OPIS SKRÓCONY

Z IBEX-em do IMAP-a: badanie oddziaływania wiatru słonecznego z ośrodkiem międzygwiazdowym na podstawie obserwacji atomów neutralnych i modelowania

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With IBEX to IMAP: investigating the interaction of the solar wind with the interstellar medium based on observations of neutral atoms and modeling

Science objective

The objective of the project is to improve the understanding of the interaction of interstellar matter in the immediate neighborhood with the solar wind, the processes operating in this interaction region, the physical state of the Very Local Interstellar Medium (VLISM), as well as the heliolatitude structure of the solar wind and the solar EUV output. Another goal is to identify best science opportunities in the ISN gas sampling planned for a NASA mission Interstellar Mapping and Acceleration Probe (IMAP; McComas et al., 2018), which will be launched in Oct. 2024. The project is a continuation of the Polish involvement in the NASA space mission Interstellar Boundary Explorer (IBEX, McComas et al. 2009) and in the mission IMAP, presently in Phase A.

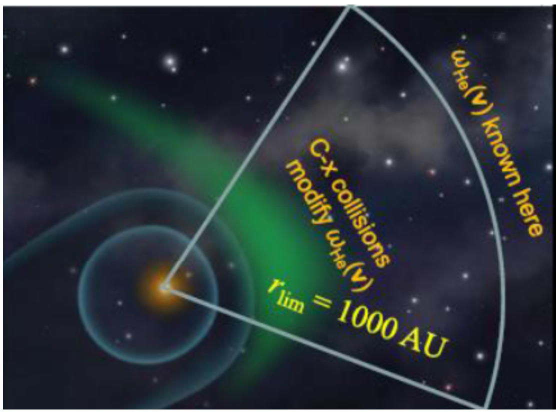

Figure 1 Artist's vision of the heliosphere and its boundary region (outer heliosheath, green). The region ahead of the OHS is almost unperturbed by solar emissions. The Sun is moving relative to the interstellar medium towards the right edge of the figure. The atoms observed by IBEX and IMAP come from a conical region (gray outline). The flow of ISN gas is modified in the OHS due to charge exchange with the perturbed interstellar plasma, flowing past the heliopause (an open contour). The Sun is the bright spot a little off-center of the nearly spherical termination shock of the solar wind. The energetic neutral atoms, observed by IBEX and IMAP, are produced between the termination shock and the heliopause.

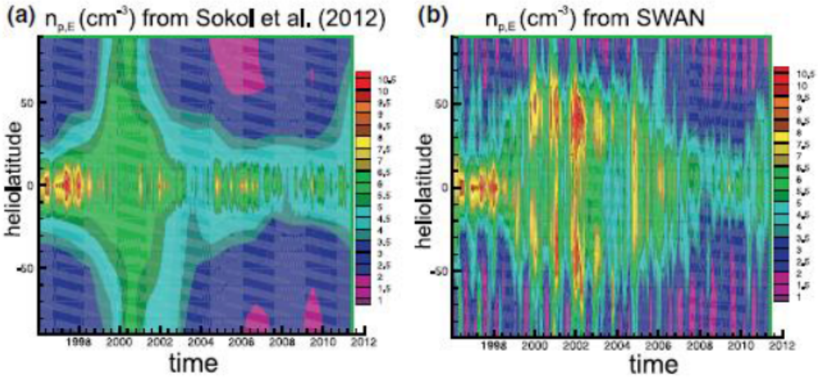

Figure 2. Differences between the solar wind structure obtained from scintillation observations (left, Sokół et al. 2013) and from analysis of helioglow observations (Katushina et al. 2013). Note the yellow-red bands of high density at mid-latitudes in the right panel, absent in the left panel, and the differences in the latitudinal span of the slow solar wind. Source: Katushkina et al. (2013).

Within the project, we plan to determine the magnitudes of the physical parameters of the VLISM (Fig.1): the temperature, the velocity vector relative to the Sun, the strength and direction of interstellar magnetic field, the density of interstellar plasma (H^+ and He^+), and the densities of the ISN H and He populations. This will be done by fitting direct-sampling observations of interstellar neutral (ISN) gas, collected by IBEX, using a hybrid model composed of a MHD-kinetic global model of the heliosphere (the Huntsville model; Heerikhuisen & Pogorelov 2010) and the newest version of the Warsaw Test Particle Model (WTPM) of the ISN gas distribution inside the heliosphere (Bzowski et al. 2019). For the first time, data from the entire cycle of solar activity will be used.

