THE ENERGY-DEPENDENT POSITION OF THE IBEX RIBBON DUE TO THE SOLAR WIND STRUCTURE

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ABSTRACT

Observations of energetic neutral atoms (ENAs) allow for remote studies of the condition of plasma in the heliosphere and the neighboring local interstellar medium. The first results from the Interstellar Boundary Explorer (IBEX) revealed an arc-like enhancement of the ENA intensity in the sky, known as the ribbon. The ribbon was not expected from the heliospheric models prior to the launch of IBEX. One proposed explanation for the ribbon is the mechanism of secondary ENA emission. The ribbon reveals energy-dependent structure in the relative intensity along its circumference and in its position. That is, the geometric center of the ribbon varies systematically by about 10° in the energy range 0.7–4.3 keV. Here, we show by analytical modeling that this effect is a consequence of the helio-latitudinal structure of the solar wind reflected in the secondary ENAs. Along with a recently measured distance to the ribbon’s source just beyond the heliopause, our findings support the connection of the ribbon with the local interstellar magnetic field by the mechanism of secondary ENA emission. However, the magnitude of the center shift in the highest IBEX energy channel is much larger in the observations than expected from the modeling. This may be due to another, not currently recognized, process of ENA generation.

Key words: instrumentation: detectors – ISM: atoms – methods: data analysis – solar wind – Sun: heliosphere

1. INTRODUCTION

The Sun continuously emits an outward flow of plasma called the solar wind (Parker 1958). The interaction of this flow with the partially ionized, magnetized local interstellar medium (LISM) creates a cavity in the interstellar matter called the heliosphere, with the heliopause as its boundary (Parker 1961). The supersonic solar wind expands from the solar corona almost radially up to the termination shock, where its bulk speed decreases rapidly, and most of its kinetic energy is transferred into the internal energy of the plasma. The emerging plasma flow lines bend in front of the heliopause, which has an elongated, comet-like shape due to the relative motion of the Sun and the LISM.

The speed of the solar wind varies with heliographic latitude and time during the solar cycle. The solar wind can be investigated in situ by spacecraft measurements or remotely by observations of interplanetary scintillations. During the solar minimum the slow wind occupies an equatorial band, while the fast wind is restricted to the polar caps. During the solar maximum the slow and fast streams of the solar wind are interspersed at all latitudes. The latitudinal structure of the solar wind with fast flow at high latitudes was inferred from observations of interplanetary scintillation (e.g., Kakinuma 1977; Coles et al. 1980) and observed in situ by Ulysses (Phillips et al. 1995; McComas et al. 2008).

Remote sensing of the condition of plasma in the heliosphere and its neighborhood is carried out indirectly, by observations of energetic neutral atoms (ENAs) by the Interstellar Boundary Explorer (IBEX, McComas et al. 2009b). Observations available from the IBEX-Hi sensor (Funsten et al. 2009a) are carried out in several energy bands that cover the range 0.4–6 keV, i.e., energies typical for the solar wind.

The first sky maps obtained by IBEX revealed an arc-like structure extending over a large part of the sky (Funsten et al. 2009b; Fuselier et al. 2009; McComas et al. 2009a), dubbed the ribbon, which was not expected from simulations prior to the launch of IBEX (Schwadron et al. 2009). This discovery resulted in the formulation of various hypotheses to explain the origin of the ribbon, which suggest that the source region for the ribbon is located in different regions of the heliosphere (McComas et al. 2009a, 2014b). In a later analysis, Swaczyna et al. (2016) determined the heliocentric parallax of the ribbon, and thus the distance to its source at 140±38 au. This finding favors the hypothesis that the ribbon is generated by the mechanism of secondary ENA emission. In this mechanism, the primary ENAs, produced in the heliosphere, escape beyond the heliopause, where, after two subsequent charge-exchange processes, they create a population of secondary ENAs, a part of which is observed by IBEX on the Earth’s orbit (McComas et al. 2009a). The highest signal is expected in the part of the sky where the lines of the local interstellar magnetic field, draped over the heliopause, are almost perpendicular to the lines of sight (Heerikhuisen et al. 2010).

The ribbon is observed in all IBEX-Hi energy channels, but its intensity varies along its circumference and among the energy channels (McComas et al. 2012; Funsten et al. 2015). Funsten et al. (2013) found that the positions of the maximum signal, obtained from the profiles across the ribbon, form shapes that may be approximated by circles or ellipses in the sky, and their centers in the sky shift systematically with energy. The variation in intensity along the ribbon was qualitatively explained by McComas et al. (2012) as being due to the structure of the supersonic solar wind, which is the main contributor to the primary ENA flux, but the shift of the ribbon center by ∼10° between energies of 0.7 keV and 4.3 keV remained unexplained. It was expected that the energy dependence of the cross sections for the charge-exchange reaction, and consequently of the distances to the secondary ENA source, could explain this shift. However, Zirnstein et al. (2016a) simulated this effect and showed that the shift in the ribbon center due to the effect should be ∼2° and should occur only along the plane defined by the undisturbed magnetic field vector and the Sun’s velocity relative to the LISM, at odds with observation.

