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The Role of Pickup Ion Dynamics Outside of the Heliopause in the Limit of Weak Pitch Angle Scattering: Implications for the Source of the *IBEX* Ribbon

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Abstract

We present a new model of the *Interstellar Boundary Explorer* (*IBEX*) ribbon based on the secondary energetic neutral atom (ENA) mechanism, under the assumption that there is negligible pitch angle scattering of pickup ions (PUIs) outside the heliopause. Using the results of an MHD-plasma/kinetic-neutral simulation of the heliosphere, we generate PUIs in the outer heliosheath, solve their transport using guiding center theory, and compute ribbon ENA fluxes at 1 AU. We implement several aspects of the PUI dynamics, including (1) parallel motion along the local interstellar magnetic field (ISMF), (2) advective transport with the interstellar plasma, (3) the mirror force acting on PUIs propagating along the ISMF, and (4) betatron acceleration of PUIs as they are advected within an increasing magnetic field towards the heliopause. We find that ENA fluxes at 1 AU are reduced when PUIs are allowed to move along the ISMF, and ENA fluxes are reduced even more by the inclusion of the mirror force, which pushes particles away from *IBEX* lines-of-sight. Inclusion of advection and betatron acceleration do not result in any significant change in the ribbon. Interestingly, the mirror force reduces the ENA fluxes from the inner edge of the ribbon more than its outer edge, effectively reducing the ribbon's width by $\sim 6^\circ$ and increasing its radius projected on the sky. This is caused by the asymmetric draping of the ISMF around the heliopause, such that ENAs from the ribbon's inner edge originate closer to the heliopause, where the mirror force is strongest.

1. Introduction

The Sun emits the solar wind (SW) plasma, which flows radially away at $\sim 350\text{--}800\text{ km s}^{-1}$. The interstellar plasma interacts with the SW, forming the heliosphere. While the SW and very local interstellar medium (VLISM) plasmas are separated at the heliopause (a tangential discontinuity), interstellar neutral gas flows unimpeded into the heliosphere. The interstellar gas is directly measured by the *Interstellar Boundary Explorer* (*IBEX*; McComas et al. 2009a), an Earth-orbiting spacecraft, allowing us to determine the thermodynamic properties of the VLISM (e.g., McComas et al. 2009b, 2015; Möbius et al. 2009, 2015; Bzowski et al. 2015; Schwadron et al. 2015, 2016; Sokół et al. 2015; Swaczyna et al. 2015; Kubiak et al. 2016; Park et al. 2016). *IBEX* also measures energetic neutral atoms (ENAs) at $\sim 0.1\text{--}6\text{ keV}$ that are generated by charge-exchange interactions between the interstellar gas and energetic

SW ions downstream of the heliospheric termination shock. ENA measurements contain an imprint of the structural and thermodynamic properties of the termination shock and heliosheath (e.g., McComas et al. 2009b, 2014, 2017; Schwadron et al. 2011, 2014; Reisenfeld et al. 2012, 2016; Zirnstein et al. 2016a, b, 2017a, b).

In 2009, *IBEX* discovered an unpredicted band of enhanced energetic neutral atoms (ENAs) approximately forming a circle in the celestial sky (McComas et al. 2009b). Dubbed the “ribbon,” its intensity was shown to be a factor ~ 2 -3 times brighter than the surrounding, globally distributed flux. Analyses of the ribbon in the framework of 3D global MHD simulations (Pogorelov et al. 2009) of the heliosphere showed that the directions toward the ribbon are correlated with lines-of-sight perpendicular to the local interstellar magnetic field (ISMF; Schwadron et al. 2009). McComas et al. (2009b) suggested a number of possible sources for the ribbon, including the inner heliosheath (IHS), the heliopause, and the outer heliosheath (OHS). Since then, more possibilities have been suggested (for review, see McComas et al. 2014; see also new models by Isenberg 2014; Giacalone & Jokipii 2015).

The most widely accepted process for generating the ribbon is the secondary ENA mechanism. As the interstellar neutral gas flows into the heliosphere, it charge-exchanges with SW ions, creating pickup ions (PUIs) that are picked up by the SW, and a new “primary” neutral atom (primary ENA). In the supersonic SW, newly-formed primary ENAs propagate nearly radially away from the Sun. Because of their large mean free paths, most of these ENAs escape the heliosphere and propagate into the OHS. These ENAs eventually charge-exchange in the dense OHS (proton density is ~ 50 times larger in the OHS compared to the IHS), creating energetic PUIs that gyrate around the ISMF. Depending on the physical mechanisms that dominate the spatial and velocity distribution of PUIs outside the heliopause, after a second charge-exchange these PUIs can create secondary ENAs that may be preferentially-directed back towards Earth in *IBEX* look-directions perpendicular to the ISMF that drapes over the heliopause surface.

The physical processes governing the transport of PUIs outside the heliopause is a topical subject for understanding the origin of the ribbon. There are two common scenarios that have been suggested and developed: (1) PUIs experience negligible pitch angle scattering outside of the heliopause, such that their anisotropic distribution in velocity space is primarily the reason why *IBEX* observes an enhanced flux in radial directions ($\mathbf{R}$) perpendicular to the ISMF, i.e., $\mathbf{B} \cdot \mathbf{R} \sim 0$ (e.g., Heerikhuisen et al. 2010; Chalov et al. 2010; Möbius et al. 2013; Zirnstein et al. 2013, 2015a); (2) PUIs experience strong pitch angle scattering either due to PUI self-generated waves or existing Alfvénic turbulence (e.g., Florinski et al. 2010; Schwadron & McComas 2013; Isenberg 2014, 2015; Niemiec et al. 2016) – see Gamayunov et al (2010, 2017) and Giacalone & Jokipii (2015) for scenarios where pre-existing turbulence in some form maintains a quasi-anisotropic PUI pitch angle distribution in space that is observable by *IBEX*.

