, \( x \) is distance along a magnetic field line from the center of the source region. The scale-length of the exponential tail is \( 1/\beta \). In the specific case of spatial retention [11], \( 1/\beta = 2r v_A/v \), where \( r \) is the distance to the source.

In the case of weak scattering, the scale-length is related to the scattering coefficient \( \kappa_\parallel \) along the magnetic field: \( 1/\beta = 2\sqrt{\kappa_\parallel \tau_x} \) where \( \tau_x \) is the charge-exchange rate, \( \tau_x = 1/(n_{H-OSH} \sigma v) \), \( n_{H-OSH} \) is the neutral hydrogen density in the outer heliosheath, \( v \) is the particle speed and \( \sigma \) is the charge-exchange cross-section.

The superposition of sources along the line-of-sight leads to the formation of kappa distributions [16]. Statistics involving a collection of variable states has been considered in many different areas of study [17, 18]. For example, in the case of solar flares, waiting times between subsequent solar flares are distributed according to a power-law that emerges from randomly distributed processes [19]. A given random (or Poisson) process with an average occurrence rate \( \lambda \) yields an exponential probability distribution of waiting time \( t \) between subsequent events, and there is an equal probability for an event occurring after time \( t \) for \( t < 1/\lambda \). This uniform probability distribution of waiting times is required for any Poisson process. The superposition of exponential waiting time distributions leads to a kappa distribution, which has the observed power-law behavior for waiting times.

In analogy to the waiting time distribution of flaring processes, we consider the superposition of individual exponential spatial distributions. Each spatial distribution is defined by an exponential \( f \propto \exp(-\beta x) \) with inverse scale-length \( \beta \) centered on the secondary ENA source beyond the heliopause. In this analog, the parameter \( \beta \) is the counterpart of an occurrence rate for a Poisson process.

The remainder of the derivation to describe the superposition of states follows previous work [16]. We identify each spatial exponential distribution of ENAs as a state, and consider the superposition of these states along the line-of-sight. The number of states for inverse scale-lengths in the range \( \beta \) and \( \beta + d\beta \) is defined \( F(\beta)d\beta \). The entropy of states, defined as \( S = -\int d\beta F(\beta) \ln[F(\beta)] \), is maximized for the functional form \( F(\beta) = \exp(-\beta/\beta_0)/\beta_0 \). In this case, the superposed distribution \( \tilde{f} \) of source protons within the ribbon takes the following form:

\[
\tilde{f} = A(|\beta_0 x| + 1)^{-3}
\]

where \( A \) is the amplitude of the distribution.
The observations of IBEX are mapped by angle over the plane of the sky. The angular distribution corresponding to equation (1) is:

\[
\tilde{f}(\theta) = A((|\gamma_0(\theta - \theta_0)| + 1)^{-3}.
\]

Here $\gamma_0$ is the average inverse angular width of the ribbon, $\theta_0$ is the central latitude in the reference frame centered on the ribbon, and $\theta$ represents a given latitude in the reference frame center on the ribbon. In the following section, we use the derived kappa distribution to provide fits to the observed ENA distributions.

3. Spatial Fitting of the IBEX Ribbon

We demonstrate the fitting methodology using the first three years of IBEX observations from 2009 through 2011, and order observations as a function of latitude in the reference frame centered on the ribbon. In this reference reference frame, the pole at 90° latitude corresponds to the ribbon center (taken as ecliptic longitude 221° and ecliptic latitude 39°. In this coordinate system, we average over longitude and display the data as a function of latitude. A uniform circular ribbon would appear at a fixed latitude, and if the ribbon formed a great circle, it would appear at 0° latitude.
Figure 2. RMS deviations of the fits to the ribbon distribution shown in Figure 1.

Figure 3. Fit parameters derived from the superposition of states that yields a kappa distribution for the ribbon (2): (top) the latitude in the frame centered on the ribbon, (bottom) the ribbon’s FWHM.
Figure 1 shows the kappa function fits using the functional form in equation (2) for the ribbon and a sloped line for the globally distributed flux (GDF). There are five parameters for each fit: the height and slope of the GDF linear fit, and the center, width, and height of the kappa distribution for the ribbon (from equation 2). The root-mean-square (RMS) deviation between the fits and the observations is very low, typically less than 5% (Figure 2).

