Summary of Research

Program:	Heliophysics Guest Investigators - Open 2020 Program
Grant number:	80NSSC21K0582
Project title:	Separation and Time-evolution of the Ribbon ENA Source Observed by IBEX

ACCOMPLISHMENTS

1. What were the major goals and objectives of this project?

Interstellar Boundary Explorer (IBEX) is a space mission observing energetic neutral atoms (ENAs). The first results from IBEX showed that two separate sources of ENA fluxes could be distinguished: the globally distributed flux (GDF) and the IBEX ribbon. The GDF originates primarily from the inner heliosheath and is seen in all directions in the sky. This component was anticipated before the mission launch. The IBEX ribbon was discovered in the first full-sky maps of ENA fluxes as a relatively narrow emission from an almost complete circular band in the sky, likely created in the outer heliosheath in the region where the magnetic field lines are perpendicular to the line-of-sight through a secondary ENA mechanism. Since these two components have different physical origins, analyses of the IBEX data require a separation method of these two sources. In this project, we developed a novel separation technique based on a spherical harmonic decomposition of the GDF. Our approach exploits the fact that the structures in these two sources have different angular scales. The project answered the following scientific questions as stated in the proposal:

Q1. What is the angular size of the spatial structures observed in the globally distributed flux? Are these structures different in angular scales when compared with structures associated with the ribbon?

Q2. How do the separated ribbon intensity and position change with the solar cycle? How does the accuracy of these observables increase due to the separation?

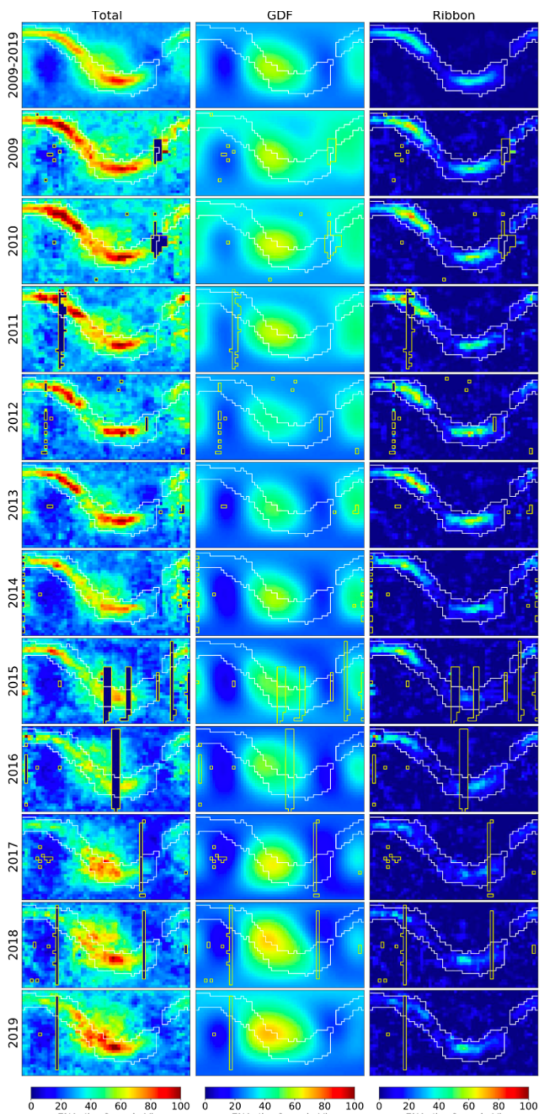

Figure 1 The combined (left), GDF (center), and ribbon (right) flux maps obtained by modeling the GDF with low-degree spherical harmonics. Adapted from Figure 8 in [P1].

The proposal outlined two separation methods using spherical harmonics. The first method is based on the orthogonality of spherical harmonics assuming that the flux is known over the entire sky. This method followed the idea presented by Sokół et al. (2015, Sol Phys 290, 2589) to fill gaps in the maps of solar wind speeds derived from interplanetary scintillations. The second method explored the possibility of using a χ^2 fitting in connection with a regularization. The goal was to provide separate sky maps of the GDF and the ribbon flux. These maps are needed for detailed analyses of the time evolution of the IBEX ribbon and comparison with models.

