

Spatial Retention of the IBEX Ribbon Source Particles – Further Work on the Dominant Turbulence Model

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Abstract. We present an overview of the “dominant turbulence” picture of pickup proton isotropization and its recent application to the spatial retention of these particles in the nearby interstellar medium as an explanation for the IBEX ribbon structure. We report the progress of further modeling in this area, expanding the published model to 3D and adding a contribution of energetic neutral atoms from the inner heliosheath to the ribbon volume. We find that the ribbon flux expected at IBEX from this model is still below the observed value, but the discrepancy is much smaller than that of our previous result.

1. Introduction

The “IBEX ribbon” is a narrow region of enhanced energetic neutral atom (ENA) flux detected by the Interstellar Boundary EXplorer (IBEX) spacecraft. This enhancement is $\sim 20^\circ$ wide, and emits a factor of 2 - 3 larger ENA flux than the surrounding regions. The energy spectrum is broad, but peaks at ~ 1 keV. Its position on the sky is well-defined as a circle around the heliosphere satisfying $\hat{\mathbf{r}} \cdot \hat{\mathbf{b}} = 0$, where $\hat{\mathbf{r}}$ is the heliospheric radial direction and $\hat{\mathbf{b}}$ is the direction of the local interstellar magnetic field according to current best estimates.

Since its discovery in 2009, a number of hypotheses have been advanced to explain the ribbon (see McComas et al. [1, 2] or Schwadron et al. [3] for extensive lists and discussion). However, at this point none of these hypotheses have convincingly modeled all the observed features. The most advanced scenario is the “secondary ENA” model first proposed by McComas et al. [1] and further elaborated by Heerikhuisen et al. [4] and Möbius et al. [5] (see also Chalov et al. [6] for a somewhat different treatment). In this picture, the ribbon is the product of a multi-step process that starts with the well-known pickup of inflowing interstellar hydrogen in the solar wind. The charge-exchange interaction creating the pickup protons in the solar wind also produces a radially expanding wind of hydrogen atoms streaming at the solar wind speed, ~ 1 keV. These ENAs pass through the heliosheath and become ionized and picked up in the cool, dense interstellar medium (ISM). These secondary pickup protons gyrate around the ISM magnetic field until some of them are neutralized by yet another charge-exchange. At this time, those new ENAs that were moving toward the Earth when they were neutralized will continue that straight-line motion and can be detected at IBEX.

The main difficulty with this scenario comes from its explanation of the ribbon spatial structure. The original idea required the pickup protons in the ISM to remain near their initial pitch angle in phase space until they were re-neutralized. The initial pitch-angle cosine of radially streaming solar wind ENAs is $\mu_o = \hat{\mathbf{r}} \cdot \hat{\mathbf{b}}$, and only those pickup protons with instantaneous motion back along the



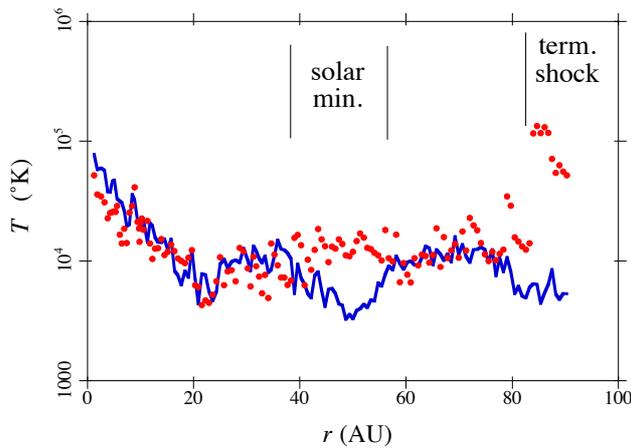


Figure 1. Application of the DT formalism to the outer solar wind. Red dots show the core proton temperature, averaged over 3 solar rotations, as measured at Voyager 2. Blue line shows the predictions of a DT model [17], using solar wind measured at 1 AU as input. During solar minimum, the ecliptic solar wind measured at 1 AU is not representative of the higher latitude solar wind encountered at Voyager.

radial direction can be detected at IBEX. For these particles to coincide with $\hat{\mathbf{r}} \cdot \hat{\mathbf{b}} \approx 0$, the secondary ENAs cannot change their pitch angles very much before they are neutralized. If this requirement is somehow accomplished, the estimated flux from such a configuration is consistent with that observed by IBEX [5].