Since the plasma flow in the OHS is sensitive to solar wind flux and ram pressure, we plan to verify if the latitudinal distribution of these quantities indeed features maxima at middle heliolatitudes, suggested based on observations of the heliospheric backscatter glow in the Lyman-α line by SWAN/SOHO (Katushkina et al. 2013, 2019, Koutroumpa et a. 2019), which is at odds with conclusions from observations of interplanetary scintillations (Tokumaru et al.2015, Sokół et al. 2013, 2015), as shown in Fig. 2. This will be done by fitting photometric maps of the heliospheric Lyman-α glow, observed by SWAN/SOHO (Bertaux et al. 1995) since mid-1990s, with a model of the helioglow based on WTPM, calculated with the most recent model of the solar illumination (Kowalska-Leszczynska et al. 2018), the solar wind, and the solar EUV output (Bzowski et al. 2013, Sokół et al., 2019a) and allowing for adjustable variations in the heliolatitudinal structure of the solar EUV output.

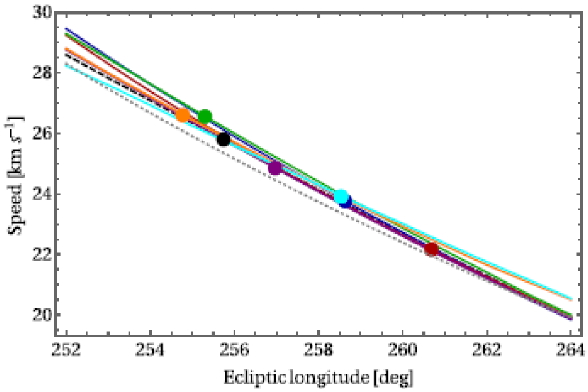

Figure 3. The components of ISN flow velocity and the ISN temperature obtained from direct sampling by IBEX feature an appreciable correlation: the uncertainties are not homogenous in the parameter space, which is illustrated as correlation lines and a scatter of yearly determinations along those lines. This is caused by the lack of speed resolution of atoms impacting the detector and limiting IBEX observations to great sky circles perpendicular to antisolar lines. IMAP will not have this restriction and our project will determine the best observation strategy to remove the parameter correlation. Bzowski et al. (2015)

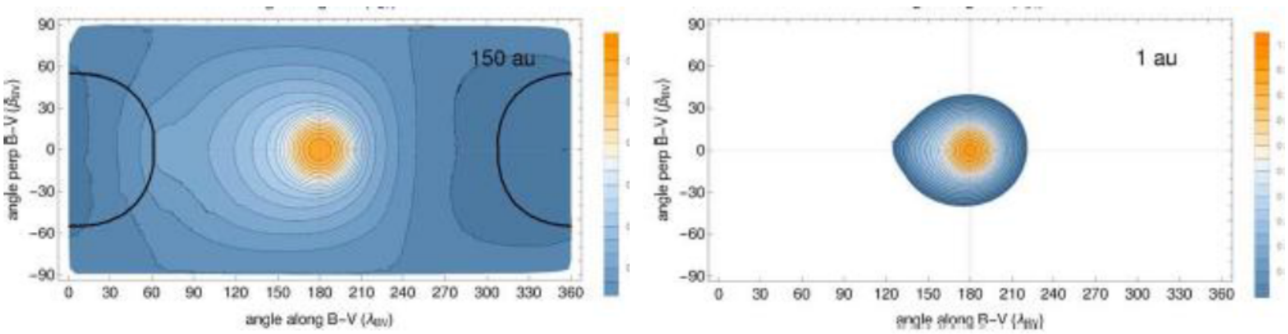

Figure 4. Maps of speed-integrated distribution function of ISN He in the OHS at 150 au upwind (left) and at 1 au upwind (right), simulated by Kubiak et al. 2019 using the WTPM model, taking charge-exchange production and losses of He atoms into account. The reference frame is based on a plane defined by the flow vectors of the Warm Breese and ISN He, determined by Kubiak et al. 2016 and Bzowski et al. 2015 from IBEX observations; this is also the plane containing the unperturbed interstellar magnetic field. While at 150 au the distribution function is strongly non-Maxwellian, strong kinematic selection effects result in relatively small deflections of the distribution function at 1 au. The little-perturbed ISN He is the yellow regions at the center. The form of the distribution function at 1 au is strongly location-dependent because of gravitational bending of the atom trajectories. With large statistics, IBEX and IMAP are able to distinguish the effects of charge exchange coupling in the outer heliosheath.