In this paper, we use an analytical model of the secondary ENA mechanism supplemented with the helio-latitudinal
structure of the solar wind. The fluxes calculated from this model are fitted to follow a circle or an ellipse for each IBEX energy channel (Section 2). The fitted parameters are compared to those obtained in the data analysis by Funsten et al. (2013) (Section 3). The results strongly support the secondary ENA mechanism (Section 4).

2. METHODS

In the past, analyses of the secondary ENA emission were performed using both magnetohydrodynamic simulations (e.g., Heerikhuisen et al. 2010) and simplified analytical models (Möbius et al. 2013; Schwadron & McComas 2013; Isenberg 2014). Although details of these models are different, the main mechanism is the same. That is, the primary ENAs produced in the heliosphere escape through the heliopause to the outer heliosheath, where they are ionized, picked up by the draped interstellar magnetic field, and start to gyrate around the field lines. Eventually, they are re-neutralized via charge exchange with ambient neutral atoms, and some of them re-enter the heliosphere. When the original ENA velocity is perpendicular to the magnetic field line, the guiding center of the created pick-up ion is pinned to the field line, and the resulting secondary ENA can be directed back toward the Sun. These ENAs collectively form the ribbon.

Here, we focus on the effect of the helio-latitudinal structure of the solar wind on the position of the ribbon. First, we model the flux of the primary ENAs originating from the supersonic solar wind (Section 2.1), and subsequently this flux is used in the analytical model of secondary ENA emission (Section 2.2). On the basis of the constructed model, we show the mechanism of the shift in the peak position of the ribbon (Section 2.3). The obtained signal is subsequently fitted to circles and ellipses (Section 2.4).

2.1. Flux of the Neutral Solar Wind

The primary ENAs are created both in the supersonic solar wind and in the inner heliosheath. Zirnstein et al. (2016a) found that in magnetohydrodynamical models of the secondary ENA mechanism the contribution of the ENAs created in the inner heliosheath can be neglected. Therefore, in this analysis we take into account only the contribution of the neutral solar wind (NSW) from the inner heliosphere.

The NSW is a supersonic solar wind, expanding inside the termination shock, that has been neutralized. The neutralization occurs mostly due to the charge-exchange process between solar wind protons and the interstellar neutral atoms that have penetrated inside the termination shock. In this analysis, we take into account the helio-latitudinal structure of the supersonic solar wind.

The observations of interplanetary scintillations collected by Institute for Space-Earth Environmental Research at Nagoya University (Tokumaru et al. 2010) allow for determination of Carrington maps of the solar wind speeds. We use the solar wind structure as a function of heliographic latitude following a model by Sokol et al. (2013, 2015) based on the solar wind speed derived from the observations of interplanetary scintillations and in situ in-ecliptic observations collected in the OMNI database (King & Papitashvili 2005). This model provides a structure of the solar wind speed and density at 1 au that is continuous in time and complete in latitude, as a function of heliographic latitude and time from 1985 to 2013.

The supersonic solar wind is decelerated due to momentum loading into the plasma by ionization and charge exchange of the background neutrals. This slowdown of the solar wind was predicted theoretically (Fahr & Ruciński 2001, 2002) and observed in situ by Voyager 2 (Richardson et al. 2008). We adopt a simple model of the inner heliosphere (Lee et al. 2009), in which the bulk speed $v$ of the solar wind is decreasing linearly with the distance from the Sun $r$: $v(r) = v_0 \left(1 - \frac{1 - \frac{1}{\gamma - 1}}{2\gamma - 1} \frac{r}{\lambda_{ml}}\right)$, (1)

where $v_0$ is the bulk speed of the solar wind at 1 au, $\gamma = 5/3$ is the ratio of specific heats of the solar wind plasma, and $\lambda_{ml}$ is the characteristic length for mass loading, given by the formulae:

$$\lambda_{ml} = \left(\lambda_{cx}^{-1} + (n_0 v_0)^{-1}(\nu_{H} n_{H} + 4\nu_{He} n_{He})^{-1}\right)^{-1},$$

$$\lambda_{cx} = (\sigma_{cx} v_0)^{-1}.$$  

In these equations, $\sigma_{cx}$ is the charge-exchange cross section between protons and hydrogen atoms (Lindsay & Stebbings 2005), $n_{H}$ and $n_{He}$ are the number densities of the background interstellar neutral hydrogen and helium gas, $n_0$ is the density of the solar wind at 1 au, and $v_{H}$ and $v_{He}$ are the photoionization rates for hydrogen and helium, respectively, at 1 au (Bzowski et al. 2013a, 2013b).