2. What was accomplished under these goals?

In the first phase of the project, we focused on the first separation method that exploited the orthogonality of spherical harmonics. This method required identifying a ribbon mask encompassing all pixels in the IBEX sky maps with the ribbon component. We employed an iterative method to derive this mask as pixels in which low-degree spherical harmonics could not well represent the flux. Subsequent iterations were applied to each considered map to estimate the flux within data gaps and under the ribbon mask. Eventually, this method provided the GDF maps reconstructed from spherical harmonics up to the degree of 3, and the ribbon maps calculated as a difference between the original map and the reconstructed GDF map. The developed methodology was applied to IBEX maps from each year separately (see Figure 1 with maps obtained for energy step centered at 1.7 keV). While the ribbon ENAs arrive from the directions with the ribbon mask, the result ribbon maps include some statistically significant fluctuation outside the mask due to small-scale structures in the GDF. We estimated the magnitude of these structures, which turned out to be much smaller than those in the ribbon. This partially answers question **Q1**. Our results were published in paper [P1] led by Pawel Swaczyna (project PI).

The results from the first separation method have been used in a study described in paper [P2] led by Eric J. Zirnstein (project Co-I) to compare the solar cycle evolution of the separated ribbon flux with the modeled flux in two opposing limits of pitch-angle scattering rates: weak and strong. The details of this scattering are critical to understanding the IBEX ribbon physics. For this task, a new model of the neutral solar wind, including the neutralized pickup ions, has been developed. The model provides a time-dependent representation reflecting changes in the solar wind latitudinal

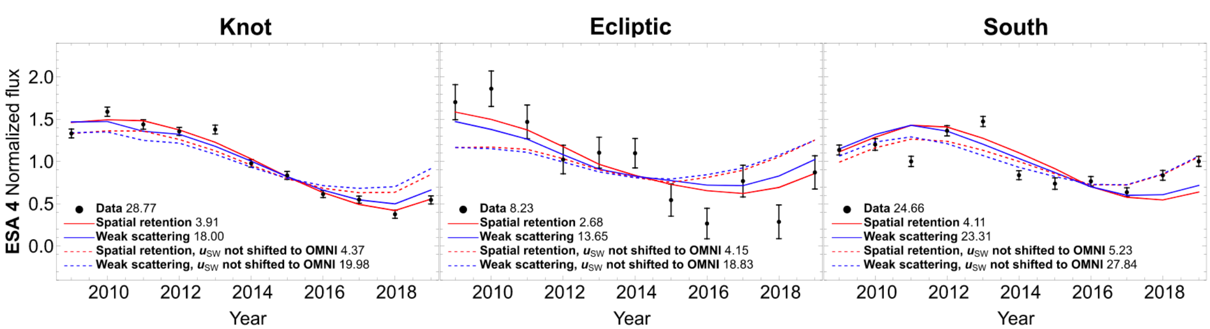

Figure 2 Time evolution of the normalized IBEX ribbon flux in three 20°×60° regions of the sky: (left) northern "knot" region, where the ribbon in ESA 5 & 6 was particularly dynamic in the early years of the IBEX mission, (center) "ecliptic" region where the ribbon crossed the ecliptic plane, and (right) "south" region around the southern part of the ribbon. The red and blue lines show two considered scenarios of the secondary ENA mechanism, and the dashed lines show the result for an alternative solar wind speed model. Adapted from Figure 9 in [P2].

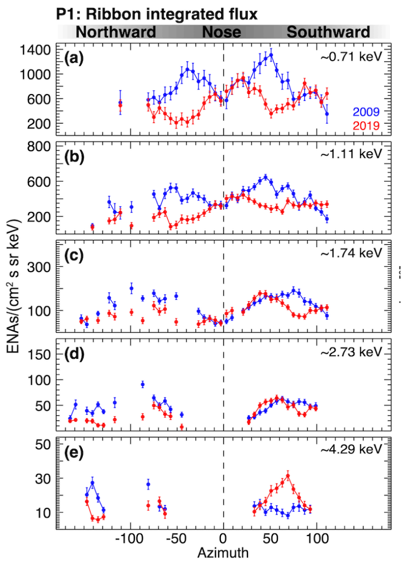

Figure 3 Ribbon integrated flux as a function of the azimuth angle in the ribbon-centered frame for two years: 2009 (blue) and 2019 (red). Adapted from Figure 3 in [P3].

structure and the distance evolution based on the recent New Horizons observations. The resulting relative flux evolutions in both considered scenarios are comparable and qualitatively in agreement with the evolution shown by the separated ribbon flux (see Figure 2). However, the magnitude of the modeled ribbon flux in the strong scattering case is significantly lower than observed. On the other hand, the geometry of the ribbon supports this scenario. This study showed that the temporal evolution of the IBEX ribbon geometry is too small to be identified in the IBEX observations, partially answering question **Q2**.