The fitting parameters from equation (2) include the average latitude of the ribbon in the ribbon-centered reference frame, and the full-width-half-max of the ribbon as a function of energy. These fit parameters and their uncertainties are shown in Figure 3.

The quality of the fits in Figure 1 and the relatively low RMS deviations in Figure 2 suggest that the functional form, equation (2), associated with the superposition of multiple sources along the line-of-sight provides reasonable agreement with IBEX observations in the 2009–2011 timeframe. In the next section we utilize the results of these fits to aid in our interpretation of the properties of the IBEX ribbon.

4. Conclusions

The fits (Figure 1) and the fitting parameters (Figure 3) show a number of important features that elucidate the properties of the ribbon. We observe the center of the ribbon at latitudes (Figure 3, top panel) in the ribbon frame that are relatively close to the equator (<18°). This suggests that the ribbon is close to being a great-circle. Note that the ribbon center shifts steadily from 17.2° ± 0.3° latitude at ~0.71 keV down to 12.8° ± 1.0° latitude at ~4.29 keV. This shift suggests that we are observing increasingly large line-of-sight distances within the ribbon at increasing energies [20, ], which suppresses the effect of magnetic field draping near the heliopause.

We find that the ribbon FWHM minimizes at the energy step centered on ~1.1 keV (with energy range 0.84–1.55 keV), with a large increase of the ribbon width at increasing energy. This behavior suggests that the we are observing a source with an intrinsic width at low energies, and that the width of the ribbon increases at higher energies due to increasing ion mobility.

The ribbon FWHM from the 0.84–1.55 keV energy step is found to be ΔαA = 14.6° ± 1.4°. We consider the speed of ENAs at the low end of this IBEX ENA energy range, near 0.84 keV, since the energy spectrum preferentially weights the lower energy ENAs within the observed energy range. With a speed of v = 400 km/s at 0.84 keV, we can use the relationship between the width of the ribbon and Alfvén wave production in the retention region to derive an Alfvén speed, vA. Specifically, with ΔαA ≈ 2vA/v [11], we find an Alfvén speed vA ~ 50 km s⁻¹.

Given a proton density of 0.07 cm³ [21] in the plasma beyond the heliopause where the ribbon is generated, we find a magnetic field strength of B ~ 6 µG, which is similar to the 4.5 – 6 µG found in Voyager 1 observations beyond the heliopause [22, 23]. The ribbon width observed by IBEX is likely broadened due to variations along the line-of-sight and due to the angular response of IBEX-Hi. Therefore, our calculation slightly overestimates both the Alfvén speed and the magnetic field strength within the ribbon.

The broadening of the ribbon at higher energies from IBEX may be associated in part with increased ion mobility along the magnetic field. In the case of weak scattering, the width of the ribbon is related to the scattering mean free path, Δα ~ 2√κ∥τx/r. Given τx ~ 2 years at 4.29 keV and a ribbon width Δα = 39.6° ± 7.5°, we find a scattering mean free path parallel to the magnetic field given by λ∥ = λ0r²/R²130 where λ0 = 15 au and R130 is 130 au. Note that the width of the ribbon at this energy corresponds to a physical distance of 90 au for a ribbon that is produced near 130 au. The derived scattering mean free path is therefore smaller, but of the rough order-of-magnitude of the ribbon width. Therefore, the effect of scattering is significant within the ribbon, and the increased mobility at higher energies causes broadening.

We have analyzed the properties of the ribbon over the first three years of IBEX observations by considering the superposition of spatially distributed sources along the line-of-sight. We find
that this superposition yields a specific kappa function that provides excellent fits to the IBEX observations. These fits are used to determine properties associated with ribbon source. The width of the ribbon provides for an estimate of the Alfvén speed, $v_A \sim 50 \text{ km s}^{-1}$, beyond the heliopause near the ribbon source, and the increased mobility of ions at the higher energies observed by IBEX leads to ribbon broadening. Thus, we provide a framework to analyze the IBEX ribbon taking into account distributed neutral atom sources within the very local interstellar medium.

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