This model assumes that the background densities of neutral hydrogen ($n_{H} = 0.09$ cm$^{-3}$) (Bzowski et al. 2008) and helium ($n_{He} = 0.015$ cm$^{-3}$) (Gloeckler et al. 2004) are constant in the inner heliosphere and equal to those at the termination shock. In reality, the density of neutral hydrogen is not uniform and varies with the angle from the upwind direction and with distance from the Sun. The density of neutral hydrogen decreases for greater angles by a significant percentage (e.g., see Heerikhuisen et al. 2006; Izmodenov et al. 2013). Additionally, the density is depleted inside $\sim 10$ au, and its structure is complex and evolves with time due to time-dependent ionization processes (Bzowski et al. 2001; Tarnopolski & Bzowski 2009). In this analysis, we are interested in the NSW flux at the termination shock, regardless of the actual distances at which neutralizations occur. Therefore, the total column densities of the neutrals accumulated between the Sun and the termination shock are important, and the depletion for greater angles is partially compensated by the simultaneously increasing distance to the termination shock (Pogorelov et al. 2009). Moreover, the nonuniform distributions at a few au from the Sun do not significantly affect the total column density. Consequently, the assumption of constant densities is reasonable in the presented model.

In this analysis, we build a time-averaged model, thus the probability distribution function of the NSW flux is constructed by averaging over a period of solar activity. Zirnstein et al. (2015) found that the time delays between creation of the primary ENAs and observation of the secondary ENAs range from $\sim 4$ to $\sim 9$ yr, depending on the energy channel. Consequently, the secondary ENAs observed by IBEX in the years 2009–2011, i.e., the years used in the analysis by Funsten et al. (2013), originate from the primary ENAs created between 2000 and 2007. Therefore, we averaged the NSW flux over solar cycle 23, which includes this interval. The model of the solar wind we use has a time resolution of one Carrington...
Rotation (CR) (Sokół et al. 2015), and in consequence, we average over the parameters obtained for the time range from CR 1909 to CR 2065. With this, we use the following formula for the NSW flux at the termination shock for heliographic latitude \( \Theta \) and energy \( E \):

\[
I_{\text{NSW,TS}}(E, \Theta) = \frac{1}{N} \sum_{i=1}^{N} \int_{d_0}^{d_i} v_{0,i}^2(\Theta) \delta_0^2 \frac{d^3}{dTS} \times \frac{e^{-r/\lambda_{TS}}}{\lambda_{ex}} N(v_i, \delta v/\sqrt{2E/m}) \frac{1}{\sqrt{2\pi m E}} dr.
\]

(4)

In this formula \( i \) enumerates the parameters of the solar wind (density \( n_{0,i} \) and bulk speed \( v_{0,i} \) at 1 au for the requested latitude) for each selected CR \((N = 156)\). Here we first generate the NSW flux for each CR, and then average the results, which is different to what one would obtain by averaging the profile of the solar wind speed over the solar cycle first and calculating the NSW flux from the averaged solar wind later.

Independently of the charge exchange, the fluxes of the supersonic solar wind and the already created NSW decrease with distance, thus at the termination shock they need to be multiplied by the squared ratio of distances at 1 au \( (d_0) \) and at the termination shock \( (d_{TS}) \):

\[
d_0^2/d_{TS}^2.
\]

The charge-exchange process that is the source of the NSW is also responsible for the exponential decrease in the proton flux of the solar wind \( (e^{-r/\lambda_{ex}}) \). The bulk speed \( v_i(r) \) decreases according to Equation (1). We smooth the NSW speed distribution using a normal (Gaussian) distribution \( N \) with a mean value equal to the speed at the considered distance \( v_i(r) \) and a standard deviation \( \delta v = 100 \text{ km s}^{-1} \), equal to the spread of the model speeds from Sokół et al. (2015) and those observed by in-ecliptic spacecraft, collected in the OMNI database. We do so because in situ observations show that the velocity distribution function of the solar wind accumulated over the intervals of CRs is much wider than would be implied by the purely thermal spread of proton velocities. The last term in Equation (4) is the result of the conversion of variables. That is, the normal distribution gives probability density in speed, thus we multiply it by \( dv/dE = 1/\sqrt{2\pi m E} \) to get probability density in energy. Figure 1 presents the differential NSW flux given by Equation (4) as a function of energy and heliographic latitude.

2.2. Analytical Model of Secondary ENA Emission

In this analysis, we use an analytical model of the ribbon generation by the secondary ENA mechanism based on the observational constraints on the position and width of the ribbon in the sky. The model is an extension of the model by Möbius et al. (2013). We employ the version of the model previously used in the assessment of the expected secondary helium ENA emission by Swaczyna et al. (2014). With some rearrangement, the formula for the differential intensity of ENAs at IBEX can be expressed as

\[
\frac{dJ_{\text{ENA}}}{dE} = \frac{1}{2\pi} \frac{J_{\text{NSW,TS}}(E)}{G} D_{\text{NSW,TS}}(E, \Theta),
\]