The same results have been used in a study led by Maher A. Dayeh (project Co-I) in paper [P3] to explore the change in the ribbon between 2009 and 2019. These two years show the ribbon from approximately the same phase of the solar cycle. The separated ribbon maps are used to comprehensively analyze the geometry of the IBEX ribbon in the ribbon-centered frame. The flux magnitude (see Figure 3), radius, and width of the ribbon are compared between the two years showing that the ribbon in 2019 returned to the 2009 shape only over part of the sky southward of the nose region, where the heliopause is the closest. Interestingly, the ribbon's radius appears slightly larger in 2019 in all ESA steps, although the change is not statistically significant, complementing the answer to question **Q2**.

Finally, we developed the second separation method in paper [P4] led by Pawel Swaczyna. While this method also requires a definition of the ribbon mask, the spherical harmonic coefficients are obtained from χ^2 analysis. The method consists of two regularized χ^2 fittings, one applied to the complete flux from the entire sky and the second applied only to the pixels outside of the ribbon mask. In this analysis, we use spherical harmonics up to the degree of 22 to fully represent all features observed in the sky. However, we need to include regularization terms that prevent variations in data gap and ribbon mask region. The results of the fitting to the complete maps are the spherical harmonic representation of the total flux, while the fitting excluding the ribbon mask provides the representations of the GDF. The spherical harmonic representations of the ribbon are given as the difference between these two results. This methodology enables the complete representation of

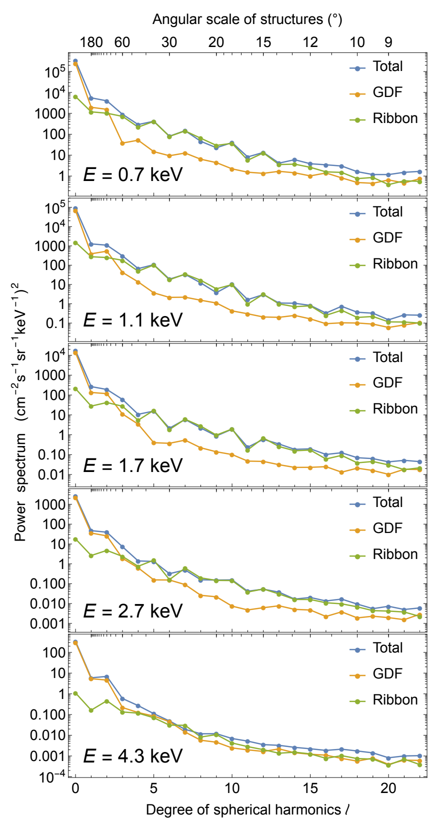

Figure 4 Angular power spectrum of structures in the total (blue), GDF (orange), and ribbon (green) components as a function of the degree of spherical harmonics. Reproduced from Figure 10 in [P4].

the IBEX ribbons in an alternative form to traditional pixelized IBEX maps. The separation was used to characterize the power spectrum of the GDF and ribbon flux as a function of the structure size, which showed that the ribbon dominates the structures between ~12° and ~60° in angular size (see Figure 4). This complemented the answer to scientific question **Q1**.

The project achieved the goals and objectives outlined in the proposal. We fully implemented the proposed research plan. The separated GDF and ribbon flux maps are publicly available on Zenodo [**D1-D2**].

3. **What opportunities for training and professional development has the project provided?**

The project allowed the investigators to learn new techniques and methods they could employ in future projects. For example, the regularization used in paper [P4] can be used in various fitting analyses when the problem may be ill-conditioned because the number of fit parameters is large. The spherical harmonic decomposition of a function in the sky is another technique that may be employed in other studies.

4. **How were the results disseminated to communities of interest?**

The results have been disseminated through papers and conference presentations listed under the product section of this report.

5. **What do you plan to do during the next reporting period to accomplish the goals and objectives?**

Nothing to report. This is the final report.

PRODUCTS (papers, data releases, & presentations)

The project's core results have been presented in the following peer-reviewed papers acknowledging support from the grant (project team members are bolded):

[P1] **P. Swaczyna**, T. J. Eddy, **E. J. Zirnstein**, **M. A. Dayeh**, D. J. McComas, H. O. Funsten, and N. A. Schwadron, 2022, *IBEX Ribbon Separation Using Spherical Harmonic Decomposition of the Globally Distributed Flux*, ApJS, **258**, 6, https://doi.org/10.3847/1538-4365/ac2f47

[P2] **E. J. Zirnstein**, **P. Swaczyna**, **M. A. Dayeh**, and **J. Heerikhuisen**, 2023, *Constraints on the IBEX Ribbon's Origin from its Evolution over a Solar Cycle*, ApJ, **949**, 45, https://doi.org/10.3847/1538-4357/acc577