Based on the possibility that PUIs may maintain an anisotropic pitch angle distribution for several years before charge-exchange (see arguments by, e.g., Liu et al. 2012; Summerlin et al. 2014; Florinski et al. 2016; Florinski & Heerikhuisen 2017), in this paper we are motivated to develop a 3D model of the ribbon under the “weak” pitch angle scattering limit,

to help us understand if this physical scenario is viable. In the following sections, we present a model of the ribbon based on the transport of PUIs using guiding center theory (see, e.g., Chen 1984), compute the ribbon ENA fluxes at 1 AU, and discuss the effects of different transport terms on the ribbon flux, and their implications for understanding the observations. We plan a more detailed comparison to *IBEX* observations of the ribbon in a follow-up study.

2. Model

2.1. Guiding Center Theory

Depending on the energies of PUIs ($\sim$ few keV), their charge-exchange lifetimes ($\sim$ few years), and the scale size of the system ($\sim$ 10's to 100's of AU), different guiding center transport terms may be required to properly model the *IBEX* ribbon. In the limit of negligible pitch angle scattering, the guiding center will move parallel to the ISMF initially with speeds determined by their initial pickup velocity and pitch angle. This motion is straightforward to include, and may be important since PUIs can travel significant distances along the field within their lifetime if their initial pitch angle is small (e.g., Chalov et al. 2010). PUIs also advect with the VLISM plasma flow component perpendicular to the ISMF as the VLISM plasma flows toward, and past, the heliopause (i.e., the $\mathbf{E} \times \mathbf{B}$ drift). Though this effect may be small, it is straightforward to include. The motion of PUIs from these effects is given by

$$\mathbf{v}_{\parallel} = (\mathbf{v}_0 \cdot \mathbf{b}_0)\mathbf{b}, \mathbf{v}_{\perp} = \mathbf{u}_{\perp} = \mathbf{u}_p - (\mathbf{u}_p \cdot \mathbf{b})\mathbf{b}, \quad (1)$$

where $\mathbf{v}_{\parallel}$ is the PUI velocity parallel to the field, $\mathbf{v}_{\perp}$ is the $\mathbf{E} \times \mathbf{B}$ drift speed perpendicular to the ISMF resulting in a guiding center moving with the perpendicular component of the bulk flow $\mathbf{u}_{\perp}$, $\mathbf{v}_0$ is the initial PUI velocity, $\mathbf{b} = \mathbf{B}/|\mathbf{B}|$ is the local ISMF unit vector ($\mathbf{b}_0$ is the ISMF at the initial position of the PUI), and $\mathbf{u}_p$ is the local plasma flow velocity.

The draping and compression of the ISMF around the heliopause introduces effects such as magnetic mirroring force and betatron acceleration of PUIs moving into and out of regions of compressed ISMF. When a PUI sees a slowly varying magnetic field, a situation that occurs near the heliopause in our simulation of the heliosphere (Zirnstein et al. 2016b), the magnetic moment is conserved ($\mu = 1/2 m w_{\perp}^2 / B = \text{constant}$, where $w_{\perp}$ is the perpendicular gyration velocity of the PUI). This implies that as a PUI experiences a magnetic field that slowly increases or decreases in magnitude, the PUI's parallel speed will change according to

$$\frac{dv_{\parallel}}{dt} = -\frac{\mu}{m} \frac{\partial B}{\partial s_{\parallel}}, \quad (2)$$

where m is the proton mass, and $s_{\parallel}$ is the spatial coordinate parallel to the ISMF. Considering that PUIs may have a significant $v_{\parallel}$, we include this effect in the model.

PUIs that are advected with the VLISM plasma will experience adiabatic (i.e., “betatron”) acceleration perpendicular to the ISMF, according to

$$\frac{dE_{\perp}}{dt} = \mu \frac{\partial B}{\partial t}. \quad (3)$$

where they may gain or lose perpendicular energy depending on the change in the ISMF magnitude. It is possible that PUIs will gain a significant amount of energy if they survive from charge-exchange for a few years. For example, if a 1 keV PUI advects with the VLISM plasma at $\sim 25 \text{ km s}^{-1}$ for two years, it may be advected up to $\sim 10 \text{ AU}$ in the direction perpendicular to the field. This distance is small compared to the scale at which changes in the ISMF magnitude occur. However, a small change in perpendicular energy may have an important effect on the particle pitch angle, which is a sensitive property for *IBEX* observations. Therefore, we include this effect in our model in order to understand its significance.

We neglect gradient and curvature drifts because (1) most PUIs outside the heliopause do not travel far before they experience charge-exchange, and (2) the $\sim \text{keV}$ PUI gyro-radius is much smaller than the distances at which significant changes in the ISMF occur. Thus, the guiding center terms defined in Equations (1)-(3) are introduced into our model of the ribbon. The method of solving the transport of PUIs and converting their distribution into ENA fluxes is described in Section 2.2.

2.2. Solving PUI Transport and Secondary ENA Flux

To simulate the above-mentioned dynamics (Equations 1-3), we trace the location of the gyro-centers and energization of PUIs backwards in time using a Runge-Kutta (RK) integrator (for simplicity, we use a second-order, predictor-corrector method). The motion of PUIs is deterministic in the limit of negligible pitch angle scattering, allowing us to work backwards from the position and time of secondary ENA emission (final position, pitch angle, and energy are known from a desired *IBEX* line-of-sight and ENA energy).

We step radially outward along an *IBEX* line-of-sight, and at each radial step outside of the heliopause, we integrate the PUI guiding center Equations (1)-(3) backwards in time starting from the position at which a secondary ENA (with some desired energy and pitch angle corresponding to the *IBEX* energy bin and line-of-sight we are computing) is created. Thus, we integrate over the range $0 \leq t \leq t_{\text{max}}$ (where $t_{\text{max}} \gg \tau_{\text{ex}}$, and $\tau_{\text{ex}} = (\eta_{\text{H}} \sigma_{\text{ex}} v)^{-1}$ is the PUI charge-exchange mean free time), tracking the guiding center motion of a PUI and its change in energy and pitch angle. This is illustrated in Figure 1.

