Summary of Research

Program: ROSES 2019 - Outer Heliosphere Guest Investigator

Grant number: 80NSSC20K0781

Project title: Angular Scattering of Neutral Atoms: Observations and Interpretation from IBEX and Consequences for IMAP

ACCOMPLISHMENTS

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

In the project, we studied the effects of angular scattering of interstellar neutral (ISN) atoms in charge exchange (CX) and elastic collisions. These collisions modify the distribution functions of ISN atoms beyond the heliopause and thus may affect the determination of physical conditions in the very local interstellar medium (VLISM). The VLISM relative velocity and temperature are mainly inferred from observations of these atoms by instruments located close to the Sun, e.g., by IBEX. So far, analyses of ISN atom observations from IBEX-Lo and Ulysses/GAS have neglected elastic scattering and assumed that particles in CX collisions conserve momenta of parent particles, i.e., that there is no angular scattering in these collisions. We want to quantitatively verify the importance of angular scattering for the populations of ISN atoms observed by IBEX-Lo and, in the future, by IMAP-Lo. The project goals are summarized by the following scientific questions, as stated in the proposal:

Q1. How does angular scattering in CX and elastic collisions change distribution functions of ISN atoms at 1 au? How is this change reflected in IBEX-Lo observations?

Q2. Are physical parameters of the VLISM obtained from analyses of the ISN helium observations from IBEX-Lo affected by angular scattering in the outer heliosheath?

Q3. Do IBEX-Lo observations support an out-of-equilibrium distribution of the pristine ISN atoms ahead of the heliosphere?

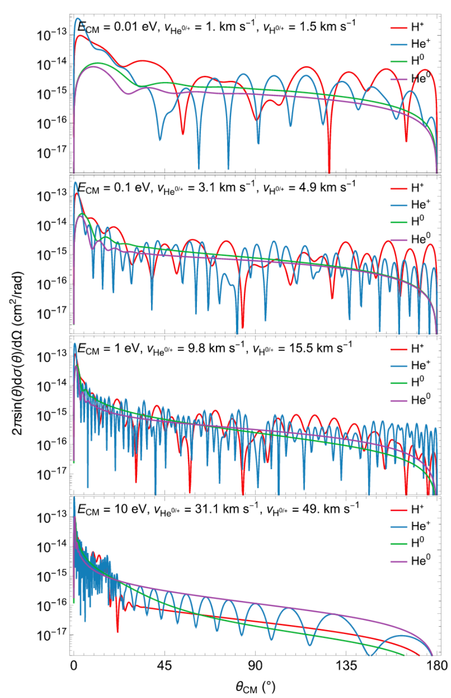

Figure 1 Differential cross sections for collisions of He atoms with various species for four collision energies typical for the outer heliosheath. Reproduced from Figure 1 in [P1].

2. What was accomplished under these goals?

The main challenge in the project was to develop a system to calculate the evolution of the ISN helium distribution function through the outer heliosheath accounting for angular scattering in elastic collisions. In our first study, we started with a simple one-dimensional cut of a global heliosphere model provided by Dr. Jacob Heerikuisen (project Collaborator) along the inflow direction. Because most atoms observed at 1 au arrive from a small cone around this direction, using a simple model for our first study was justified. Because we could not find a suitable source of needed differential cross sections, we derived them using the JWKB method and known interaction potential. As such cross sections may have wide application in other studies, we released them to the public in a numerical form on Zenodo [D1]. Examples of these cross sections are shown in Figure 1. With these cross sections, we used Monte Carlo integration of the ISN helium atom transport. We found that each ISN helium atom is scattered, on average, 4 times as it passes through the outer heliosheath, and only about 1.5% of atoms remain "pristine," i.e., travel through the outer heliosheath without any collision. Therefore, even though the scattering angles are typically small, multiple scatterings combine to non-negligible effects. Based on this study, we found that the mean speed decreases by ~0.45 km/s while the temperature increases by ~1100 K. We also found that the resulting population at the heliopause cannot be correctly described using a single Maxwell distribution. We introduced an asymmetric kappa-distribution to describe this population. We found that this population is anisotropic, but the temperature anisotropy is not as strong as identified by Wood et al. (2019, ApJ 881:55). The results are in **paper [P1]**.

