Heliospheric physics

(Laboratory for solar system physics and astrophysics)

The supersonic, ionized solar wind, emitted by the Sun, carves out a cavity in the interstellar matter called the heliosphere. Its size is determined by a balance between the pressures of the magnetized solar wind and of the interstellar gas, which is also magnetized. The heliosphere is bounded by a contact discontinuity layer called the heliopause, which separates the solar wind and interstellar plasmas. While the interstellar plasma is deflected and flows past the heliopause, the neutral component, mainly hydrogen and helium, penetrates freely into the heliosphere, where it can be directly observed. An artist vision of the heliosphere, with explanation of some terms used below, is presented in Figure 8.

The heliospheric structure can be sampled by means of energetic neutral atoms (ENA) that are created by multiple charge exchange reactions between interstellar neutral atoms and protons from the solar wind. One of the important aspects of this interaction is the so-called IBEX Ribbon, which is a large, arc-like region of enhanced ENA emission, unexpectedly discovered shortly after the beginning of observations by the NASA space probe Interstellar Boundary Explorer (IBEX). This mission was developed and is led by the Southwest Research Institute in San Antonio, TX under the NASA Small Explorers program. It is managed by the Goddard Space Flight Center for the NASA Science Mission Directorate in Washington, DC. Research is carried out by the IBEX Science Team of researchers from the United States, Poland, Switzerland, Germany, and Russia. SRC PAS has participated in the IBEX effort since the planning phase at the Co-Investigator level.