For each step along the guiding center motion (with time step Δt), we interpolate the local SW/VLISM properties from our MHD-plasma/kinetic-neutral simulation to update the parameters in Equations (1)-(3). After each step, we calculate the local production of PUIs

with the energy and pitch angle properties we are tracing, from our local primary ENA phase space distribution (Heerikhuisen & Pogorelov 2010). Then, the contribution of these PUIs in creating secondary ENA flux back at the original starting position ($\mathbf{r}$) is determined by weighting their flux by the probability for the PUIs to survive charge-exchange before traveling from their creation point $\mathbf{r}'$ to the original start position $\mathbf{r}$. We weight using a normalized charge-exchange time scale, similar to the method used by Zirnstein et al. (2015b):

$$W(t) = \frac{\exp(-t/\tau_{ex})}{\int_0^{t_{max}} \exp(-t'/\tau_{ex}) dt'}, \quad (4)$$

where we integrate up to $t_{max} = 4\tau_{ex}$. For simplicity, we only calculate τ_{ex} once at $t = 0$ (i.e., the secondary ENA flux creation point, and the PUI end position). This assumption is sufficient because the majority of PUIs that can create ENAs observable by *IBEX* do not travel far, with pitch angles near $\sim 90^\circ$.

Thus, the secondary ENA differential flux equation is given by (similar to Zirnstein et al. 2015b)

$$\Delta J(\mathbf{r}, \mathbf{v}) = \frac{1}{m} v p(\mathbf{r}, \mathbf{v}) \times \left[\int_0^{t_{max}} W(t) \frac{1}{2\pi} \int_{\Omega} f_H(\mathbf{v}_H, \mathbf{r}') n_p(\mathbf{r}') v_{rel} (|\mathbf{v}_H - \mathbf{u}_p(\mathbf{r}')|) \sigma_{ex}(v_{rel}) d\Omega dt \right] dr, \quad (5)$$

where n_p is the proton density at PUI creation position $\mathbf{r}'$, f_H is the phase space distribution of primary ENAs in the Sun frame (for details, see Heerikhuisen et al. 2016) that are converted to protons at position $\mathbf{r}'$ by integrating over a ring beam in velocity space ($d\Omega$) at each step t along the PUI guiding center history, with properties that match the local PUI energy and pitch angle we wish to create, v_H is the parent ENA velocity in the Sun frame (initially, $v_H = nu$; but this changes in time t according to Equations 1-3), P is the secondary ENA survival probability from position $\mathbf{r}$ back towards Earth (however, similar to the published *IBEX* data, we only account for losses outside 100 AU from the Sun), and v_{rel} is the relative interaction velocity between parent ENA and the background plasma distribution (assumed to be Maxwell-Boltzmann) according to (e.g., Ripken & Fahr 1983; Heerikhuisen et al. 2006)

$$v_{rel} = v_{th,p} \left[\frac{\exp(-\omega^2)}{\sqrt{\pi}} + \left(\omega + \frac{1}{2\omega} \right) \text{erf}(\omega) \right], \quad \omega = \frac{1}{v_{th,p}} |\mathbf{v}_H - \mathbf{u}_p|, \quad (6)$$

where $v_{th,p}$ is the plasma thermal velocity. The formula for the energy-dependent, charge-exchange cross section (σ_{ex}) is taken from Lindsay & Stebbings (2005). We compute the contribution of secondary ENA flux for each step Δt along the PUI history, adding them up and weighting by Equation (4). Then, once we have accumulated the total secondary ENA flux at $\mathbf{r}$, we step along the *IBEX* line-of-sight $\mathbf{r} + \Delta \mathbf{r}$, and repeat the above processes. The same procedure is followed for each line-of-sight in the sky.

2.3. Simulation of the Heliosphere

For the ribbon model calculations performed in this study, we utilize the results from a three-dimensional simulation of the SW and VLISM interaction (Zirnstein et al. 2016b). This simulation is based on a three-dimensional plasma-neutral code that solves magnetohydrodynamic equations for the plasma and Boltzmann's equation for neutral hydrogen. The plasma and neutrals are coupled via energy-dependent, charge-exchange source terms (Pogorelov et al. 2008). We utilize the simulation results from the $3 \mu\text{G}$ interstellar magnetic field case from Zirnstein et al. (2016b; see their Table 1), with interstellar plasma/neutral temperature 7500 K, and speed 25.4 km s^{-1} from inflow direction $(255.7^\circ, 5.1^\circ)$ in ecliptic J2000 coordinates (McComas et al. 2015). The SW boundary conditions at 1 AU are given by plasma density 5.74 cm^{-3} , temperature 51,100 K, speed 450 km s^{-1} , and magnetic field radial component $37.5 \mu\text{G}$. Neutral hydrogen atoms generated in the supersonic SW in the kinetic-neutral module are assigned velocities as a function of heliolatitude from SW speeds derived from an interplanetary scintillation observation-based model, allowing us to emulate the latitudinal SW structure (for more details, see Sokół et al. 2013; Zirnstein et al. 2013, 2015b, 2016b).

While the choices of the SW and VLISM boundary conditions will affect the ribbon model results, such as the neutralized SW production rate and the draped interstellar magnetic field, they are chosen based on remote and in situ spacecraft observations, such that the model reproduces (1) the distance to the heliopause in the *Voyager 1* direction (Gurnett et al. 2013), (2) the average ribbon center and structure (Funsten et al. 2013), (3) the consistency of the interstellar neutral hydrogen deflection plane and B - V plane (Lallement et al. 2005, 2010), and (4) the interstellar neutral hydrogen density at the nose-ward termination shock ($\sim 0.1 \text{ cm}^{-3}$; Bzowski et al. 2009).

3. Results

3.1. PUI Guiding Center Motion

In this section, we first present an example of PUI guiding center motion outside of the heliopause which demonstrates how each guiding center term affects the motion and energization of PUIs. Table 1 lists the four primary guiding center terms included in the

model. The variables used to identify the terms in Table 1 are used elsewhere in the paper to help the reader identify the different processes.