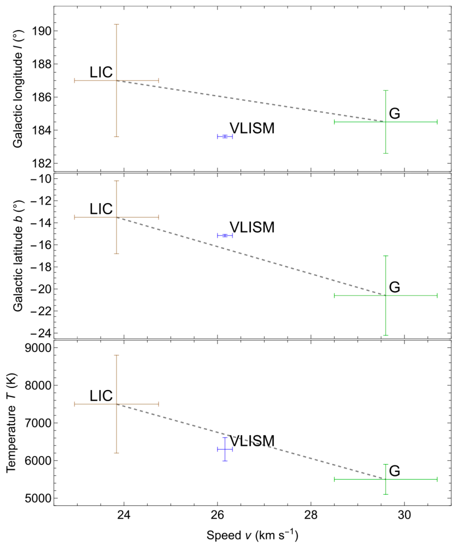

Figure 2 Comparison of flow parameters between the interstellar clouds (LIC and G) and the flow near the heliosphere (VLISM). Adapted from Figure 2 in [P3].

The results of our first study were implemented in **paper [P2]**, in which the IBEX-Lo data from the first 12 years of the IBEX mission were used to find the interstellar flow velocity and temperature. As the amount of data has grown significantly compared to the earlier studies, the uncertainties of the derived best-fit values for these parameters have reduced significantly. Therefore, appropriate corrections due to the angular scattering must be applied before the local flow parameters are compared with other astrophysical observations. This study also addressed the hypothesis that the flow parameters may change at a short time scale due to turbulence in the local interstellar medium. We did not find statistically significant changes in any parameters describing the velocity and temperature. Moreover, the upper limits on the change in the flow longitude based solely on IBEX data are about 3 times smaller than the change previously identified by Frisch et al. (2013, Sci, 341, 1080) using multiple data sources.

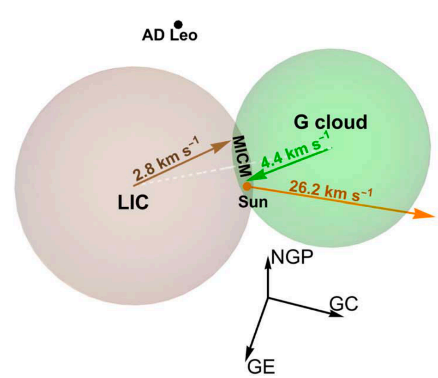

Figure 3 Schematic view of the mixing regions formed by the collision of the LIC and G cloud. Adapted from Figure 4 in [P3].

While observations of absorption lines in the UV spectra of nearby stars allowed for the identification of multiple interstellar clouds (Redfield & Linsky 2008, ApJ 673:283), each with a different bulk velocity, these observations cannot unambiguously resolve in which of the two nearest ones our heliosphere is embedded. With the updated flows from IBEX combined with the

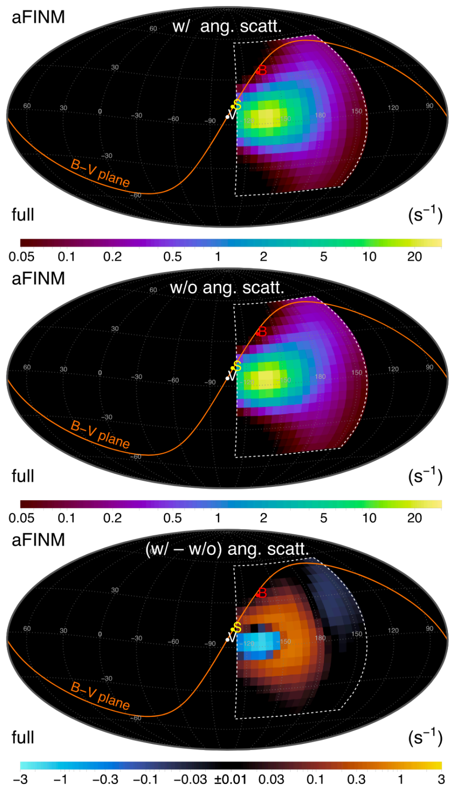

Figure 4 Expected ISN helium fluxes projected in the sky. Panels from top to bottom show the results with angular scattering, without angular scattering and their difference. Reproduced from Figure 11 in [P4].