(5)

where

\[
J_{\text{NSW,TS}}(E, \Theta) = \frac{d_{TS}^2}{\lambda_{HT} \lambda_p} \int_{d_{HT}}^{\infty} e^{-v_2 d_{HT}} dr_1 \int_{r_1}^{\infty} e^{-v_2 r_1} dr_2,
\]

(6)

This form consists of three factors: the geometric factor \( G \), the NSW flux at the termination shock \( I_{\text{NSW,TS}} \), and the dimensionless factor \( J_{\text{NSW,TS}}(E, \Theta) \) that accounts for the ionization and re-neutralization of the NSW, with the inverse-square law for the NSW flux included. The geometric factor had been originally expressed (Möbius et al. 2013; Swaczyna et al. 2014) as \( \Delta \psi/(2\pi \Delta \Omega) \), where \( \Delta \Omega \) is the solid angle of the field of view of IBEX, and this is equivalent to the expression presented here because \( \Delta \Omega \approx \Delta \psi^2 \). Below, we describe the necessary modification of this formula in our analysis.

In the original form it was assumed that the NSW flux is monoenergetic, so the flux was presented as a simple product of the density and speed of the NSW. The total flux was assumed to fit into a single IBEX energy channel of width \( \Delta E \). Here, we replace this term with the differential NSW flux at the termination shock \( I_{\text{NSW,TS}}(E, \Theta) \), which depends on the energy \( E \) and heliographic latitude \( \Theta \).

The factor \( J_{\text{NSW,TS}}(E, \Theta) \) represents the effective part of the NSW that forms the secondary ENAs. It is normalized to the flux of the solar wind at the termination shock. This is a convenient choice because the accumulation of the NSW ceases at the termination shock. In the formula \( d_{TS} \) and \( d_{HT} \) represent the distances to the termination shock and to the heliopause, respectively. The integrals run over \( r_2 \), which

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1 The solar wind densities and speeds from Sokół et al. (2015) are available as supplementary materials at http://dx.doi.org/10.1007/s11207-015-0800-2.
denotes the distance of the ionization of the primary ENAs, and $r_1$, which denotes the distance where the re-neutralization occurs. The distance to the termination shock is assumed to be omnidirectionally constant and equal to 90 au, i.e., midway between the two distances of the termination shock crossing by Voyager 1 and Voyager 2 at 94 au and 84 au, respectively (Burlaga et al. 2005, 2008; Gurnett & Kurth 2005, 2008). For the distance to the heliopause we use a simple axisymmetrical model of the heliosphere with incompressible plasma flow by Suess & Nervey (1990), for which we select the parameters so that the distance to the termination shock is 90 au, and the distance to the heliopause in the direction of Voyager 1 is 121 au, as observed (Gurnett et al. 2013). With this model, the distance to the heliopause in the directions along the ribbon changes in the range 120–200 au. The model used for the distance to the heliopause does not contain magnetic field and does not reconstruct the observed two-lobed structure of the heliotail (McComas et al. 2013). One of these lobes is coincident with the natural continuation of the ribbon’s location, and the ribbon signal is suppressed in this part of the sky. This effect is not reproduced by our model, but we drop this part of the ribbon from the analysis for the reasons described below. Finally, the distance to the heliopause is solely a function of the angular distance to the heliospheric nose, denoted as $\eta$, i.e., it is assumed to feature axial symmetry around the inflow direction.

The mean free path for ionization of ENAs in the LISM, $\lambda_H$, and the effective mean free path for neutralization of the pick-up protons in the LISM, $\tilde{\lambda}_p$, depend on the considered energy and are given by the following formulæ:

$$\lambda_H(E) = (\sigma_{cx}(E)n_p + \sigma_{ion}(E)n_H)^{-1}, \quad (7)$$

$$\tilde{\lambda}_p(E) = \left(\sigma_{cx}(E)n_H\right)^{-1} \frac{V_{Sun,LISM}\sin\theta_{RV}}{\sqrt{2E/m}}, \quad (8)$$

where $\sigma_{cx}$ and $\sigma_{ion}$ are cross sections for the charge exchange between a hydrogen atom and protons (Lindsay & Stebbings 2005) and for the ionization of a hydrogen atom by the impact of another hydrogen atom (Barnett 1990), respectively. The quantities $n_p = 0.06$ cm$^{-3}$ and $n_H = 0.2$ cm$^{-3}$ are the densities of protons and hydrogen atoms in the LISM (Frisch et al. 2011). The effective mean free path for protons also depends on the velocity of the Sun in the LISM, $V_{Sun,LISM} = 25.8$ km s$^{-1}$ (Bzowski et al., 2015), and the angle $\theta_{RV}$ formed by this velocity and the direction of the magnetic field. For this angle we adopt the value of 48° formed by the direction of the Sun’s motion from the analysis of interstellar neutrals (Bzowski et al. 2015) and the energy-averaged center of the ribbon (Funsten et al. 2013). The resulting value of the factor $J(d_{TS}, d_{HP}, \lambda_H, \tilde{\lambda}_p)$ is presented in Figure 2. This factor has values in the range of 2.5%–6% with these assumptions, and depends moderately on the energy.