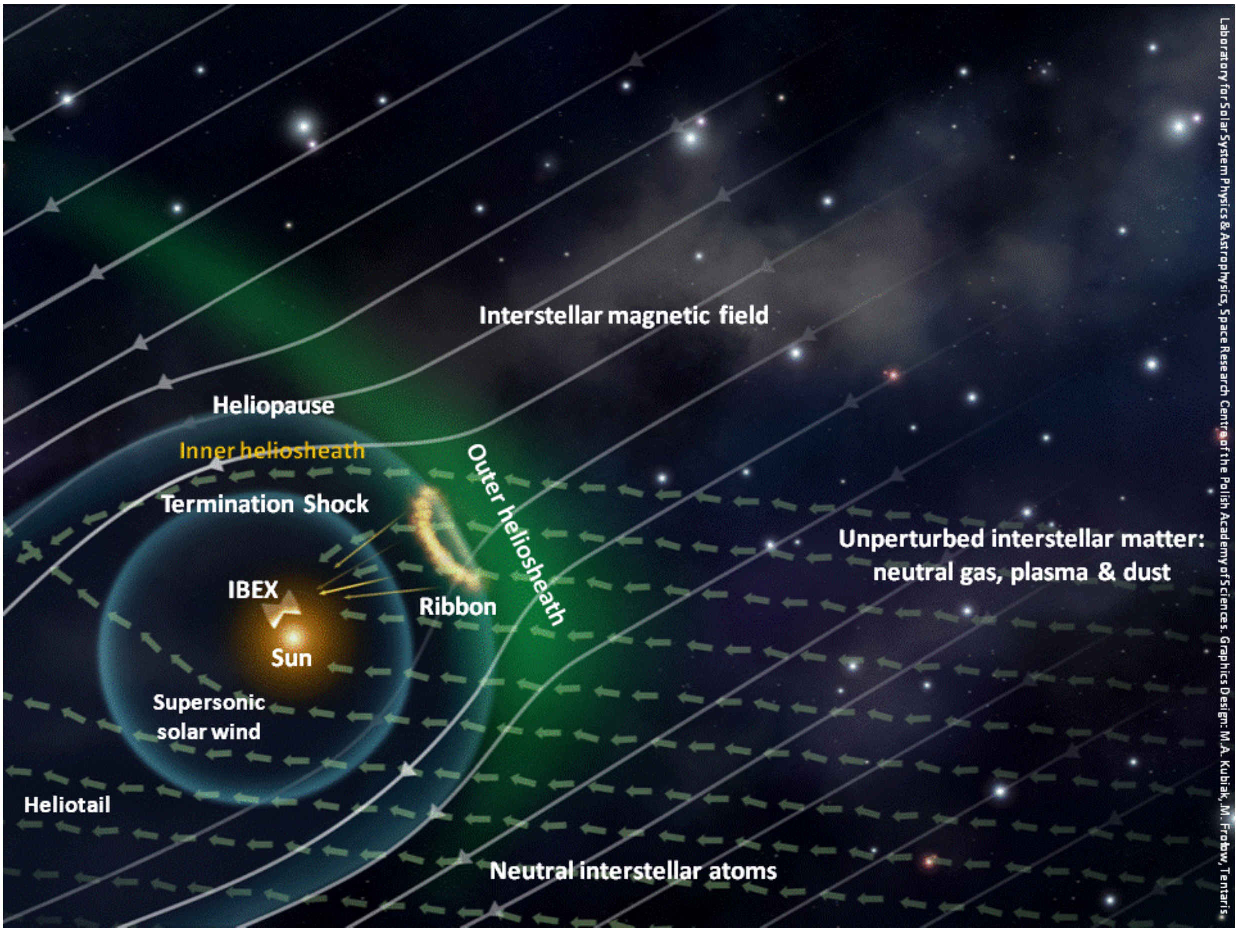

Figure 8. Artist's vision of the heliosphere and its nearest Galactic neighborhood as it emerges from recent IBEX analysis and several years of research carried out in the Laboratory for Solar System Physics and Astrophysics. The Sun is embedded in the Local Cloud of interstellar matter composed of *ionized and neutral atoms* and *dust grains* of various sizes. It is one of many similar clouds within the Local Interstellar Medium, which is a ~200 pc remnant of a series of Supernova explosions a few million years ago. The Sun moves through the cloud from right to left, emitting the *solar wind* - an ever-evolving, omnidirectional, latitudinally structured, hypersonic *outflow of solar plasma*. Subjected to the ram pressure of the ambient interstellar matter, the solar wind slows down through a shock wave called the solar wind *termination shock* and eventually flows downstream, forming a contact discontinuity surface called the *heliopause*, which separates the solar and *interstellar plasmas*, and an elongated *heliotail* (lower-left corner of the figure). The heliopause, hardly penetrable for charged particles, is transparent for *neutral atoms*. Energetic neutral atoms form everywhere in the heliosphere due to the charge exchange reaction between the ions from local plasma and neutral interstellar atoms. Charge exchange operates both in the supersonic solar wind and in the *inner heliosheath*, i.e., in the region between the termination shock and the heliopause. Some of those atoms run away freely from the heliosphere and due to eventual collisions slightly modify the inflowing interstellar gas. Other run in the opposite direction and reach the IBEX detectors (schematically drawn close to the Sun). Neutral atoms from the interstellar matter (whose streamlines are marked by the short arrows) also freely enter the heliosphere and some of them are detected by IBEX. In front of the heliosphere forms a disturbed region called the *outer heliosheath* (the green haze in the figure). In this region, the flows of interstellar plasma and interstellar neutral gas decouple. As a result, due to charge exchange another population of neutral atoms (former outer heliosheath ions) is formed. Some of them also enter the heliosphere and are detected by IBEX as the so called *secondary population of neutral interstellar gas*. Together with all other populations of neutral atoms they are important diagnostic means for the physical state of the distant regions where they originate. IBEX has discovered the surprising Ribbon – an arc-like, almost circular region of enhanced neutral atom emission on the sky. It seems the Ribbon is formed somewhere close to the heliopause, likely in the outer heliosheath, where the IBEX look direction is perpendicular to the local direction of interstellar magnetic field lines (marked by the long arrows that are draped at the heliopause). The currently most probable hypothesis is that the *Ribbon* center points towards the direction of the *interstellar magnetic field*. The action of interstellar *magnetic field distorts the heliosphere* from axial symmetry and likely pushes the heliotail to the side. Depending on the magnetic field strength, direction, and the relative speed between the Sun and the interstellar gas, the outer heliosheath may or may not be terminated by a shock wave called the *bow shock*. Assuming the interstellar gas velocity as obtained from the recent IBEX measurement, there is no bow shock, but the character of the wave-like structures in front of the heliosphere is much more complex than previously thought. Graphics design: Marzena A. Kubiak, Maciej Frołow, Tentaris.

Among the most important results obtained by the Lab members is under-standing the nature of the heliospheric Warm Breeze and of the source me-chanism of the IBEX Ribbon. The IBEX Ribbon is a large arc-like region in the sky with an increased flux of energe-tic neutral atoms (ENA). The Warm Breeze, discovered by scientists from SRC PAS in 2012, is an inflow of neutral helium into the heliosphere. When projected on the sky, it partly overlaps with the location of neutral inter-stellar gas. The location of the Ribbon in the sky and its shape are presented in Figure 9, and the region in the sky where the Warm Breeze and neutral interstellar gas are observed are shown in Figure 10.