parameters derived from Ulysses observations and STEREO, we addressed this problem in **paper [P3]**. We found that the Sun is unlikely in the local interstellar cloud (LIC) or G cloud. However, we found that the flow in the heliosphere is statistically compatible with a linear combination of the flows in these clouds, which may be expected in a mixing region between these clouds (see Figure 2). We determined that the Sun is inside a narrow mixing interstellar cloud medium (MICM); see Figure 3. The MICM presence is supported by higher densities of ISN hydrogen near the heliosphere and along some lines of sight. Furthermore, the temperature anisotropy may be related to the not fully equilibrated distribution of ISN helium atoms originating from both clouds.

Following up on the study in paper [P1], we expanded the calculations of the filtration processes in our next study published in **paper [P4]**. First, we included a full 3-dimensional model of the heliosphere rather than a simple one-dimensional cut through the heliosphere. We also included charge exchange collisions, including any angular scattering based on the differential cross sections. The results are similar to those discussed above. However, we were able to examine other aspects that could not be done using the one-dimensional approach. We found that the density and bulk velocity of the ISN helium populations depend on their entry point to the heliosphere, i.e., these populations are not homogenous. The distribution functions at the heliopause have been implemented in the UNH analytical full integration model (aFINM). The expected ISN helium fluxes from both populations change due to accounting for the angular scattering (see Figure 4).

IBEX studies that analyze the primary ISN helium population focused on just 6 (out of 60) spin angle bins centered around the peak of the distribution collected over a few weeks around the helium peak. In this range, the incoming helium atom energy variance in the spacecraft frame is small. Thus, these analyses used a simplified approach to the energy response of the instrument. However, the effects of elastic and charge exchange collisions are visible primarily outside this limited range, and thus, the considered energy range is much wider. Unfortunately, the knowledge of the instrument

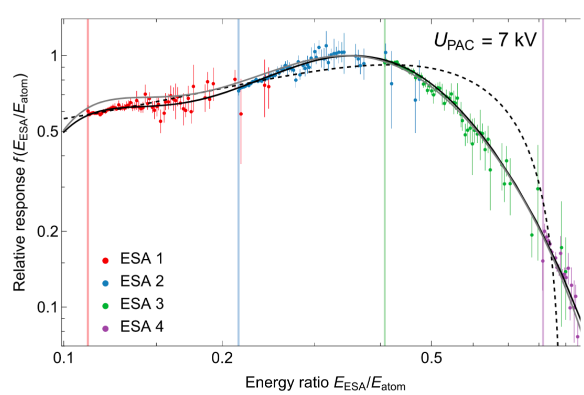

Figure 5 Relative response function for ISN atoms observed by IBEX-Lo as a function of the ratio between the nominal energy of energy step to the energy of incoming atoms. Adapted from Figure 7 in [P5].

response function from the laboratory calibration is limited. In **paper [P5]**, we showed that the IBEX observations in multiple energy steps may be used to derive the relative response function. Figure 5 presents the derived response function that is very important in our next study.

The ISN helium observations encompassing a wide range of bins are studied in **paper [P6]**. The tools developed in the above-described studies have been fully applied to combined observations of the primary and secondary populations. We performed χ^2 comparison of the observations with modeling based on the global heliosphere model. We found the best-fit parameters for the interstellar conditions around the heliosphere. We checked how the IBEX observations constrain them, including correlations. We confirmed the importance of angular scattering of ISN helium atoms in elastic and charge exchange collisions.