The factor $J$ is a function of the physical properties of the outer heliosheath: the proton density, the hydrogen density, the velocity of the Sun, and the angle between this velocity and the direction of the magnetic field. We adopt the values for them as constant throughout the outer heliosheath. This is an approximation, but fortunately the factor $J$ is relatively robust. For example, the mean free paths given by Equations (7) and (8) with the presented values for energy 1.7 keV are $\lambda_H(1.7$ keV) $\approx 780$ au and $\tilde{\lambda}_p(1.7$ keV) $\approx 7.7$ au. With the distance to the termination shock $d_{TS} = 90$ au and to the heliopause $d_{HP} = 150$ au, one obtains the value of $J = 3.78\%$. Increasing or decreasing $\lambda_H$ by 10% results in the $J$ values of 3.54% and 4.05%, respectively. For the same modification of $\tilde{\lambda}_p$, the resulting values are 3.76% and 3.81%. Consequently, the factor $J$ depends weakly on the physical conditions of the outer heliosphere.

The geometric factor $G$ defines the solid angle into which the secondary ENAs are emitted. This factor effectively reflects the draping of the interstellar magnetic field and the creation and stability of the ring distribution of the pick-up primary ENAs. If the magnetic field alone does not reconstruct the observed two-lobed structure of the heliotail (McComas et al. 2013), one of these lobes is coincident with the natural continuation of the ribbon’s location, and the ribbon signal is suppressed in this part of the sky. This effect is not reproduced by our model, but we drop this part of the ribbon from the analysis for the reasons described above. Finally, the distance to the heliopause is solely a function of the angular distance to the heliospheric nose, denoted as $\eta$, i.e., it is assumed to feature axial symmetry around the inflow direction.

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![Figure 2](image-url)
where $G(\phi)$ is the geometric factor given by Equation (9), $I_{\text{NSW,TS}}(E, \Theta)$ is the NSW flux, given by Equation (4), and $J$ is the reflectance factor, defined as in Equation (6).

2.3. Mechanism of the Shift of the Ribbon

Analysis of the ribbon’s peak position is simplest in an auxiliary coordinate system with the pole close to the ribbon center. We follow Funsten et al. (2013) to construct such a coordinate system. Namely, we define a spherical coordinate system (hereafter the ribbon coordinates) so that the point ($\lambda_{\text{rib}}, \beta_{\text{rib}}$) is the pole, and the prime meridian contains the direction of the heliospheric nose at ($\lambda_{\text{nose}}, \beta_{\text{nose}}$) = (255°8, 5°16) (Bzowski et al. 2015). We denote the angular distance from the pole as $\phi$ and the azimuthal angle as $\theta$. Funsten et al. (2013) used a slightly different position of the pole and the meridian, but this does not influence the results of the presented analysis.

The mechanism of the shift of the ribbon can be tracked by analysis of the relative contributions of the three factors forming the ribbon signal in Equation (10). Figure 3 illustrates how these factors vary along two exemplary azimuthal profiles for different energies. We normalize them so that their maxima at the presented range are equal to 1. The geometrical factor $G$ is the same for each energy by definition, and the variation of the normalized factor $J$ with energy is small. However, the NSW fluxes, which are functions of heliographic latitude, strongly influence the ribbon’s peak positions. The peak position is shifted in the same direction as the increase in the NSW flux. Consequently, there is systematic progression of the maxima of the secondary ENA intensity with increasing energy in each azimuthal profile. Effectively, they are combined to result in the progression of the ribbon centers with energy.

2.4. Fitting of Circles and Ellipses

We calculate the ENA intensity over the sky using the model of secondary ENA emission presented above. Below, we describe the procedure used to find the circular and elliptic fits to the locations of the maximal signal along the ribbon. The procedure was tuned to follow the idea used previously by Funsten et al. (2013) to obtain the fits to the data.

We integrate the signal given by Equation (10) over $6^\circ \times 6^\circ$ bins in the ribbon coordinates and over energies with the IBEX-Hi energetic response function (Funsten et al. 2009a) for the respective energy channel. The same pixelization scheme was previously used in the data analysis by Funsten et al. (2013). It is a different scheme from the scheme typically used to present IBEX data, where the basis is the ecliptic coordinate system (McComas et al. 2014a). Subsequently, for each of the 60 meridian profiles we select seven pixels so that the center pixel has the highest signal. The selected range of pixels is fitted to the Gaussian shape given by the formula: $A + B \exp(-(\phi - \phi_0)^2/(2\sigma^2))$. The fitted peak positions do not contain the uncertainties resulting from the statistical scatter, which is the main contributor to the total uncertainty in the analysis of the observations (Funsten et al. 2013).

