

The Local Interstellar Magnetic Field and the IBEX Ribbon

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Abstract. It is well known that the Interstellar Boundary Explorer (IBEX) discovered a region of enhanced energetic neutral atom (ENA) emission seen in all-sky maps as a ribbon. The enhanced fluxes of ENAs were between 2 and 3 times greater than adjacent regions of the sky. The ribbon itself was not predicted by any models of the heliosphere interface. In the paper by Ratkiewicz, Strumik and Grygorczuk published in the *Astrophysical Journal*, 756:3, 2012 the authors presented some arguments to show that it was possible to predict the IBEX ribbon. In the current paper the numerical results obtained by three-dimensional MHD simulations of the interaction between the solar wind and interstellar medium by Ratkiewicz et al. [2012] are summarized. Some new aspects of this issue are discussed.

1. Introduction

The heliosphere, a cavity carved in the local interstellar medium (LISM) by the solar wind (SW) blowing out from the Sun is a region filled by the SW plasma emerged in the solar magnetic field and remains under the substantial influence of the LISM ionized and neutral components and of the local interstellar magnetic field (ISMF; see e.g. Linde et al. 1998; Pogorelov & Matsuda 1998; Ratkiewicz et al. 1998, 2000, 2008; Ratkiewicz & Ben-Jaffel 2002; Opher et al. 2007, 2009; Izmodenov et al. 2009; Pogorelov et al. 2009; Strumik et al. 2011; Ben-Jaffel & Ratkiewicz, 2012; Ben-Jaffel et al. 2013, Zank 2015 and references therein). The heliosphere is separated from the LISM by the heliopause (HP) around which the SW decelerated by the termination shock (TS) is transported at its inner side. The LISM flow decelerated by the bow shock (BS) is flowing around the HP at its outer side. The region between the TS and the BS forms the heliosphere interface, between TS and HP - the inner heliosheath (IHS), and between HP and BS - the outer heliosheath (OHS). Hydrogen energetic neutral atoms (ENAs) produced by the solar-interstellar interaction has been discovered to form a ribbon seen by the Interstellar Boundary EXplorer in the sky maps as enhanced emission sites (IBEX; Funsten et al. 2009; Fuselier et al. 2009; McComas et al. 2009; Schwadron et al. 2009). Such a phenomenon as the ribbon was not predicted by any model of the heliosphere interface. Immediately after the discovery, McComas et al. (2009) proposed an interpretation of the ribbon as resulting from ENA production in locations in space ordered by the ISMF. The so-called secondary ENA mechanism for ribbon formation was proposed (Heerikhuisen et al. 2010; Chalov et al. 2010), where the ribbon was shown to be possibly associated with a region outside the HP, where the local ISMF \mathbf{B} is perpendicular to radial vectors \mathbf{r} from the Sun ($\mathbf{B} \perp \mathbf{r}$, i.e., $\mathbf{B} \cdot \mathbf{r} = 0$), which was also a posteriori suggested by McComas et al. (2009).



Several asymmetries and distortions associated with exterior field-flow obliquity were discussed in detail by Ratkiewicz et al. [2000], who pointed out the important influence of the ISMF on the shape and structure of the heliosphere. They noticed that, due to the draping effects around the HP just beyond it, the strength of the ISMF along the field lines achieves its maximum in a direction quasi-perpendicular to the ISMF direction. This result was used by Chalov et al. [2010]. They found by numerical simulations the location of domains of increased and minimal magnitudes of the ISMF (see their Fig. 1). The authors also pointed out that the transport of PUIs in the OHS is considerably affected in the regions of the strong magnetic field, which can be considered as magnetic mirrors or stagnation regions (see their Fig. 2), where the motion of charged particles along field lines is decelerated and some portion of the particles is reflected. These regions in the OHS are ideal places for the production of ENAs forming the ribbon. Therefore, provided that the regions of strong magnetic compression are located in the all-sky maps in the proximity of locations where $\mathbf{B} \cdot \mathbf{r} \approx 0$, the mirror effect may significantly contribute to the increased ENA fluxes. These considerations have become a base for exploration of physical arguments for the direct connection between the ribbon and the strong ISMF compression regions by Ratkiewicz et al. [2012]. They presented some arguments to show that it was possible to predict the IBEX ribbon.