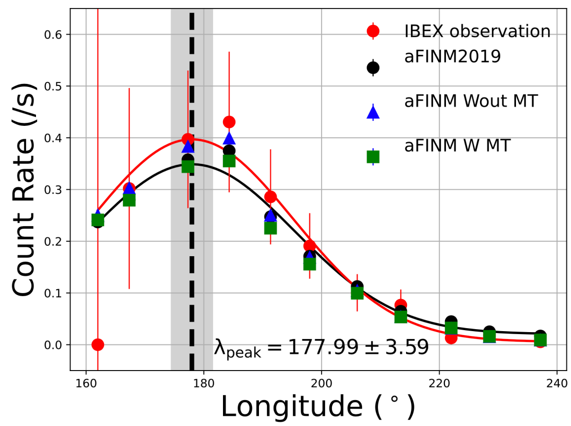

Figure 6 The ISN hydrogen peak flux as a function of the longitude. The red symbols show the IBEX data, the black symbols show the previously used model, while the blue and green symbols show the results for the new model without and with accounting for the angular scattering. Reproduced from Figure 4 in [P7].

Our last analysis in this project is presented in **paper [P7]** led by Dr. Fatemeh Rahmanifard (project Co-I). We adopted the previously developed tools to introduce angular scattering in the transport of ISN hydrogen. It is also the first study of ISN hydrogen observations from IBEX that does not directly use the approximation of the primary and secondary ISN hydrogen populations with Maxwell distributions. We found that the changes to the properties of the primary and secondary populations are less significant than for helium because the role of angular scattering compared to changes due to charge exchange collisions is smaller. Figure 6 compares the peak fluxes as a function of Earth's longitude observed by IBEX with the model predictions. We found that the inclusion of angular scattering does not impact the peak position significantly and thus does not explain the discrepancy between the radiation pressure strength derived from the position of this peak and direct observations of the solar Lyman-α line.

In this project, we explored the consequences of angular scattering of ISN atoms in the outer heliosheath in binary collisions with other particles. Most importantly, we found that the populations at the heliopause significantly deviate from Maxwell distributions. We proposed an asymmetric kappa-distribution and composite of multiple Maxwell distributions to describe the primary and secondary populations, respectively. These results published in papers [P1], [P4], and [P7] answer question **Q1**. Furthermore, we found that the angular scattering effects are strong and influence the derivation of interstellar parameters from the IBEX observations. Details on our findings answering question **Q2** can be found in papers [P2] and [P6]. Finally, we confirmed that IBEX observations suggest that the Sun is inside a mixing region between two interstellar clouds, which is not fully equilibrated, see paper [P3], answering question **Q3**. Our project indicates the importance of angular scattering in interpreting IBEX-Lo and future IMAP-Lo data.

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

Within the project, we learned new techniques needed to achieve the goals of this project. Among others, we derived differential cross sections using the JWKB methodology and integrated the stochastic transport of ISN atoms using the Monte Carlo technique. We will be able to use these techniques in future studies. We further developed a modified version of aFINM, which is more precise in terms of trajectories of ISN atoms entering the heliosphere and can be paired with global models. This modified version can be used for future scientific endeavors.

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**, **F. Rahmanifard**, **E. J. Zirnstein**, D. J. McComas, **J. Heerikhuisen**, 2021, *Slowdown and Heating of Interstellar Neutral Helium by Elastic Collisions beyond the Heliopause*, ApJL, **911**:36, https://doi.org/10.3847/2041-8213/abf436

[P2] **P. Swaczyna**, M. A. Kubiak, M. Bzowski, J. Bower, S. A. Fuselier, A. Galli, D. Heirtzler, D. J. McComas, E. Möbius, **F. Rahmanifard**, N. A. Schwadron, 2022, *Very Local Interstellar Medium Revealed by a Complete Solar Cycle of Interstellar Neutral Helium Observations with IBEX*, ApJS, **259**:42, https://doi.org/10.3847/1538-4365/ac4bde