However, the ring distributions corresponding to $\hat{\mathbf{r}} \cdot \hat{\mathbf{b}} \approx 0$ are known to be highly unstable to pitch-angle scattering by ambient and self-generated waves [7, 8]. The time scale for significant pitch angle scattering of these rings is several days [9, 10], but the charge-exchange time is much longer, about 2 years [9, 11]. If these pickup protons become substantially isotropized before they can be neutralized by charge-exchange, the resulting ENAs would come from all directions and there would be no distinct ribbon structure.

To deal with this issue, Schwadron & McComas [12] suggested a modification to this scenario. Rather than somehow suppressing the pitch-angle scattering of the ISM pickup protons, they proposed that the pickup protons did scatter to isotropy and generated strong turbulent fluctuations in the process. One expects that the turbulence generated by a ring of protons at $\hat{\mathbf{r}} \cdot \hat{\mathbf{b}} = 0$ would be stronger than that generated by pickup protons starting at other pitch angles. In this way, the spatial region defined by $\hat{\mathbf{r}} \cdot \hat{\mathbf{b}} \approx 0$ would become more turbulent, transport of 1 keV protons along the magnetic field would become more difficult there, and these protons could be preferentially retained in that region as source particles for a ribbon.

Such a retention process requires a physical mechanism to distinguish between conditions of strong pitch-angle scattering, leading to isotropization and diffusively inhibited transport of the pickup protons, and weak pitch-angle scattering, which allows the pickup protons to effectively stream along the field away from the ribbon. In a recent paper, Isenberg [13] presented a quantitative mechanism based on the “dominant turbulence” (DT) approximation. This concept was first developed to describe the pickup-proton-driven turbulence in the outer solar wind, whose dissipation can heat the core solar wind protons [14, 15]. In subsequent works, incorporating increasing levels of detail [16-19], this quantitative description has been shown to successfully match the solar wind temperature measurements at Voyager 2 out to the solar wind termination shock (Figure 1). Isenberg [13] applied this mechanism to a simplified model of the heliosphere and the surrounding ISM, and showed that a qualitatively reasonable ribbon structure could be produced. However, the ENA flux emitted by this simple ribbon model was considerably less than that implied by the IBEX measurements, so more detailed models are required.

In this paper, we will extend the 2D model of [13] to 3D and present preliminary results incorporating the addition of ENAs from the inner heliosheath. In §2 we briefly review the DT formalism as applied to the ISM, and in §3 we outline the basics of the earlier [13] model. In §4, we describe the extensions made here and the results obtained. In §5, we discuss these results and present our conclusions.

2. The dominant turbulence assumption

Pickup protons interact with their surrounding plasma primarily through cyclotron-resonant scattering by parallel-propagating MHD waves. Four modes of these waves are available: right-circularly polarized fast mode waves and left-circularly polarized ion-cyclotron waves, each propagating in either direction along the magnetic field. The waves will scatter the protons toward isotropy in the plasma reference frame, and the final shape of the fully-scattered distribution depends on the relative intensities of the four resonant wave spectra. In general, a given pickup proton is able to resonate with two modes at a time. Scattering by one mode (“unstable”) will cause the proton to lose energy in the plasma frame, and scattering by the other mode (“stable”) will add energy to the proton. These energy changes are matched by changes in the wave intensities, growing or damping, such that each interaction conserves the total energy of waves and particles.

One standard treatment is to assume that the damped wave modes, those that give energy to the protons, disappear quickly, so the scattering is controlled by the interaction with the growing modes. This is called the “bispherical” assumption, since it results in proton shell distributions composed of two spherical sections, and it typically leads to the prediction of intense resonant waves. This assumption was developed to model the ion pickup around comets, where the production rate of new ions is very large, so the damping of the stable waves is very strong [20, 21]. The prediction of intense growth of the unstable waves has been borne out by observations in these cases.