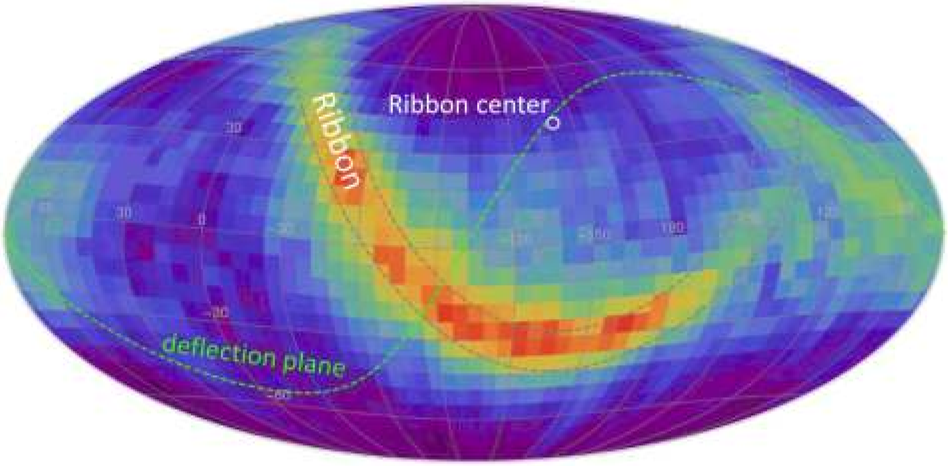

Figure 9. Sky map of the Energetic Neutral Atom flux in the energy band 1.7 keV, observed by IBEX-Hi. The large arc-like structure is the IBEX Ribbon; its center is marked by the small white circle. Approximate boundaries of the Ribbon are marked by gray the broken lines. The green broken line is a projection on the sky of the deflection plane of the secondary neutral gas. The constituent hydrogen atoms are created mostly due to the process of charge exchange between the inflowing neutral interstellar hydrogen gas and pickup ions, embedded in the solar wind within the inner heliosheath, i.e., between the termination shock of the solar wind and the heliopause. These ENAs travel towards the Sun at about 500 km/s. The exception are the atoms forming the Ribbon. While detected at the same energy, they are created beyond the heliopause in the secondary ENA emission mechanism. The blue colors mark low flux values, the yellow and red colors high flux values.