Before discussing the results in Figures 2 and 3, we note that the example in these figures shows the transport of a PUI with a large parallel speed towards the heliopause. However, this scenario is unlikely to occur in reality. Most PUIs created outside the heliopause are from primary ENAs traveling radially away from the Sun (a more diffuse population originates from the inner heliosheath, allowing for wider angles). Most PUIs created from these ENAs would not be initially traveling with large parallel motion closer towards the heliopause. If they have a sufficiently large parallel speed, they would travel away from the heliopause.

However, we choose to show this particular example for several reasons: (1) it clearly illustrates the effects of the transport terms on the PUI transport, showing visible changes in the PUI position and properties over time (see also Figure 3); (2) since most secondary ENAs that *IBEX* does observe are created from PUIs with large initial pitch angles, they do not travel very far from their initial position – this would not result in a good illustration of the transport model. Therefore, the example shown in Figures 2 and 3 are meant to demonstrate the effects of the transport model. For the remaining results presented in Section 3, however, we use a realistic source of PUIs from our simulation of the heliosphere in order to model the ribbon and discuss which transport terms are important for understanding the source of the ribbon under the limit of negligible pitch angle scattering.

Thus, to illustrate how the transport terms in Table 1 may affect particles outside the heliopause, Figure 2 shows an example of a PUI that becomes a 1.11 keV ENA at 200 AU from the Sun, in the direction of $(270^\circ, -17^\circ)$ ecliptic J2000, which is near the peak of the ribbon flux. The PUI has a final pitch angle such that after it experiences charge-exchange, it would create a secondary ENA observable by *IBEX*. As one can see, the guiding center motion of the PUI takes it closer to the heliopause, mostly moving south-ward and port-ward along the ISMF. The particle slightly gains energy, but only over a distance much longer than its average lifetime, and its pitch angle changes as it approaches its final position.

The particular reasons for this motion are explained in more detail in Figure 3. Figure 3 shows how each guiding center term (see Table 1) affects the transport of the PUI from the example in Figure 2. First, the parallel speed of the PUI ($v_{\parallel}$) carries it along the ISMF closer towards the heliopause. Second, when the $\mathbf{E} \times \mathbf{B}$ drift term is included ($v_{\perp}$), the particle is slowly advected towards the heliopause with the bulk plasma flow – thus, the PUI originates slightly farther away from the heliopause compared to the first case. Third, when we include the magnetic mirror force (F_M) and betatron acceleration force (F_B) terms, the particle's history is significantly different. The guiding center trajectory changes mostly because of the mirror force. As the particle moves along the field, it slows down as the ISMF magnitude increases. Thus, in order to end up at the same position with the same energy and pitch angle as the other examples, the PUI had to originate farther away with larger parallel speed. This can be seen in the right panel, which shows the change in pitch angle, mostly due to the magnetic mirror force. Note that the pitch angle is initially greater than 90° , because it is

streaming anti-parallel to the ISMF. As the particle approaches its final position, the pitch angle decreases towards 90° before becoming an ENA.

The addition of betatron acceleration does not significantly change the transport of the PUI (the trajectory is nearly the same with and without F_B), although it does slightly change the pitch angle due to its coupling to the perpendicular energy. As the PUI is carried with the bulk plasma perpendicular to the ISMF, it travels into a more compressed ISMF. This increases the perpendicular energy of the PUI, proportional to the change in ISMF magnitude. However, most $\sim$ keV PUIs do not survive charge-exchange for more than a few years, so the majority of ribbon ENAs observed by *IBEX* won't originate from PUIs that traveled very far from their initial position. Also, from our discussion above, most PUIs won't be travelling with significant parallel speed closer to the heliopause since most parent ENAs travel radially away from the Sun. Nevertheless, Figures 2 and 3 clearly demonstrate how the different guiding center effects may alter the trajectories of PUIs outside the heliopause. In the following sections, we will show quantitatively how each term affects the ribbon flux based on a more realistic simulation of the neutralized SW distribution.

3.2. Ribbon ENA Fluxes at 1 AU

Figures 4 and 5 show the simulated ribbon fluxes at 1.11 and 2.73 keV when we consecutively include different PUI guiding center transport terms. First, we show the ribbon flux when there are no transport effects. This means that there is no change in position, energy, or pitch angle of the PUI after it was created. Next, when we include the parallel speed term ($v_{\parallel}$), the ribbon flux decreases in intensity almost uniformly over the whole sky. This is because most PUIs that are observable by *IBEX* must have pitch angles near $\sim 90^\circ$. If PUIs are allowed to move along the ISMF, then a fraction of them stream away from locations where the spacecraft line-of-sight (approximately radial with respect to a Sun-centered frame) is perpendicular to the ISMF, i.e., $\mathbf{B} \cdot \mathbf{R} \sim 0$. Next, adding the advective term ($v_{\perp}$) to the guiding center motion does not significantly affect the ribbon flux. However, the magnetic mirror force (F_M) both (1) decreases the ribbon flux, and (2) appears to decrease the width of the ribbon. Finally, adding the betatron acceleration term (F_B) does not appear to significantly affect the ribbon fluxes. Similar behavior is seen over a range of ENA energies.

In Figure 6 we show a side-by-side comparison between our model of the ribbon in the “weak” pitch angle scattering limit (when all transport effects are included), and *IBEX* observations where the GDF was masked out (Schwadron et al. 2014). Generally, the model ribbon intensities approximately match *IBEX* observations. There appears to be less flux in the observed ribbon at ecliptic longitude/latitude $(-60^\circ, 0^\circ)$ compared to our model – this is either due to an inaccurate model of the neutralized SW, or some of the ribbon flux may have been removed with the GDF. Our model also appears to predict a ribbon slightly narrower than the observed ribbon, but the angular binning of *IBEX* data may artificially increase the ribbon width.