[P3] **P. Swaczyna**, N. A. Schwadron, E. Möbius, M. Bzowski, P. C. Frisch, J. L. Linsky, D. J. McComas, **F. Rahmanifard**, S. Redfield, R. M. Winslow, B. E. Wood, G. P. Zank, 2022, *Mixing Interstellar Clouds Surrounding the Sun*, ApJL, **937**:32, https://doi.org/10.3847/2041-8213/ac9120

[P4] **P. Swaczyna**, **F. Rahmanifard**, **E. J. Zirnstein**, **J. Heerikhuisen**, 2023, *Filtration of Interstellar Neutral Helium by Elastic and Charge Exchange Collisions in Heliospheric Boundaries*, ApJ, **943**:74, https://doi.org/10.3847/1538-4357/acaa36

[P5] **P. Swaczyna**, M. Bzowski, S. A. Fuselier, A. Galli, **J. Heerikhuisen**, M. A. Kubiak, D. J. McComas, E. Möbius, **F. Rahmanifard**, N. A. Schwadron, 2023, *Relative In-flight Response of IBEX-Lo to Interstellar Neutral Helium Atoms*, ApJS, **266**:2, https://doi.org/10.3847/1538-4365/acc397

[P6] **P. Swaczyna**, M. Bzowski, **J. Heerikhuisen**, M. A. Kubiak, **F. Rahmanifard**, **E. J. Zirnstein**, S. A. Fuselier, A. Galli, D. J. McComas, E. Möbius, N A. Schwadron, 2023,

Interstellar Conditions Deduced from Interstellar Neutral Helium Observed by IBEX and Global Heliosphere Modeling, ApJ, **953**:107, https://doi.org/10.3847/1538-4357/ace719

[P7] **F. Rahmanifard**, **P. Swaczyna, E. J. Zirnstein**, **J. Heerikhuisen**, A. Galli, J. M. Sokół, N. A. Schwadron, E. Möbius, D. J. McComas, S. A. Fuselier, 2023, *The Effect of Angular Scattering Imposed by Charge Exchange and Elastic Collisions On Interstellar Hydrogen Atoms*, ApJ, ***under revision***, https://arxiv.org/abs/2306.04598

The following supporting papers also acknowledged 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] A. Galli, P. Wurz, N. A. Schwadron, K. Fairchild, D. Heirtzler, E. Möbius, H. Kucharek, R. Winslow, M. Bzowski, M. A. Kubiak, I. Kowalska-Leszczyńska, S. A. Fuselier, J. M. Sokół, **P. Swaczyna**, D. J. McComas, 2022, *One Solar Cycle of Heliosphere Observations with the Interstellar Boundary Explorer: Energetic Neutral Hydrogen Atoms Observed with IBEX-Lo from 10 eV to 2 keV*, ApJS, **261**, 18, https://doi.org/10.3847/1538-4365/ac69c9

Papers [P1-7] and [S1-2] are or will be published in Open Access by publishers on the CHORUS Publisher Member list.

The results of the projects are also included in the following derivative products released on Zenodo:

[D1] **P. Swaczyna**, 2021, *Differential cross sections for collisions of He atoms with H^+, He^+, H^0, and He^0*, Zenodo, https://doi.org/10.5281/zenodo.4555715

[D2] **P. Swaczyna**, M. A. Kubiak, M. Bzowski, J. Bower, S. A. Fuselier, A. Galli, D. Heirtzler, D. J. McComas, E. Möbius, **F. Rahmanifard**, N. A. Schwadron, 2022, *Derivative products: "Very Local Interstellar Medium Revealed by Complete Solar Cycle of Interstellar Neutral Helium Observations with IBEX" by Swaczyna et al.*, Zenodo, https://doi.org/10.5281/zenodo.5842421

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

[T1] **P. Swaczyna**, *Interstellar Neutrals Atoms from the Very Local Interstellar Medium to 1 au*, talk, **Outer Heliosphere Workshop**, July 21-23, 2021, Hybrid, Boulder, CO, USA.