However, the bispherical assumption cannot be used to treat pickup proton isotropization in circumstances where the production of new protons is slow, such as in the outer solar wind and the ISM. In this case, the damping of stable waves is weak and nonlinear turbulent processes can be fast enough to maintain the presence of all four resonant modes. When all the resonant modes take part in the scattering process, the fully-scattered pickup protons will be more isotropic than in the bispherical prediction and the net energy given to the fluctuations by isotropization of new pickup protons is significantly smaller than the bispherical value.

This distinction was central to the successful modeling of the core proton temperature measured by Voyager 2 in the outer solar wind. The fact that the bispherical assumption completely overestimates the core proton heating [22] strongly indicates that some level of stable waves are continually present to contribute to the scattering. Our DT hypothesis, which assumes that turbulence maintains equal intensities of these four modes on the production timescale for new pickup protons, has done a very good job of matching the observed temperatures, as shown in Figure 1.

The quantitative application of this approximation is based on the total energy of the fully-scattered pickup proton shell, representing the gain or loss of fluctuation energy by the isotropization of newly ionized hydrogen. The specific DT assumptions take the intensities of the four resonant wave modes to be equilibrated by nonlinear wave-wave interactions on a time scale faster than others in the system, and assumes that the spectra of each of these modes is kept as a power law in wavenumber

$$I_{\pm}(k) \sim |k|^{-5/3}. \quad (1)$$

Newly ionized protons are scattered to a closed-shell distribution, $\nu(\mu)$, on a kinetic time scale faster than the macroscopic fluid time scales of ISM evolution. The shape of this distribution is given by (see [15])

$$\frac{d\nu}{d\mu} = \left[\sum_j V_j \frac{I_j(k_r)}{|\mu\nu - W_j|} \left(1 - \frac{\mu V_j}{\nu} \right) \right] \left[\sum_j \frac{I_j(k_r)}{|\mu\nu - W_j|} \left(1 - \frac{\mu V_j}{\nu} \right)^2 \right]^{-1}, \quad (2)$$

where the sums are taken over all the cyclotron resonances at that value of $v_{\parallel} = \mu\nu$. The functions V_j and W_j are the resonant wave phase and group speeds, respectively, obtained from the cold plasma dispersion relation, and the individual resonant wavenumbers are given by the cyclotron resonance condition as

$$k_r = \frac{\Omega}{\mu\nu - V_j}. \quad (3)$$

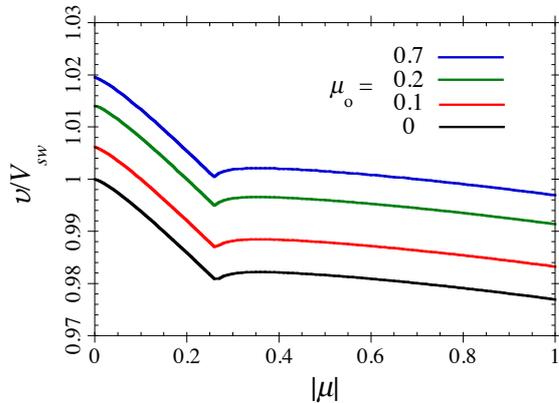


Figure 2. Shapes of the fully-scattered pickup proton shell, $v(\mu)$, for different initial pitch angles, μ_o , taking $V_A/V_{sw} = 1/18$. At the initial pitch angle, the speed of the pickup proton is $v(\mu_o) = V_{sw}$.