3.2.1. Effects of Guiding Center Motion on Ribbon Intensity—In Figure 7, we can see more clearly how each guiding center transport term affects the ribbon flux. This figure

shows the percent change in 1.11 keV ribbon flux as we consecutively add each transport term, similar to Figures 4 and 5. To aid the reader, we also plot an isocontour at the 25% level of the maximum model ribbon flux in the sky before the addition of a transport term. For example, panel (a) shows the change in ribbon flux from (1) the case when we do not include any transport terms to (2) the case when we allow for the parallel speed of PUIs. The isocontour shows the ribbon shape before adding the transport term. This overall shows a reduction in ribbon flux of $\sim 25\%$ near the ribbon. Interestingly, there is a slightly greater reduction of $\sim 50\%$ on the right edge of the ribbon. We will show later in Section 3.2.2 that this is a reflection of the asymmetric draping of the ISMF around the heliopause.

In Figure 7b, we show the change in flux when we add the perpendicular advection term ($v_{\perp}$), compared to the case when only $v_{\parallel}$ was included. It is clear that this motion, by itself, does not significantly affect the ribbon flux. This is because the VLISM flow is quite slow, and does not carry the PUIs over a significant distance before they experience charge-exchange.

In Figure 7c, we add the magnetic mirror force to the PUI transport (such that $v_{\parallel}$, $v_{\perp}$, and F_M are included). Adding this term again significantly reduces the ribbon flux. Interestingly, it decreases the flux more on the right edge of the ribbon ($\sim 80\%$; see dark blue band on right edge of the ribbon), and not as much on the left edge ($\sim 30\%$). This effectively reduces the width of the ribbon (see also Section 3.3). The reason for this behavior is related to how the ISMF drapes around the heliosphere. The ISMF is compressed more strongly closer to the heliopause (see Figures 2 and 3), where the highest ribbon ENA intensity is generated (see Zirnstein et al. 2015a, Figure 1). Due to the unique draping of the ISMF around the heliopause (e.g., Pogorelov et al. 2011), and the curvature of the $\mathbf{B} \cdot \mathbf{R} \sim 0$ plane and, thus, the ribbon source region as a function of distance from the heliopause (Zirnstein et al. 2015a, 2016b), ENAs observed from the right edge of the ribbon originate closer to the heliopause. PUIs that were parent to ENAs observed from the right edge of the ribbon experienced a stronger magnetic mirror force during their lifetime, and therefore more strongly affected the ribbon flux at 1 AU.

Finally, when we add the betatron acceleration term (F_B) in Figure 7d, the ribbon flux does not significantly change. We conclude that (1) the ability of PUIs to move parallel to the ISMF significantly reduces the ribbon flux, and (2) the magnetic mirror force on PUIs near $\mathbf{B} \cdot \mathbf{R} \sim 0$ also reduces the ribbon flux, but more so on the right edge of the ribbon due to the origin of these ENAs being closer to the heliopause (see Figure 7e for the effect of all terms together). In summary, the greatest effect that the PUI transport terms have on the ribbon flux at 1 AU is a significant reduction in ENA fluxes, particularly on the inner edge of the ribbon, since fewer secondary ENAs coincide with *IBEX* lines-of-sight.

In Figure 7 we saw how the parallel speed and magnetic mirror force acting on PUIs significantly changes the ribbon flux at 1 AU. To better understand how this occurs, Figure 8 shows the line-of-sight average change in parallel energy ($E_{\parallel}$), perpendicular energy ($E_{\perp}$), and pitch angle (α) of PUIs outside the heliopause, weighted in directions where the most significant changes in ENA flux occur when all PUI guiding center transport terms are included. Note that the calculations in Figure 8 are for PUIs that result in 1.11 keV ENAs at

1 AU. These maps are calculated similarly to Equation (5): at each step along the PUI guiding center history, we integrate not the local ribbon flux, but the accumulated change in the PUI property, e.g., $E_{\parallel}$, still weighted by the survival probability from Equation (4). This yields the average change in PUI parameter $\langle \Delta E_{\parallel}(\mathbf{r}) \rangle$ that contributed to ENA fluxes at each line-of-sight step r . Then, we integrate this value along the line-of-sight, weighted by the local ribbon flux $J(\mathbf{r})$, divided by the total line-of-sight integrated ENA flux $J_{\text{tot}}(\mathbf{r})$. Finally, we weight this value by the change in ENA flux of each pixel compared to the maximum change in the entire sky ($|J_{\text{All}}(\mathbf{r}) - J_{\text{None}}(\mathbf{r})|/\text{MAX}[|J_{\text{All}}(\mathbf{r}) - J_{\text{None}}(\mathbf{r})|]$), where “All” and “None” refer to the ribbon models where all 4 guiding center motion terms are included, and the model where none are included, respectively. We also show an isocontour at 25% of the maximum ribbon flux for the model without guiding center dynamics.

First, in Figure 8a we see how the parent PUI energy parallel to the ISMF ($E_{\parallel}$) changes as a function of the observed change in ribbon ENA flux when the PUI guiding center terms were added. We can see that the parallel energy of PUIs decreased by ~ 50 eV before creating ENAs on the right edge of the ribbon. The majority of these PUIs experience a reduction in their parallel speed due to the magnetic mirror force, reducing their parallel energy. Elsewhere along the ribbon, there is little change in ribbon flux and PUI $E_{\parallel}$. In Figure 8b, we show the average change in the PUI perpendicular energy, $E_{\perp}$. Again, the most significant change in the ribbon flux occurred on its right edge, where the PUIs' $E_{\perp}$ also increased by ~ 50 eV. This is largely because of the conservation of magnetic moment of PUIs, in response to their reduction in parallel energy by the magnetic mirror force. While betatron acceleration does increase the PUI energy, this is small compared to the changes from the magnetic mirror force. Thus, the total PUI energy does not significantly change (Figure 8c).

Finally, in Figure 8d, we see the average change in PUI pitch angle α . Where there was the most significant change in the ribbon, the average PUI pitch angle increased $\sim 6^{\circ}$. Therefore, we see that the primary reason why the ribbon intensity on the right edge of the ribbon decreased when adding the magnetic mirror force term is that transport history of parent PUIs reflected a change in their pitch angle, but not total energy. This behavior is a reflection of the asymmetric draping of the ISMF around the heliopause, and the corresponding distance from the heliopause where ENAs from the right edge of the ribbon originate. This is examined in more detail in Section 3.2.2.