2. Summary of the method and results

For this purpose Ratkiewicz et al. [2012] investigated the magnetic field draping effects in the OHS for many different heliospheric geometries. They tested the Ratkiewicz et al. [2000] postulate by studying sky map locations of magnetic compression regions and their relation to positions of $\mathbf{B} \perp \mathbf{r}$ in the OHS. More specifically, the regions of strong magnetic compression were identified as the maximum strength $|\mathbf{B}^{\parallel}_{\max}|$ along the field lines, consistent with the physics of the mirror effect. Numerical computations showed the physical process leading to correlations between the perpendicularity and strong magnetic compression regions and further on to the ISMF–ribbon relationship.

The results in original paper were presented in the form of all-sky maps using the Mollweide projection in the ecliptic coordinates. The relation $|\mathbf{B} \cdot \mathbf{r}| \leq 0.05$ (here \mathbf{B} and \mathbf{r} are versors) was used in all figures presented to show the regions in the maps, where the perpendicularity condition $\mathbf{B} \perp \mathbf{r}$ was approximately satisfied. Obtained results in Figures 2–4 (Ratkiewicz et al. 2012) were presented for a range of ISMF strengths equal to 1.8, 2.4, 3.0, 3.6, 4.0, and 4.2 μG (rows) and for inclination angles 5° , 30° , 40° , 50° , and 85° (columns) to study quasi-parallel (5°) and quasi-perpendicular (85°) magnetic field directions in addition to oblique orientations.

Figure presented in the current paper summarizes the results shown in the original paper in Figures 2–4 for the inclination angle 40° and ISMF strengths equal to 1.8, 2.4, 3.6, and 4.2 μG . Plots in the left column illustrate the influence of the magnetic field draping effects on the geometry of the perpendicularity regions in the all-sky maps, i.e. the comparison of regions $\mathbf{B} \perp \mathbf{r}$ computed for an unperturbed (stripe between red lines) and perturbed (stripe between green lines) ISMF, respectively. Plots in the middle column show the comparison of regions $\mathbf{B}^{\parallel}_{\max} \perp \mathbf{r}$ (in gray, where $|\mathbf{B}^{\parallel}_{\max}|$ is the maximum strength along the given \mathbf{r}) with locations of the maximum of the ISMF strength $|\mathbf{B}^{\parallel}_{\max}|$ along the field lines (crosses). Plots in the right column show the comparison of the observed ribbon (black circles) with the regions shown in the middle column.

Full set of results in the original paper showed that the ribbon was reproduced best for the magnitude $3.6 \pm 0.6 \mu\text{G}$ and orientation $40^\circ \pm 10^\circ$ of the ISMF.

The systematic study made by Ratkiewicz et al. [2012] suggested the existence of a strong physical relationship between the ribbon and the ISMF. Hence, the conclusion was that by analyzing ENA detection from the perspective of the ISMF’s influence on the heliospheric asymmetries (Ratkiewicz et al. 2000) it might have been possible to predict the IBEX ribbon. The open question, however, which was left, concerned the physical mechanism supporting a large enough number of energetic ionized particles necessary for ENA production in the near vicinity of the HP in regions of maximum strength of the draped ISMF. We expected that a direct leakage of high energy ions from the inner to the outer heliosheath through the HP could ensure sufficient plasma

particles in the OHS (Schwadron et al. 2011). This expectation to some extent is confirmed by the recent paper by Zirnstein et al. [2016]. The authors conclude: “Our results suggest a significant number of primary ENAs from the inner heliosheath may contribute to the pickup ion source population outside the heliopause, depending on the ENA energy and SW speed.”