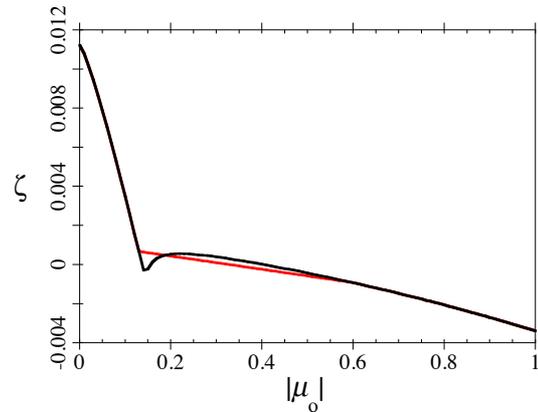


Figure 3. Fractional energy released to turbulent fluctuations by isotropization of a pickup proton with initial pitch angle μ_o . The current model uses the straight red segment to replace a portion of this function.

With the relative intensities given by (1), equation (2) can be integrated to give the fully scattered distribution, which only depends on the value of V_A/V_{sw} and the initial pitch angle of the ring-beam. (We consider here that the ENAs, and therefore the newly ionized protons have speeds equal to V_{sw} .)

In Figure 2, we show the shape of the fully-scattered shell, $v(\mu)$, for a typical Alfvén speed in the ISM, $V_A = 25 \text{ km s}^{-1}$ and for protons picked up at $V_{sw} = 450 \text{ km s}^{-1}$. The shape does not vary much for different initial pitch angles, but the condition that $v(\mu_o) = V_{sw}$ means that the total energy of the shell is larger when the newly ionized ENA has substantial motion along the magnetic field. The fractional change in proton energy which results from the scattering to a closed shell is given by the integral over these shapes. We define the function $\zeta(\mu_o)$ to be the fractional energy released to the resonant fluctuations by scattering process, such that the energy added to turbulence by each new ionization is $E_w = 0.5 \zeta m V_{sw}^2$. This function is plotted in Figure 3 for the same parameter values as in Figure 2.

We note that the function ζ passes through zero, so scattering to near-isotropy from some initial pitch angles will add energy to the turbulence, while scattering from other angles will drain energy (if any is present) from the turbulence. This property provides the physical mechanism that helps to distinguish the pickup protons which are diffusively retained in the plasma which ionized them from those protons which continue to stream away from the region of the ribbon. In our modeling thus far, we have used a simplified form of the ζ function, where a portion of the curve is replaced by the straight red segment shown in Figure 3.

3. Ribbon structure from spatial retention

In [13], we applied this DT formalism to a simple model of the ISM as the first step toward constructing a spatial retention model for the IBEX ribbon. We took the ISM to be a uniform magnetized plasma approaching the Sun with a velocity \mathbf{V}_{ISM} , ignoring any effects of flow deflection or field draping at the spherical heliopause. We considered the ionization, pickup and isotropization of secondary ENAs from the solar wind in the plane containing \mathbf{V}_{ISM} , the uniform field \mathbf{B}_{ISM} , and the Sun (see Figure 4). We defined a 2D Cartesian system, where x is the coordinate along the magnetic field and y points away from the Sun perpendicular to the field. We considered only particles of energy $\sim 1 \text{ keV}$, taking the speed of the ENAs and their pickup proton products to be $V_{sw} = 450 \text{ km s}^{-1}$.

As detailed in [13], we derived model equations for the pickup proton density $n(x, y)$

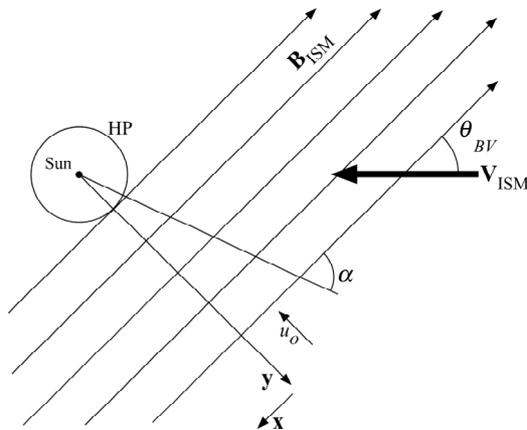


Figure 4. Model diagram of the nearby ISM in this paper. The ISM plasma streams to the left at $V_{\text{ISM}} = 23.2 \text{ km s}^{-1}$, carrying a constant magnetic field oriented at $\theta_{BV} = 45^\circ$ to the flow. The heliopause (HP) is taken to be a sphere, which reflects incident pickup protons. The ISM is uniform, with proton density $n_p = 0.07 \text{ cm}^{-3}$ and hydrogen density $N_H = 0.16 \text{ cm}^{-3}$, as in [13].