IBEX observations of ISN gas are limited to lines of sight perpendicular to the spacecraft – Sun directions, which results in a relatively large correlations in the fitted ISN gas flow vector components (Fig. 3) and limits the time during the year available for observations. IMAP will have a capability adjust the angle of its viewing direction relative to the spacecraft rotation axis, which will extend the yearly observation time and enable removing the correlation of the parameters of the ISN (Sokół et al., 2019c). We will develop an optimum observation strategy to exploit this capability and perform an optimization study, identifying other resulting science opportunities. We will identify the times and preferred elongations of the IMAP-Lo LOS from the Sun for the determination of the ionization rate of ISN He inside the Earth orbit, for searching for hypothetical departures of the distribution function of ISN gas from Maxwell-Boltzmann state (a bi-Maxwellian vs kappa distributions, Woods et al. 2018 vs Swaczyna et al. 2019, respectively) and for signatures of filtration of ISN gas in the OHS.

Significance

Interstellar Neutral (ISN) gas, mostly He, but also H, D, O, and Ne, is sampled by IBEX at 1 au from the Sun (Möbius et al., 2009, Bochsler et al. 2012). Because of the charge-exchange interaction between the perturbed plasma flowing past the heliopause and the unperturbed ISN gas, a new population of ISN atoms is injected into the flow, the so-called secondary population (Baranov & Malama 1993). Hence, ISN atoms bring information on the processes operating in the outer sheath of the heliosphere (OHS) and on the physical state of the VLISM to the detector located at 1 au (Fig. 4). Recently, we determined the temperature of the VLISM and the velocity vector of the Sun (Bzowski et al. 2015, Schwadron et al. 2015, McComas et al. 2015) and discovered an additional population of ISN atoms: the Warm Breeze in the flow of ISN He (Bzowski et al. 2012, Kubiak et al. 2014). The latter one was shown to be the secondary population of ISN He (Bzowski et al. 2017), created in the OHS due to charge exchange between ISN He atoms and interstellar He^+ ions (Fig. 1, 4). We found that the plane defined by the inflow velocity vectors of the Warm Breeze and ISN He is the plane containing the vector of Sun's motion through the VLISM and of the VLISM magnetic field vector (Kubiak et al. 2016). We also showed that the ISN He signal observed by IBEX and IMAP is sensitive to the physical state of the VLISM. Using values of relevant VLISM parameters known from independent analyses (Zirnstein et al. 2016) and the Huntsville global model of the heliosphere, we determined the density of interstellar He^+, and using information from independent studies we found the ionization state of the VLISM and the total plasma density (Bzowski et al. 2019).

Investigating the OHS and VLISM has been done by forward modeling and model parameters were fitted using a sophisticated chi-square minimization method (Swaczyna et al. 2015). The magnitude of the minimum reduced chi-square obtained so far is ~2, i.e., is statistically too large, which suggests that either the model used is not fully adequate or that parameters adopted as fixed and known are in fact not accurate. Determining the physical state of the VLISM is important both to understand the interaction of the Sun with its interstellar environment and for understanding the VLISM itself. Estimates of the VLISM kinematics and temperatures done using studies of absorption lines towards nearby stars do not yield a fully conclusive image of the solar interstellar environment (e.g., the multi-cloud model by Redfield & Linsky et al. (2008) and, Linsky et al. (2019) vs one non-homogenous cloud model by Gry et al. 2014). Measuring the parameters of interstellar matter from the solar perspective is just a single point measurement from the global VLISM perspective, but the detail of the data used for this measurement makes it an important complement to large-scale line-of-sight studies.