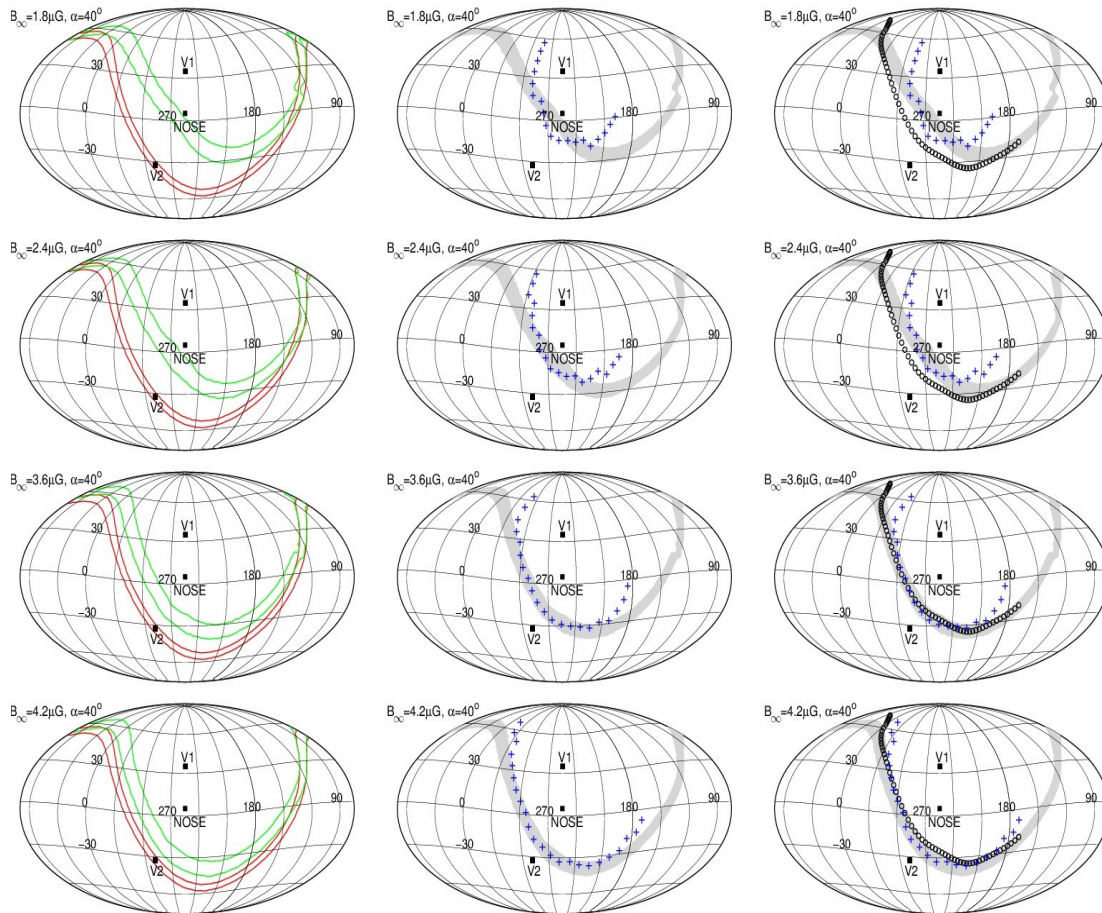


Figure. The influence of the magnetic field draping effects on geometry of the perpendicularity regions in the all-sky maps, i.e. the comparison of regions $\mathbf{B} \perp \mathbf{r}$ computed for an unperturbed (stripe between red lines) and perturbed (stripe between green lines) ISMF, respectively (left column). A comparison of regions $\mathbf{B}^{\mathbf{r}}_{\max} \perp \mathbf{r}$ (in grey, $\mathbf{B}^{\mathbf{r}}_{\max}$ is maximum of ISMF strength along lines of sight) with locations of the maximum of the ISMF strength $|\mathbf{B}^{\mathbf{fl}}_{\max}|$ along the field lines (crosses) (middle column). A comparison of regions $\mathbf{B}^{\mathbf{r}}_{\max} \perp \mathbf{r}$ (in grey) with locations of the maximum of the ISMF strength $|\mathbf{B}^{\mathbf{fl}}_{\max}|$ along the field lines (crosses) with the observed ribbon (black circles) (right column).

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