$$-u_o \frac{\partial n}{\partial y} = \frac{\partial}{\partial x} \left(D \frac{\partial n}{\partial x} \right) + P - L, \quad (4)$$

the turbulent intensity in Elsässer units $Z^2 = \langle \delta v^2 \rangle + \langle \delta b^2 / 4\pi\rho \rangle$,

$$-u_o \frac{\partial Z^2}{\partial y} = -\frac{2Z^4}{\lambda_{\parallel} V_A} + Q, \quad (5)$$

and the turbulent correlation length, λ_{\parallel} , which quantifies the dissipation scale

$$-u_o \frac{\partial \lambda_{\parallel}}{\partial y} = \frac{2Z^2}{V_A} - (\lambda_{\parallel} - \lambda_{res}) \frac{Q}{Z^2} S(Q), \quad (6)$$

as the ISM plasma flows toward the Sun with normal component u_o . In these equations, D is the spatial diffusion coefficient along the field, determined from quasilinear theory to be $\sim \lambda_{\parallel}^{2/3}/Z^2$. The charge-exchange production and loss rates of pickup protons are given by P and L , respectively, and are functions of position. The characteristic wavelength of the pickup-proton waves is $\lambda_{res} = 2\pi V_{sw}/\Omega_p$. The turbulence is modeled phenomenologically by designating the total intensity and the correlation length, as discussed by Breech et al. [23] and Oughton et al. [19]. The turbulent driving from the pickup proton scattering is denoted by $Q = \zeta V_{sw}^2 P/n_p$, where n_p is the ISM proton density, and it appears as a signed source term in the turbulence equations. Please see [13] for a more extensive explanation.

To specify the criterion between pickup protons that are scattered fast enough to complete their nearly isotropic shells, and those that are not, we require the scattering rate to be faster than the production rate for new pickup protons. This reduces to a limit on the turbulent intensity, such that if

$$Z^2 > (1 + r_A) \frac{\sigma n_p}{\Omega} V_A^2 V_{sw} \quad (7)$$

(where σ is the charge-exchange cross-section and r_A is the Alfvén ratio of the turbulence) we take the pickup protons to be nearly isotropic and coupled to the plasma. Otherwise, we assume that the new pickup protons are able to stream away and we set $n = 0$ there.

In [13], we solved the system of equations (4) - (6) from an outer boundary at $y = 2100 \text{ AU}$ in to the position of the heliopause, taken as a circle of radius 150 AU . At the outer boundary, we set the density and the turbulent intensity to zero, so the model ribbon is purely a local phenomenon, generated out of the ENAs produced in the solar wind. The pickup protons tend to be spatially retained around the region where $\hat{\mathbf{r}} \cdot \hat{\mathbf{b}} = 0$, despite their diffusion along the field away from this region. Integrating the sunward ENAs emitted by these nearly isotropic pickup protons along the line of sight to IBEX, we found that the ENA flux was enhanced in a qualitatively ribbon-like structure. However, the enhanced region spanned $\sim 30^\circ$ at the half-maximum point, wider than the observed ribbon, and the peak flux was only $22.4 \text{ (cm}^2 \text{ sr s keV)}^{-1}$, substantially lower than the $\sim 120 \text{ (cm}^2 \text{ sr s keV)}^{-1}$ inferred by Schwadron et al. [3].