The fitted shapes (circles and ellipses) are not expected to reproduce the ribbon precisely. They are intended to be alternative, simplified descriptions of the ribbon’s morphology. In other words, we do not expect that with higher statistics the location of the maximum signal of the ribbon will approach the position encircled by the fitted circle or ellipse. Consequently, we follow the selection of pixels used in the original data analysis by Funsten et al. (2013), and we need to weight the pixels to acknowledge the relative uncertainties of the fits to the data.

Based on this prerequisite, we minimize the $\chi^2_C$ and $\chi^2_E$ estimators for the circular and elliptic models in the forms

$$\chi^2_C(\Omega_c, r_c) = \sum_i \frac{[g(\Omega_i, \Omega_c) - r_c]^2}{B_i^{-1}},$$

$$\chi^2_E(\Omega_{E1}, \Omega_{E2}, a_E) = \sum_i \frac{[g(\Omega_i, \Omega_{E1}) + g(\Omega_i, \Omega_{E2}) - 2a_E]^2}{B_i^{-1}},$$

where $\Omega$s represent the directions in the sky in whichever coordinate system, and $g$ returns the angular distance between the directions. The summation is over the ribbon’s positions $\Omega_i$ in the azimuthal sectors enumerated by $i$, which run over the same sectors as those used in the data fitting by Funsten et al. (2013). The quantities $B_i$ represent the heights of the ribbon’s profile, which we use for weighting. This weighting is intended to recognize the relative uncertainties of the original data.

Determinations of the peak positions in the data are subject to uncertainties arising from the statistical scatter of the data. These uncertainties scale in inverse proportion to the square root of the number of counts from the secondary ENA emission. The heights of the ribbon’s profile are proportional to the number of counts if the time of observations is uniformly distributed. We adopt this approach so that our fitting remains as close to the procedure adopted by Funsten et al. (2013) as possible.

In the case of the circular fit, the parameters are the position of the ribbon center $\Omega_C$ and the ribbon’s radius $r_C$. In the case of the elliptic fit, the parameters are the directions of the foci of the ellipse $\Omega_{E1}, \Omega_{E2}$ and the semimajor axis $a_E$. Equivalently, the ellipse can be described by the following set of parameters: the center direction $\Omega_{E0}$, the semimajor axis $a_E$, the semiminer axis $b_E$, and the rotation angle $\theta_E$. We also derive the eccentricity $e_E$. We transform the fitted parameters to this set, since it was used for the data analysis by Funsten et al. (2013). The rotation angle is given in the ribbon coordinates.

3. RESULTS AND DISCUSSION

The signal calculated from the presented model is compared with the signal extracted from the observations by Schwadron et al. (2014)\(^{2}\) in Figures 4 and 5. The maps are plotted in the ribbon coordinates, so they can be compared also with the maps in the previous analysis by Funsten et al. (2013, Figures 2 and 3). In Table 1 we compare these parameters obtained from our model fitting and the one found by Funsten et al. (2013) from data analysis. The mean deviations between the ribbon’s locations and the fitted ellipses and circles are denoted as $\sigma_E$ and $\sigma_C$, respectively.

We compare the fitted centers in Figure 6. The displacements of the fitted centers between subsequent energy channels obtained from the model match those obtained by Funsten et al. (2013) from the data analysis. The energy sequence is not

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\(^{2}\) The numerical values of ribbon signal extracted from the data are available as IBEX Data Release 8 (Schwadron et al. 2014) at http://ibex.swri.edu/ibexpubdata/Data_Release_8.
aligned along the plane that includes the interstellar neutral flows and the ribbon center (Kubiak et al. 2016), known as the neutral deflection plane (black line in Figure 6), but it is approximately parallel to the great circle intersecting the solar poles and the energy-averaged center of the ribbon, i.e., the local heliographic meridian (cyan line). The uncertainty analysis done by Funsten et al. (2013) was simplified, so the $\sigma_E$ parameters were adopted as the uncertainties of the ribbon centers. Such a procedure probably overestimated the actual uncertainties. Consequently, we are not able to formally check the consistency between the data and model results. The ellipticities expressed by the rotation angle and eccentricities are similar for the observations and model, even though we have assumed a simple circular shape for the geometric factor.