3.2.2. Significance of the Magnetic Mirror Force Effect—Our interpretation of the effect of the magnetic mirror force on PUIs relevant to the *IBEX* ribbon is the opposite of that concluded by Chalov et al. (2010), who also modeled the ribbon flux under the assumption of negligible pitch angle scattering (however, only including the parallel transport and magnetic mirror force terms). While they reported a $\sim 25\%$ increase in ribbon flux when the magnetic mirror force is included, our model shows there is a decrease (between $\sim 25\%$ and 80% , depending on the direction in the sky). Chalov et al. (2010) state that an increase in ribbon flux occurs because PUIs transported into regions of space with compressed ISMF (i.e., moving towards a positive gradient in the field) are able to slow down and maintain pitch angles closer to $\sim 90^{\circ}$ for longer periods of time, increasing the ribbon flux observable at 1 AU from directions near $\mathbf{B} \cdot \mathbf{R} \sim 0$.

First, it seems unlikely this is the case, since most $\sim$ keV PUIs only survive for $\sim$ 1-2 years before charge-exchange and cannot travel very far (<10 AU) into regions of significantly different ISMF. Second, the majority of parent primary ENAs at $\sim$ 0.7-3 keV are created in the supersonic SW and are traveling radially away from the Sun. ENAs that produce PUIs at large distances away from $\mathbf{B} \cdot \mathbf{R} \sim 0$ will move along the ISMF even further away from $\mathbf{B} \cdot \mathbf{R} \sim 0$ since their initial parallel velocity is always away from $\mathbf{B} \cdot \mathbf{R} \sim 0$, and will experience charge-exchange well before they can be “reflected” back towards $\mathbf{B} \cdot \mathbf{R} \sim 0$ from another large-scale gradient in the ISMF. Thus, most PUIs that create observable ribbon ENAs were created locally to $\mathbf{B} \cdot \mathbf{R} \sim 0$ with initial pitch angles near $\sim 90^\circ$. Third, since most observable ribbon ENAs likely come from PUIs with initial pitch angles $\sim 90^\circ$ near $\mathbf{B} \cdot \mathbf{R} \sim 0$, and that the ISMF magnitude appears to be strongest near $\mathbf{B} \cdot \mathbf{R} \sim 0$ in our simulation (see also Chalov et al. 2010, Figure 1; Ratkiewicz et al. 2012, Figure 1) and has a negative gradient away from $\mathbf{B} \cdot \mathbf{R} \sim 0$, then a significant number of these PUIs will be pushed away from $\mathbf{B} \cdot \mathbf{R} \sim 0$ by the magnetic mirror force, reducing the observable ribbon flux. Therefore, while it is unclear why the results from Chalov et al. (2010) differ from ours, we believe our model produces physically correct results.

3.2.3. Asymmetry of the ISMF Draped Around the Heliopause and the Ribbon Source Region

Figures 7 and 8 revealed that the ribbon is strongly affected when PUIs move parallel to the ISMF, and experience a significant magnetic mirror force. This is due to the unique tilt of the pristine ISMF far from the heliosphere and the way the ISMF drapes around the heliopause.

To illustrate this, in Figure 9 we show the 1.11 keV ribbon ENA production rate outside of the heliopause for the ribbon model where (1) no guiding center motion is included, and (2) all transport terms from Table 1 are included. In general, there is a maximum flux of ENAs near $\mathbf{B} \cdot \mathbf{R} = 0$, primarily because this is where the majority of primary ENAs can create PUIs with pitch angles that coincide with *IBEX* look directions. There is a less significant number of ENAs created away from $\mathbf{B} \cdot \mathbf{R} = 0$, likely originating from suprathermal ENAs from the IHS. This population extends below the maximum ribbon intensity region, but also appears to wrap around the heliopause as the ISMF drapes more strongly, improving the chances of observing ENAs from directions nearly perpendicular to the draped field. In the top-right of the figures, though, no ENAs are created here (we plot only ENAs that are observable by *IBEX*). This demonstrates the unique geometry of the draped ISMF, and how the ribbon ENA population depends on the primary ENA source (neutralized supersonic SW or suprathermal neutrals from the IHS; see also Zirnstein et al. 2015a).

The bottom panel of Figure 9 shows the change in ribbon ENA production rate when comparing the two models in the top panels. As one can see, the largest change is a decrease in flux near $\mathbf{B} \cdot \mathbf{R} = 0$, and close to the heliopause. This is partially caused by the parallel motion of PUIs away from $\mathbf{B} \cdot \mathbf{R} = 0$, as well as the added action of the magnetic mirror force, which is effective at pushing particles with $\sim 90^\circ$ pitch angles away from $\mathbf{B} \cdot \mathbf{R} = 0$, especially near the heliopause where the ISMF is the most compressed. Close to the heliopause ($x \sim 100$ AU, $z \sim 0$ AU) where the ENA production rate is highest, the percentage drop is significant ($\gtrsim 50\%$), thus, this is where the right edge of the ribbon decreased most in flux (see Figure 8). In the last panel, we plot the directions where the maximum ribbon flux propagates

towards 1 AU before and after adding the PUI guiding center transport terms. Since the maximum change in flux occurred close to the heliopause, which is at a slightly higher elevation, the direction of maximum flux dropped to lower elevation. This causes the reduction in ribbon width and effectively, its movement.

3.2.4. Effects of Guiding Center Motion on Ribbon Shape—In the previous section, we saw how the PUI guiding center transport terms changed the ribbon fluxes. In this section, we show how they change the position of the ribbon in the sky. Figure 10 shows the position of the ribbon using an isocontour at 25% of the peak ribbon flux, for ENA energies 1.11 and 2.73 keV. We show the outline of the ribbon after each transport term is successively added to the PUI transport model. First, at 1.11 keV, the ribbon shape does not significantly change when the parallel motion and perpendicular drift terms are included. However, the shape of the ribbon changes when the magnetic mirror force term is included (the orange and red outlines are nearly the same). The ENA flux from the right edge of the ribbon decreased, effectively reducing its width by $\sim 6^\circ$ almost uniformly along the ribbon. The left edge of the ribbon doesn't significantly change in intensity; therefore, the ribbon's width decreases.