[P3] **M. A. Dayeh**, **E. J. Zirnstein**, **P. Swaczyna**, and D. J. McComas, 2023, *Investigating the IBEX Ribbon Structure a Solar Cycle Apart*, ApJ, ***in press*** (arXiv:2304.05499)

[P4] **P. Swaczyna**, **M. A. Dayeh**, and **E. J. Zirnstein**, 2023, IBEX Ribbon Separation Using *Spherical Harmonic Decomposition of the Globally Distributed Flux*, ApJS, **266**, 26, https://doi.org/10.3847/1538-4365/accf0f

The team members have also contributed to the following papers acknowledging support from the grant:

[S1] A. Galli, I. I. Baliukin, M. Bzowski, V. V. Izmodenov, M. Kornbleuth, H. Kucharek, E. Moebius, M. Opher, D. Reisenfeld, N. A. Schwadron, **P. Swaczyna**, 2022, *The Heliosphere and Local Interstellar Medium from Neutral Atom Observations at Energies Below 10 keV*, SSRv, **218**, 31, https://doi.org/10.1007/s11214-022-00901-7

[S2] **M. A. Dayeh**, **E. J. Zirnstein**, S. A. Fuselier, H. O. Funsten, D. J. McComas, 2022, *Evolution of the Heliotail Lobes over a Solar Cycle as Measured by IBEX*, ApJS, **261**, 27, https://doi.org/10.3847/1538-4365/ac714e

[S3] **E. J. Zinstein**, T. K. Kim, **M. A. Dayeh**, J. S. Rankin, D. J. McComas, **P. Swaczyna**, 2022, *Explanation of Heliospheric Energetic Neutral Atom Fluxes Observed by the Interstellar Boundary Explorer*, ApJL, **937**, L38, https://doi.org/10.3847/2041-8213/ac92e2

Papers [P1-4] and [S1-3] are available in Open Access with publishers on the CHORUS Publisher Member list.

The separated GDF and ribbon maps have been provided as derivative data products on Zenodo:

[D1] **P. Swaczyna**, T. J. Eddy, **E. J. Zirnstein**, **M. A. Dayeh**, D. J. McComas, H. O. Funsten, and N. A. Schwadron, 2022, *Derivative products: "IBEX Ribbon Separation Using Spherical Harmonic Decomposition of the Globally Distributed Flux" by Swaczyna et al.*, Zenodo, https://doi.org/10.5281/zenodo.5562370

[D2] **P. Swaczyna**, **M. A. Dayeh**, and **E. J. Zirnstein**, 2023, *Derivative products from: "*IBEX Ribbon Separation Using *Spherical Harmonic Decomposition of the Globally Distributed Flux" by Swaczyna et al.*, Zenodo, https://doi.org/10.5281/zenodo.7683358

The following talks at conferences and meetings presented the project's results:

[T1] **P. Swaczyna**, T. J. Eddy, **E. J. Zirnstein**, **M. A. Dayeh**, D. J. McComas, H. O. Funsten, and N. A. Schwadron, *The Ribbon Separation with Spherical Harmonic Decomposition of the GDF*, talk, IBEX/IMAP Science Team Meeting, 17-18 August 2021, Hybrid, Laurel, MD, USA

[T2] **P. Swaczyna** et al., *Spherical harmonic representation and decomposition of ENA flux maps*, talk, IBEX/IMAP Science Team Meeting, 13-17 June 2022, Laurel, MD, USA

[T3] **P. Swaczyna**, H. O. Funsten, N. A. Schwadron, **M. A. Dayeh**, **E. J. Zirnstein**, and D. J. McComas, *Spherical Harmonic Decomposition of Energetic Neutral Atom Sources Observed by IBEX*, talk D1.4-0004-22, 44th COSPAR Assembly, 16-24 July 2022, Athens, Greece

[T4] **P. Swaczyna**, **M. A. Dayeh**, **E. J. Zirnstein**, David J. McComas, H. O. Funsten, and N. A. Schwadron, *Temporal Evolution of Separated Energetic Neutral Atom Flux Components Observed by IBEX*, talk, 20th Annual International Astrophysics Conference, 31 October – 4 November 2022, Santa Fe, NM, USA

[T5] **E. J. Zirnstein**, **P. Swaczyna**, **M. A. Dayeh**, and **J. Heerikhuisen**, *Constraints on the IBEX Ribbon's Origin from its Evolution over a Solar Cycle*, talk EGU23-2095, EGU General Assembly 2023, 24-28 April 2023, Hybrid, Vienna, Austria