[T2] **P. Swaczyna**, J. Bower, M. Bzowski, S. A. Fuselier, A. Galli, **J. Heerikhuisen**, D. Heirtzler, M. A. Kubiak, D. J. McComas, E. Möbius, **F. Rahmanifard**, N. A. Schwadron, **E. J. Zirnstein**, *Observations of Interstellar Neutral Helium over the Full Solar Cycle*, talk, **IBEX/IMAP Science Team Meeting**, August 17-18, 2021, Laurel, MD, USA.

[T3] **P. Swaczyna**, J. Bower, M. Bzowski, S. A. Fuselier, A. Galli, **J. Heerikhuisen**, D. Heirtzler, M. A. Kubiak, D. J. McComas, E. Möbius, **F. Rahmanifard**, N. A. Schwadron, **E. J. Zirnstein**, *Complete Solar Cycle Observations of Interstellar Neutral Helium with IBEX: Consequences of Modulation in Heliospheric Boundaries*, talk SH21B-07, **AGU Fall Meeting 2021**, December 13-17, 2021, New Orleans, LA, USA.

[T4] **P. Swaczyna**, M. Bzowski, S. A. Fuselier, A. Galli, **J. Heerikhuisen**, M. A. Kubiak, D. J. McComas, E. Möbius, **F. Rahmanifard**, N. A. Schwadron, **E. J. Zirnstein**, *Filtration and*

Scattering of Interstellar Neutral Helium beyond the Heliopause, talk EGU22-6502, **EGU General Assembly 2022**, May 23-27, 2022, Vienna, Austria.

[T5] **P. Swaczyna**, N. A. Schwadron, E. Möbius, M. Bzowski, P. C. Frisch, J. L. Linsky, D. J. McComas, **F. Rahmanifard**, S. Redfield, R. M. Winslow, B. E. Wood, G. P. Zank, *Mixed interstellar clouds surrounding the Sun*, talk, **IBEX/IMAP Science Team Meeting**, June 13-17, 2022, Laurel, MD, USA.

[T6] **P. Swaczyna**, N. A. Schwadron, E. Möbius, M. Bzowski, P. C. Frisch, J. L. Linsky, D. J. McComas, **F. Rahmanifard**, S. Redfield, R. M. Winslow, B. E. Wood, G. P. Zank, *Charting Interstellar Medium near the Heliosphere*, poster SH45G-2400, **AGU Fall Meeting 2022**, December 12-16, 2022, Chicago, IL, USA.

[T7] **P. Swaczyna** et al., *Improved analysis of IBEX-Lo interstellar neutral helium atom observations with derivation of the relative energy response and inclusion of angular scattering effects*, talk, **IBEX/IMAP Science Team Meeting**, August 15-16, 2023, Laurel, MD, USA.

[T8] **F. Rahmanifard**, **P. Swaczyna**, **E. J. Zirnstein**, **J. Heerikhuisen**, A. Galli, J. M. Sokół, N. A. Schwadron, E. Möbius, D. J. McComas, S. A. Fuselier, *The Effect of Angular Scattering Imposed by Charge Exchange and Elastic Collisions on Interstellar Neutral Hydrogen Atoms*, talk, **IBEX/IMAP Science Team Meeting**, August 15-16, 2023, Laurel, MD, USA.

[T9] **F. Rahmanifard**, **P. Swaczyna**, **E. J. Zirnstein**, **J. Heerikhuisen**, A. Galli, J. M. Sokół, N. A. Schwadron, E. Möbius, D. J. McComas, S. A. Fuselier, *The Effect of Elastic and Charge Exchange Collisions in the Outer Heliosheath on the Interstellar Hydrogen Signal Observed by IBEX-Lo*, abstract submitted to **AGU Fall Meeting 2023**, December 11-15, 2023, San Francisco, CA, USA.