Changes in the ribbon's position at 2.73 keV is more complex. The width of the ribbon at 2.73 keV decreases slightly when PUIs are allowed to propagate along the ISMF and are advected with the bulk plasma flow, but the ribbon also appears to move slightly outwards from its center position due to the magnetic mirror force action on the PUIs (as before, the orange and red outlines are nearly the same). Thus, the most significant change in the shape of the ribbon at ~ 1 keV is caused by the mirror force acting on PUIs close to the heliopause, affecting the right edge of the ribbon and decreasing its width. At higher energies, this effect is less significant since higher energy ENAs originate farther away from the heliopause (see Zirnstein et al. 2016b), there is still a small decrease in width and motion of the ribbon away from its center.

4. Conclusions and Future Work

In this paper, we aim to improve our understanding of the origin of the *IBEX* ribbon. Since physical processes governing PUIs outside the heliopause is currently a topical subject, we are motivated to model the ribbon under the assumption that there is negligible PUI pitch angle scattering outside the heliopause, such that the transport of PUIs can be modeled by guiding center theory. Our model includes four different PUI guiding center terms: parallel motion along the ISMF, $E \times B$ drift as PUIs are advected with the VLISM plasma perpendicular to the ISMF, the magnetic mirror force acting on PUIs as they move along the ISMF into regions of increasing or decreasing ISMF, and betatron acceleration force acting on PUIs as they advect toward the heliopause into the compressed ISMF draped around the heliosphere.

By including different guiding center transport effects, we are able to understand how each affects the ribbon flux at 1 AU. First, the motion of PUIs parallel to the ISMF reduces the ribbon flux almost uniformly (Figure 7). In this scenario, PUIs are allowed to move away from $B \cdot R \sim 0$ without a change in pitch angle, reducing the number of ENAs that can be

observed by *IBEX*. Second, the advective motion of PUIs by the $\mathbf{E} \times \mathbf{B}$ drift does not significantly change any observable property of the ribbon, primarily because the average distance PUIs traveled before charge-exchange is small compared to the size of the ENA source region and distances over which the ISMF changes significantly. Third, the magnetic mirror force reduces the ribbon flux (Figure 7), especially on the right edge of the ribbon, which effectively reduces the width of the ribbon (Figure 9). This occurs primarily because of the change in PUI pitch angle near $\mathbf{B} \cdot \mathbf{R} \sim 0$ (Figure 8) close to the heliopause (Figure 9). Finally, the addition of the betatron acceleration term does not significantly change the ribbon, since the energy gain is too small for the majority of PUIs observable by *IBEX*.

The significant change in the width of the ~ 1 keV ribbon due to the action of the magnetic mirror force on PUIs outside of the heliopause is a reflection of the asymmetric draping of the ISMF outside of the heliopause, and thus, the ribbon ENA source region. A significant drop in ENA fluxes at 1 AU is observed from directions on the right edge of the ribbon, since these ENAs were born from PUIs under the action of the magnetic mirror force close to the heliopause. Thus, the forces acting on PUIs near the heliopause may reveal themselves in the ribbon fluxes in an asymmetric fashion, which may be an important observation to look for in future analyses of the *IBEX* ribbon. This paper focused mainly on understanding how the transport of PUIs under the limit of weak pitch angle scattering affects the ribbon flux at 1 AU. While our current results appear to compare well to *IBEX* observations (Figure 6), in a subsequent paper, we will compare the simulations with *IBEX* observations in more detail to determine the similarities and differences in intensity, shape, and geometry in different pitch angle scattering regimes.

4.1. The Magnetic Mirror Force, the *IBEX* Ribbon, and the ISMF

Assuming that there is negligible pitch angle scattering of PUIs outside of the heliopause (further testing of this hypothesis will be the subject of a follow-up study), then the significance of the magnetic mirror force on PUIs outside of the heliopause can provide another unique constraint on the ISMF outside of the heliopause. For example, the compression of the ISMF as it drapes around the heliopause is a function of the distance from the heliopause, the scale size of the heliosphere (and SW plasma pressure inside the heliopause), and the relative magnetic and thermal pressures in the interstellar medium. Both *Voyager 1* and *IBEX* observations strongly suggest the ISMF far from the heliopause is directed near the ribbon center, with a magnitude $\sim 3 \mu\text{G}$ (e.g., Grygorczuk et al. 2014; Zirnstein et al. 2016b), but changes direction due to draping and compresses to a magnitude of $\sim 5 \mu\text{G}$ near the location of *Voyager 1* (e.g., Burlaga & Ness 2016; Pogorelov et al. 2017). The level of compression and the way it drapes around the heliosphere can affect the motion of PUIs, possibly providing another independent constraint on the ISMF using observations of the ribbon at 1 AU. Moreover, significant changes in the SW dynamic or magnetic pressure over time (e.g., co-rotating interaction regions, globally-merged interaction regions, or long-term changes in the SW pressure, see McComas et al. 2017) will propagate through the heliosheath and into the VLISM. Such disturbances affect both the ISMF strength and the geometry of the field draping (e.g., Kim et al. 2017; Pogorelov et al. 2017), and could be reflected in the ribbon flux a few years after the changes are observed at 1 AU.

4.2. Small-Scale Magnetic Turbulence from the VLISM

Giacalone & Jokipii (2015) presented a model of the ribbon under the assumption that there is pre-existing magnetic turbulence outside of the heliopause from the VLISM. While they assumed that the ISMF was uniform, and did not include effects of draping and compression of the ISMF around the heliopause, they showed that a double-peaked ribbon can form due to the interaction of PUIs with small-scale turbulent fluctuations in the magnitude of the ISMF. This can be explained by pitch angle “scattering” (by the magnetic mirror force) of PUIs in directions near $\mathbf{B} \cdot \mathbf{R} \sim 0$, whose initial pitch angles are close to 90° . While their model also predicts a double-peaked ribbon due to the preferential scattering of PUIs away from 90° pitch angle, compared to PUIs with larger or small initial pitch angles, the significance of their results is similar to our model. The magnetic mirror force, either from large-scale gradients in the draped and compressed ISMF, or from small-scale turbulent fluctuations in the ISMF, determines which PUIs have pitch angles that coincide with *IBEX* look directions.