The circular fits are intended as a sanity test for our baseline results, obtained from the elliptic fits: a qualitative difference between the two models would cast doubt on the credibility of our conclusions. But the results from the circular fits are similar to the elliptic fits. In the case of circular fits, the centers are even better aligned with the local heliographic meridian. Comparing the mean differences of the peak location to the fitted signal ($\sigma_E$ versus $\sigma_C$), it is visible that elliptic fits are better. This is a natural consequence, since the ellipse is generalization of the circle.
Figure 4. Maps of the ribbon intensity calculated from the presented model (left column) and the maps of the ribbon signal separated from the data (Schwadron et al. 2014) (right column) in the ribbon coordinates. The magenta lines mark the heliographic equator and the $\pm 30^\circ$ and $\pm 60^\circ$ parallels. The white ellipses are the fits to the maximum signal along the ribbon for the model (solid line) and reproduction of the fits to the data (after Funsten et al. 2013, Table 2) (dashed line). The centers and the lines between the foci for both ellipses are shown with white points and lines, respectively. “Nose” marks the direction of the inflow of interstellar gas on the heliosphere (Bzowski et al. 2015), and “SNP” the direction of the solar north pole. Top to bottom are the results for energy channels 0.7, 1.1, and 1.7 keV. The color scheme for each energy channel is shown on the right and is common for the model and data.
With the presented model, the peak position of the ribbon can be determined in all azimuthal sectors due to the absence of statistical scatter. This was not possible with the data because the ribbon signal is not high enough in some sectors compared to the background. The restriction of the azimuthal sectors, as well as the weighting procedure, can potentially influence the determination of the position of the ribbon center. We performed three additional fits to quantify this influence.

**Table 1** Comparison of Fitted Parameters

| E (keV) | Elliptic Fit | Circular Fit |
|---------|--------------|--------------|
|        | $\lambda_E$ (deg) | $\beta_E$ (deg) | $\theta_E$ (deg) | $\alpha_E$ (deg) | $\beta_E$ (deg) | $\theta_E$ (deg) | $\sigma_E$ (deg) | $\lambda_C$ (deg) | $\beta_C$ (deg) | $r_C$ (deg) | $\sigma_C$ (deg) |
| 0.7 d  | 219.8        | 42.2         | 97.4          | 74.9          | 73.2          | 0.22          | 1.4          | 218.5          | 43.1          | 74.8          | 2.1          |
| m      | 221.0        | 41.7         | 103.0         | 74.4          | 71.0          | 0.30          | 0.3          | 220.2          | 42.5          | 74.3          | 0.3          |
| 1.1 d  | 220.6        | 40.2         | 111.3         | 75.4          | 71.0          | 0.34          | 1.8          | 220.3          | 40.5          | 73.3          | 2.4          |
| m      | 219.9        | 41.3         | 83.5          | 74.4          | 74.0          | 0.09          | 0.3          | 219.9          | 41.3          | 74.3          | 0.3          |
| 1.7 d  | 219.9        | 39.7         | 100.0         | 74.4          | 71.8          | 0.26          | 1.5          | 219.9          | 39.8          | 73.2          | 1.7          |
| m      | 219.9        | 39.4         | 58.5          | 74.7          | 71.5          | 0.29          | 0.6          | 219.6          | 39.4          | 74.4          | 0.7          |
| 2.7 d  | 218.8        | 37.6         | 76.3          | 75.7          | 70.9          | 0.35          | 1.8          | 217.9          | 37.7          | 74.4          | 2.2          |
| m      | 219.9        | 37.6         | 60.8          | 75.3          | 67.8          | 0.43          | 0.5          | 218.9          | 37.6          | 74.8          | 0.8          |
| 4.3 d  | 215.5        | 32.5         | 65.3          | 80.3          | 75.7          | 0.33          | 2.9          | 214.2          | 32.4          | 79.2          | 3.0          |
| m      | 219.5        | 35.4         | 61.6          | 75.9          | 68.2          | 0.44          | 0.8          | 218.6          | 35.4          | 75.5          | 1.0          |

Note. *“d” denotes the parameters from the fitting to the data obtained by Funsten et al. (2013), and “m” to the signal calculated from the presented model (this analysis).
Figure 7 shows the positions of the ribbon centers from these fits. That is, we fit the model with and without the weighting (i.e., $B_i = 1$ in Equations (11) and (12)), combined either with the selection of sectors made by Funsten et al. (2013) or with all sectors. These modifications shift the ribbon center by at most 1° and the sequence of the energy channel is similar in all cases. From this test we conclude that our results and conclusions on the role of the solar wind structure in shaping the position of the ribbon are robust.

The largest discrepancy occurs for the highest energy channel. In the model, the centers for consecutive energy channels are shifted by the same magnitude for all energy channels, but in the data the highest energy channel is shifted the most, and also the ribbon’s radius increases accordingly, which is not observed in the model. Another discrepancy is in the fit for the energy 1.7 keV, which in the elliptic case agrees well in all aspects except for the rotation angle (58° for the model fit and 100° for the data fit). Most of the deviations arise due to the statistical dispersion in the data, since the deviations of the ribbon’s location from the fitted shape ($\sigma_E$) are four times larger in the data than in the model. The nonvanishing values of $\sigma_E$ for the signal calculated from the model suggest that the model of a circular or elliptic shape is too simple to adequately describe the ribbon. Moreover, we assumed that the geometric factor has a maximum along a circle on the sky, while more realistic models of the draping of the interstellar magnetic field could indicate a more complicated shape. This may be another reason for the discrepancy between the parameters fitted to the model and to the data.