Understanding the latitudinal structure of the solar wind is important for understanding the processes of acceleration of solar wind in solar-type stars in general and for understanding the structure of the heliosphere. It is disturbing when results depend on the research method employed. The scintillation method (Coles & Kaufman 1978) does not rely on any modeling of ISN H, while the helioglow method does (Katushkina et al. 2013). In the existing helioglow studies of the solar wind structure it was assumed that the illumination from the Sun is spherically symmetric, but independent analyses suggest it is not (Auchere et al. 2005). Results of our research will resolve this enigma, which will help to better understand the latitudinal distribution of the coronal and chromospheric emissions of solar-type stars.

Establishing an optimum strategy of observations by IMAP-Lo and identifying research opportunities given by the new capability of adjusting the LOS of the instrument is an element of IMAP mission preparation. The PI and one of Polish CoIs of the project are CoIs on the IMAP mission and in the IMAP-Lo instrument. The project covers their contribution to the development of the IMAP-Lo experiment.

Research concept and plan

We plan to perform the following tasks, all of them in parallel:

1. Determination of the magnitudes of the physical parameters of the Very Local Interstellar Medium based on IBEX observations of interstellar neutral atoms and modeling
2. Attempted resolving of the enigma of the 3D structure of the solar wind and the EUV output
3. New insights on the Local Interstellar Medium and the heliospheric sheath expected owing to the adjustable boresight of the IMAP-Lo instrument
4. Assessment of the evolution of the spectra of energetic neutral atoms in the heliosphere

All these tasks will be performed in parallel building on the existing and continuously updated and refined models of the heliosphere (Huntsville), ISN gas distribution (WTPM), and the Warsaw model of the solar output.

Research methodology

To determine the VLISM parameters, we will use data from IBEX-Lo from 2009—2020. We have access to IBEX data since as members of the IBEX Science Team. We will calculate a parameter grid of the Huntsville model centered about the recently obtained parameter set from Bzowski et al. 2019. We will vary each of the relevant parameters while keeping the other ones fixed. Assuming that the uncertainties of the presently adopted parameter values are close to accurate, we will need approximately 32 runs of the Huntsville model, which is feasible within the project time scope. The fitted IBEX signal will be simulated using the version of the WTPM model (Bzowski et al. 2017, 2019) where gains and losses of He atoms due charge-exchange collisions in the outer heliosheath are taken into account self-consistently with the global heliosphere model (Figs.1, 4). Chi-square minimization will be performed using an adaptation of the method from Swaczyna et al. 2015. The final result will be verified by comparing the data with a model run with the found parameters. This study will be performed in close collaboration with our international CoIs and their collaborators in their home institutions.

A series of daily sky maps of the helioglow observed by SWAN, from throughout the solar cycle, will be simulated using a helioglow model based on the WTPM model calculated using the most recent version of the evolution of solar wind obtained from scintillation studies and either with an anisotropy of the solar EUV output (radiation pressure, illumination, and photoionization) assumed or without it. The anisotropy will be given by a simple parameter function. The simulated maps will be compared with the observed ones and the parameter of the EUV anisotropy function will be fitted to match the data using a linear approximation. The anisotropy factor will be determined for all maps separately and the resulting statistics analyzed. Before using in the fits, the maps will be cleaned from contamination by extraheliospheric sources (stars, bright quasars, Milky Way) using machine learning, with the locations of EUV-bright stars obtained from the IUE spectra data base. Both the SWAN/SOHO and the IUE data are publicly available and we have already gained experience in using them.

In the preparation to the IMAP-Lo experiment, we will simulate the expected signal based on the parameters of the VLISM obtained thus far, using the synthesis method of the ISN gas signal based on simulation of charge-exchange processes in the OHS (Bzowski et el. 2017, 2019) and the global heliosphere model from our NZ Co-I. By comparing the results with the results of the simplified approach, where the primary and secondary populations are simulated as two independent Maxwell-Boltzmann populations, we will identify the times during the year and the viewing geometries best suited to differentiate between these models. Subsequently, we will modify the assumptions on the VLISM physical state, allowing for kappa-like or bi-Maxwellian distribution function, and repeat the simulations to identify the expected signatures of these effects in the signal, as well as the most favorable times during the year and LOS directions to identify them,

Studies of the modification of the spectra of heliospheric ENAs is a continuation of our contributions to the IBEX Team performed since the beginning of the mission. We will calculate the ENA survival probabilities using the our model of thee ionizing factors (Bzowski et al. 2013, Sokół et al. 2019a) and in collaboration with the Princeton Co-I of the project use them to develop science products for further analysis.

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