Including VLISM turbulence in our model of the ribbon will be the subject of a future study, since there is some level of ISMF turbulence from the VLISM, and the magnetic mirror force acting on $\sim \text{keV}$ PUIs significantly affects the ribbon flux observed by *IBEX*.

Moreover, the 3D draping of the ISMF around the heliosphere causes a spatial curvature in directions toward $\mathbf{B} \cdot \mathbf{R} \sim 0$ as a function of distance from the heliopause (Zirnstein et al. 2015; see also Section 3.2.3), which might smear out the double-peaked ribbon feature predicted by Giacalone & Jokipii (2015). This will be investigated in a future study.

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Figure 1.

Simplified illustration of the ribbon model process. Primary ENAs (PENA) give rise to PUIs with some initial speed ($v_{1,2,3\dots}$) and pitch angle ($\alpha_{1,2,3\dots}$), which then move along the ISMF before they experience charge-exchange (note that in this illustration, unlike in the model, we ignore perpendicular drifts). The final velocity and pitch angle required for secondary ENAs (SENA) to be observed by IBEX (v_4 , α_4) determines what the initial PUI (and primary ENA, PENA) speed and pitch angles must be at every step in the guiding center history. PUIs that travel the farthest (blue) before becoming a secondary ENA contribute less to the total secondary ENA flux, compared to those that originate closer (red).

Figure 2.

Example of the guiding center motion of PUIs outside of the heliopause, including all guiding center terms ($v_{\parallel}$, $v_{\perp}$, F_M , F_B). We plot the guiding center motion over a period of four times the local mean charge-exchange time (~ 7 years for this example). Our method of simulation starts at the point of secondary ENA creation. For this example, the secondary ENA energy is 1.11 keV, it is created at 200 AU from the Sun, in the direction of ecliptic J2000 (270° , -17°). Knowing the energy and direction of the final ENA, we back-track the guiding center of PUIs through the VLISM, calculating the probability for a primary ENA to produce a PUI with the correct energy and pitch angle at each step along the guiding center history. The semi-transparent background is the solar/interstellar plasma magnetic field magnitude (see color bar in upper left panel). Note that this particular example is unlikely to occur in reality (see discussion in text), but clearly illustrates how each transport term in Table 1 may affect the motion and energization of PUIs.

Figure 3.

Similar to Figure 2, except we plot the PUI history with different guiding center terms included. (left) Showing change in PUI energy. (right) Showing change in PUI pitch angle.

Figure 4.

Model ENA skymaps at 1.11 keV for different guiding center motion effects: (a) no guiding center transport terms are included; (b) PUIs move parallel to the magnetic field ($v_{||}$); (c) PUIs also advect with the bulk plasma component perpendicular to the magnetic field ($v_{\perp}$); (d) PUIs are also accelerated by the mirror force (F_M); (e) PUIs also experience betatron acceleration (F_B).

Figure 5. Same as Figure 4, except we show results for ENA energy 2.73 keV

Figure 6. (left) Model of the IBEX ribbon at (a) 1.11 and (c) 2.73 keV, when all guiding center transport terms are included. (right) IBEX observations at (b) 1.11 and (d) 2.73 keV, after removal of the GDF (Schwadron et al. 2014).

Figure 7.

Skymaps showing the percent change of 1.11 keV ENA flux (J) as individual guiding center terms are consecutively added: (a) change in flux with no PUI transport terms to a model with only $v_{\parallel}$ included; (b) change in flux when $v_{\perp}$ is included; (c) change in flux when F_M is included; (d) change in flux when F_B is included; (e) change in flux with no PUI transport terms to a model with all transport terms included. For all panels, we show the 25% peak flux contour (magenta) of the computed ribbon for each case before the addition of the new transport term. Note that the most significant changes in ENA fluxes occur when $v_{\parallel}$ and F_M are included.

Figure 8.

Skymaps showing the average change in (a) parallel energy $E_{\parallel}$, (b) perpendicular energy $E_{\perp}$, (c) total energy E , and (d) pitch angle α of PUIs outside the heliopause, weighted by directions where the most significant changes in ENA flux occurred when all PUI guiding center transport terms were included. These maps pertain to those PUIs that create 1.1 keV ENAs at 1 AU. One can see the most significant changes occur on the right edge of the ribbon (the magenta curve shows the isocontour at 25% of the maximum ribbon flux before PUI transport terms are included).

Figure 9.

1.11 keV Ribbon ENA production rate in the meridional plane of the heliosphere outside of the heliopause. (top-left) Model when no PUI dynamics are included (“before”), and (top-right) model when all transport terms are included (“after”). We also draw the surface of the heliopause (HP; thick black curve), some ISMF lines outside of the heliopause (thin black curves), the $\mathbf{B} \cdot \mathbf{R} = 0$ surface (dashed white line), and the direction from which the maximum ribbon flux comes towards 1 AU. Note that the dark blue regions produce zero ENA flux. The bottom panel shows the change in ENA production rate between the two top panels.

Figure 10.

Skymaps showing the change in shape/position of the ribbon at (left) 1.11 keV and (right) 2.73 keV. The colored lines are isocontours at 25% of the maximum flux for each model, where we consecutively add different guiding center terms (see color bar). Note that the greatest difference in position occurs when the magnetic mirror force is included.

Table 1

Guiding center terms included in the model of the IBEX ribbon.

Variable	Terminology
$v_{\parallel}$	PUI guiding center speed parallel to the local ISMF (Eq. 1)
$v_{\perp}$	PUI guiding center speed perpendicular to the local ISMF, i.e., $E \times B$ drift (Eq. 1)
F_M	Force on $v_{\parallel}$ due to the magnetic mirror force (Eq. 2)
F_B	Force on $v_{\perp}$ due to betatron acceleration (Eq. 3)