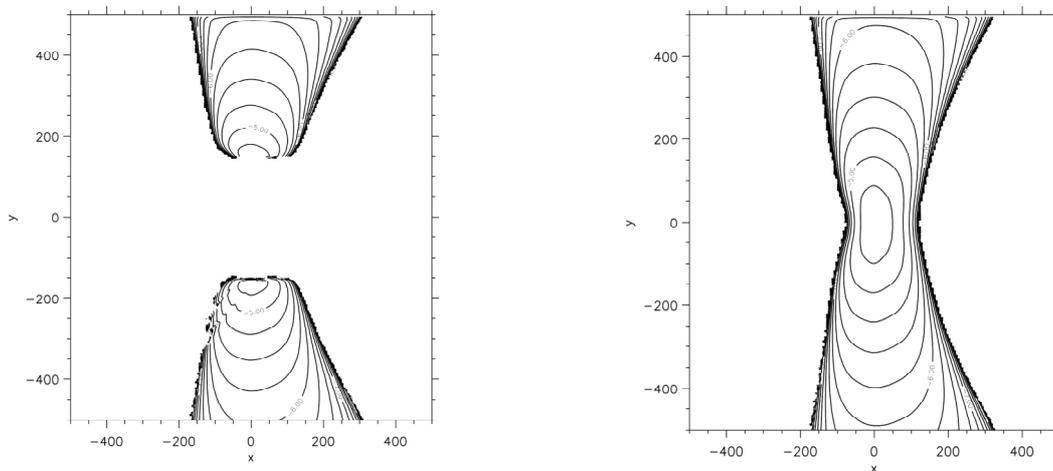


Figure 5. Model pickup proton density in 2 planes: $z = 0$ (left panel) and $z = 160$ AU (right panel). Shown are contours of $\log n$, where n is in units of cm^{-3} . Plot scales are ± 500 AU.

Still, it should be recognized that this is only the first step. Unlike the secondary ENA models assuming weak scattering, the spatial retention mechanism does not require the source ENAs to be nearly radially streaming. Since the ribbon protons are taken to scatter to isotropy, their source can come from anywhere.

4. Further modeling

Before proceeding with the effect of additional source particles for the model ribbon, we construct a 3D version of the previous model. In keeping with the simple investigative picture, we consider the heliopause to be a sphere and continue to neglect the effects of flow deflection and field-line draping by taking the ISM magnetic field to be straight and uniform. Since the interstellar magnetic field will not enter the heliosphere, we take the pickup protons in the ISM to be reflected at the heliopause surface. The ISM plasma flows parallel to the plane of the 2D model, so the 3D system is composed of more 2D planes, each defined by \mathbf{V}_{ISM} and \mathbf{B}_{ISM} , stacked in the z direction. The plasma properties in these planes are independent, so the model equations (4) - (6) can be solved separately within each plane, with only the spherically-symmetric sources and the effects of the heliopause boundary giving z -dependence of the solution.

We now wish to add the contribution of 1 keV ENAs from the inner heliosheath (IHS), defined as the spherical shell between the solar wind termination shock, taken to be at 100 AU, and the heliopause at 150 AU. To estimate the outward flux of heliosheath ENAs, we suppose the IHS to be uniformly filled with ENA-emitting material, which radiates 1 keV ENAs at some constant rate, isotropically in the rest frame of the material. We assume that the “global distributed flux” of 1 keV ENAs measured by IBEX [3] comes entirely from the IHS region. The spectrum of inward-streaming ENAs detected at IBEX is seen to vary with energy as $E^{-1.8}$ near 1 keV [24]. We assume that the IHS material is still flowing outward, with an average radial speed of 75 km s^{-1} . We then set the magnitude of the emitted flux to match these IBEX measurements, which we take to be $\sim 80 (\text{cm}^2 \text{ sr s keV})^{-1}$. A Compton-Getting transformation from the inward radial flux of the outward flowing emitters, then gives an outward ENA flux of $270 (\text{cm}^2 \text{ sr s keV})^{-1}$ at 1 keV.