The presented model of the secondary ENA mechanism with helio-latitudinal structure of the solar wind reproduces the effect of the energy dependence of the fitted centers of the IBEX ribbon very well for most of the IBEX energy channels. The discrepancy in the highest energy channel could suggest that for the highest energy at least a portion of the signal may be due to a different mechanism of ENA generation. An argument in favor of this hypothesis is that the ENA intensities obtained from INCA on board the Cassini spacecraft for energies higher than at IBEX reveal a similar feature to the ribbon, called the INCA belt (Krimigis et al. 2009;...
Figure 8. Comparison of the location of the maximum signal of the ribbon in ecliptic coordinates for the model (left panel) and the data (right panel) (Swaczyna et al. 2016). The ecliptic latitude defined by the circle centered at $(\lambda_{rib}, \beta_{rib})$ with radius $r_{rib}$ is subtracted to highlight the differences between energy channels. The right panel is adopted from Figure 9 in Swaczyna et al. (2016). The ordinate presents the difference between the ecliptic latitude of the ribbon’s location and the latitude determined from the circle found by Funsten et al. (2013) as an average from all energy channels.

Dialynas et al. (2013), but the center of the belt at $(\lambda_{rib}, \beta_{rib}) = (190^\circ, 15^\circ)$ is shifted much farther than the center of the IBEX ribbon. However, the energies of ENAs observed by INCA are well above the energies typical for the solar wind, and thus the belt is not likely explained as the reflection of the NSF.

The helio-latitudinal structure of the supersonic solar wind was previously included in several analyses (Heerikhuisen et al. 2014; Zirnstein et al. 2015, 2016b). However, these analyses did not report any findings concerning the effect of an energy-dependent shift of the ribbon center (Zirnstein et al. 2015, 2016b), or such an effect was not visible (Heerikhuisen et al. 2014).

As a by-product of the analysis of the ribbon’s parallax, Swaczyna et al. (2016) obtained deviations of the locations of the maximum signal of the ribbon in ecliptic coordinates from the positions expected from a circle centered at $(\lambda_{rib}, \beta_{rib})$ with radius $r_{rib}$. In Figure 8 we compare those results with the deviations obtained in our analysis. In the figure we do not use the fitted shapes, but the actual positions of the maximum signal obtained as the intermediate step in the fitting procedure. The model results cover almost the whole sky, because we can fit the position for any signal level, whereas when fitting the data one needs to adopt a certain threshold value for the signal-to-noise ratio to find a meaningful fit.

In the case of a perfectly adequate model the respective lines from the model should fit the data uncertainty bands, but our model is far too simple for us to expect a perfect fit. We notice, however, that the energy sequence for the ecliptic longitudes $-120^\circ > \lambda > -180^\circ$ is the same in the data and in the model. Also the discontinuities for ecliptic longitudes $\sim 75^\circ$ and $\sim 140^\circ$ are visible both in the data and in the model. These discontinuities coincide with the intersection of the heliographic equator and the ribbon’s locations. These results additionally support the connection between the NSF and the IBEX ribbon.

4. SUMMARY AND CONCLUSIONS

In this analysis we extended the analytical model of secondary ENA emission originally proposed by Möbius et al. (2013), which we supplemented with a model of the primary ENAs produced in the helio-latitudinally structured supersonic solar wind. The primary ENAs are created by charge exchange of the solar wind inside the termination shock with the neutral background atoms. The solar wind was modeled using the helio-latitudinal structure from the model by Sokól et al. (2015). The distribution of primary ENAs was built for each CR separately and then averaged over solar cycle 23. The obtained signals were subsequently fitted to circles and ellipses, as was done in the analysis of the IBEX data by Funsten et al. (2013). The fitted parameters, including the centers of the circles and ellipses, were compared between the data and the model.

The ribbon centers for the IBEX-Hi energy channels form a monotonic sequence that is well aligned with the local heliographic meridian. The obtained magnitude of this effect is similar to that observed in the data, except for the highest IBEX-Hi energy channel, for which the shift between the two highest channels in the data is much larger than for the other pairs of consecutive channels, which is not observed in the model. This, together with observations of the INCA belt, is explained for the secondary ENA mechanism that forms the ribbon, a different mechanism may be operating in the vicinity of the heliosphere, responsible for a part of the ENA signal in the highest IBEX energy channels and for the INCA belt.

With the presented model, we reproduced two important features of the ribbon structure: the evolution in relative magnitude of the signal along the ribbon and the shift of the ribbon center with increasing energy. The first effect was already understood in previous analyses (McComas et al. 2014a), but the latter one is explained for the first time. Our findings explain these important features of the ribbon as being closely related to each other and strongly support the mechanism of secondary ENA emission with the interstellar magnetic field lines draped in the outer heliosheath as the most likely mechanism for the ribbon generation. This finding is additionally supported by the distance to the ribbon, which is determined to be at about 140 au (Swaczyna et al. 2016). We thus showed that details of the ribbon depend as much on the processes operating in the outer heliosheath as on the details of the solar wind structure and its evolution during the solar cycle.

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