Adding the contribution of these ENAs to the secondary solar wind flux taken in [13] yields a higher density of pickup protons in the spatial region of the ribbon. We take the same parameter values for the ISM as in that paper. In Figure 5, we show the pickup proton density from the model equations for two values of z . Figure 5a shows the density contours in the $\mathbf{V}_{\text{ISM}}\text{-}\mathbf{B}_{\text{ISM}}$ plane containing the Sun (where the heliosphere is considered empty of these ribbon particles), and Figure 5b shows the solution in the plane 160 AU above (or below) that plane. The line-of-sight integrated ENA flux from these pickup protons, as would be seen at IBEX, is shown in Figure 6 as a function of

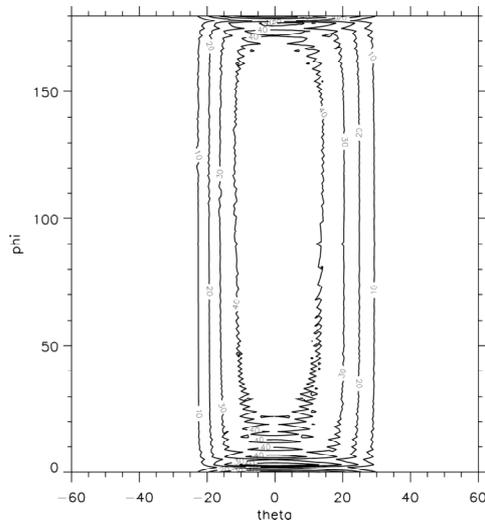


Figure 6. Model inward line-of-sight ENA flux as seen by IBEX as a function of angle from the upwind direction.

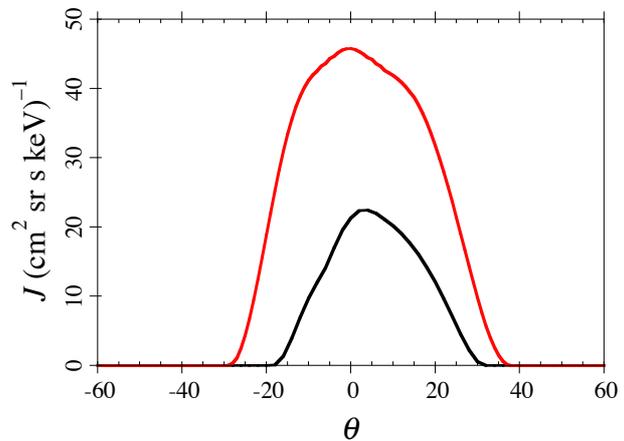


Figure 7. Model inward ENA flux in the upwind plane, as a function of angle across the ribbon. Upper red curve from this paper, lower black curve from [13].

angle on the sky. Here the wavy contours are caused by the limited grid resolution in z of our computation. The ENA flux across the ribbon structure in the upwind plane is given in Figure 7. The smaller black curve is the solution from [13], which only included the secondary solar wind source for the pickup protons. The new results here, including the IHS source, is shown by the larger, red curve. We see that the peak flux has approximately doubled, to $45.8 \text{ (cm}^2 \text{ sr s keV)}^{-1}$, but still falls short of the observed values. The more spatially distributed IHS source also leads to a broadened width of the structure.

Clearly, there is more work to be done and there are many aspects of the simple model discussed here that can be improved.

5. Summary

We have described our recent work on the spatial retention model for the IBEX ribbon, first suggested by Schwadron & McComas [12]. We extended the dominant turbulence formalism of pickup proton isotropization, developed by Isenberg [15] to explain the heating of the core protons in the outer solar wind observed by Voyager 2. This extended mechanism was applied to the conditions in the nearby interstellar medium to generate a ribbon structure of ENAs emitted from a confined spatial volume. Our first work took the solar wind secondary ENAs as the source for the ribbon pickup protons, but this model only obtained a predicted flux of $22.4 \text{ (cm}^2 \text{ sr s keV)}^{-1}$, as compared to the measured value of $\sim 120 \text{ (cm}^2 \text{ sr s keV)}^{-1}$. In this paper, we present new results, expanding the model to 3D and adding an estimated contribution of ENAs from the inner heliosheath. We find that the predicted ENA flux has improved, to $45.8 \text{ (cm}^2 \text{ sr s keV)}^{-1}$, but this value is still insufficient.

However, the model thus far is still extremely simplified. We will be exploring the effects of adding more accurate sources, modifying the isotropization and spatial diffusion behavior, and including draping of the ISM magnetic field around the heliopause.

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