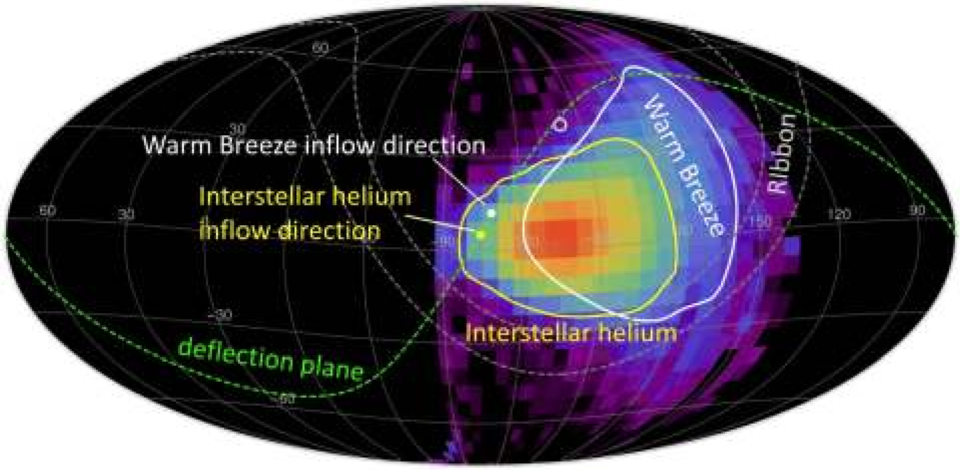

Figure 10. Sky map of neutral atom flux, observed by IBEX-Lo. The constituent atoms are mostly helium, and at a distance of 1 astronomical unit (i.e., at Earth's orbit) they run at ~50 km/s relative to the Sun and ~70 km/s relative to the IBEX spacecraft. Observed in this energy band, most of the sky is empty (black color). The blue, yellow and red colors correspond to a sequence of increasing intensities of the low-energy helium atoms observed by IBEX-Lo. The region corresponding to interstellar neutral atoms (ISN) is inside the yellow contour. The region occupied by the Warm Breeze (WB) is inside the white contour. The ISN and WB regions partly overlap. The directions of inflow of ISN and WB beyond the heliopause are marked by the yellow and white dots, respectively. The offsets of the centroids of the ISN and WB regions from the unperturbed directions of ISN and WB are due to the bending of the atom trajectories by the solar gravity force (the "gravitational lensing" effect). The green line is a projection on the sky of the plane of deflection of the secondary populations of neutral interstellar gas. Note that the center of the IBEX Ribbon, marked with the small white circle, is within this plane. The location of the Ribbon in the sky is marked by the gray arcs.

Scientists from SRC PAS determined the heliocentric parallax of the Ribbon, and on this basis they calculated the distance from the Sun to the Ribbon source region. The parallax effect is due to the fact that the same region of the sky is observed twice during the year, and during these two observations the observer is located at the opposite sides of the Sun. Therefore the projection of a relatively nearby object, like the Ribbon, on the background of very distant stars varies by a very small angle. By measuring this angle one can determine the distance to the nearby object, as illustrated in Figure 11.

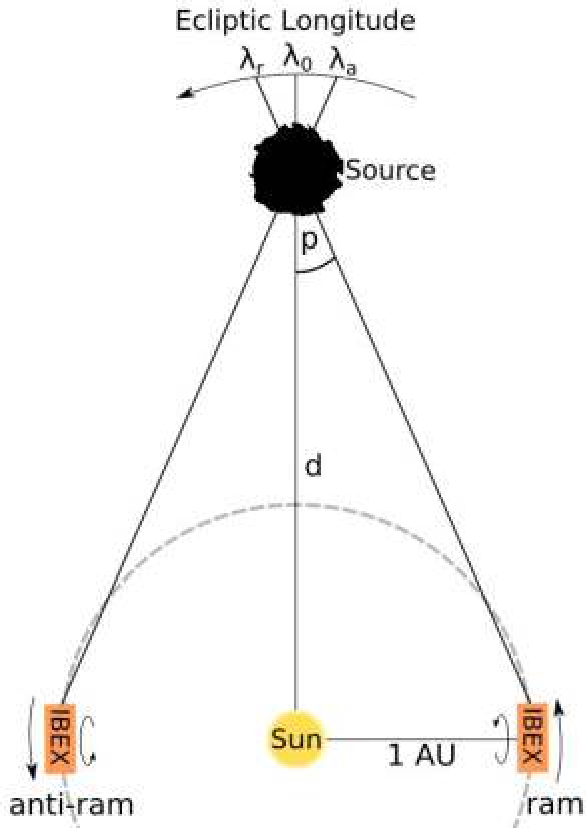

Figure 11. Illustration of the parallax effect, used by scientists from SRC PAS to determine the distance to the IBEX Ribbon. Source: Swaczyna et al., *Astrophysical Journal* Vol. 823:119, 2016.

Based on the parallax analysis, scientists from SRC PAS found that the Ribbon source is located just outside the heliopause, which suggests that the mechanism responsible for the Ribbon creation is the so-called secondary ENA emission mechanism. This mechanism was proposed by American researchers from the IBEX science team shortly after the discovery of the Ribbon as one of several hypotheses to explain the Ribbon phenomenon and was discussed in the Annual Report 2015.

The observations of ENA carried out by IBEX showed (as illustrated in Figure 12) that the centre of the Ribbon varies with the energy of its constituent atoms. Adopting the model of the mechanism of secondary ENA emission and the observation-based model of the solar wind speed as a function of heliographic latitude, recently developed in SRC PAS, scientists from SRC PAS reproduced this relationship. The agreement of predictions of a model based on the secondary ENA emission mechanism with observations strongly suggests that the secondary ENA emission mechanism is a correct explanation for the Ribbon. The energy dependence of the Ribbon centre on energy is relatively subtle, as illustrated in Figure 13, but the direction of the shift of the Ribbon centre with ENA energy is approximately perpendicular to the solar equator. In the secondary ENA emission mechanism, an important factor is the interstellar magnetic field, whose direction in the interstellar matter ahead of the Sun is approximately coincident with the centre of the Ribbon.

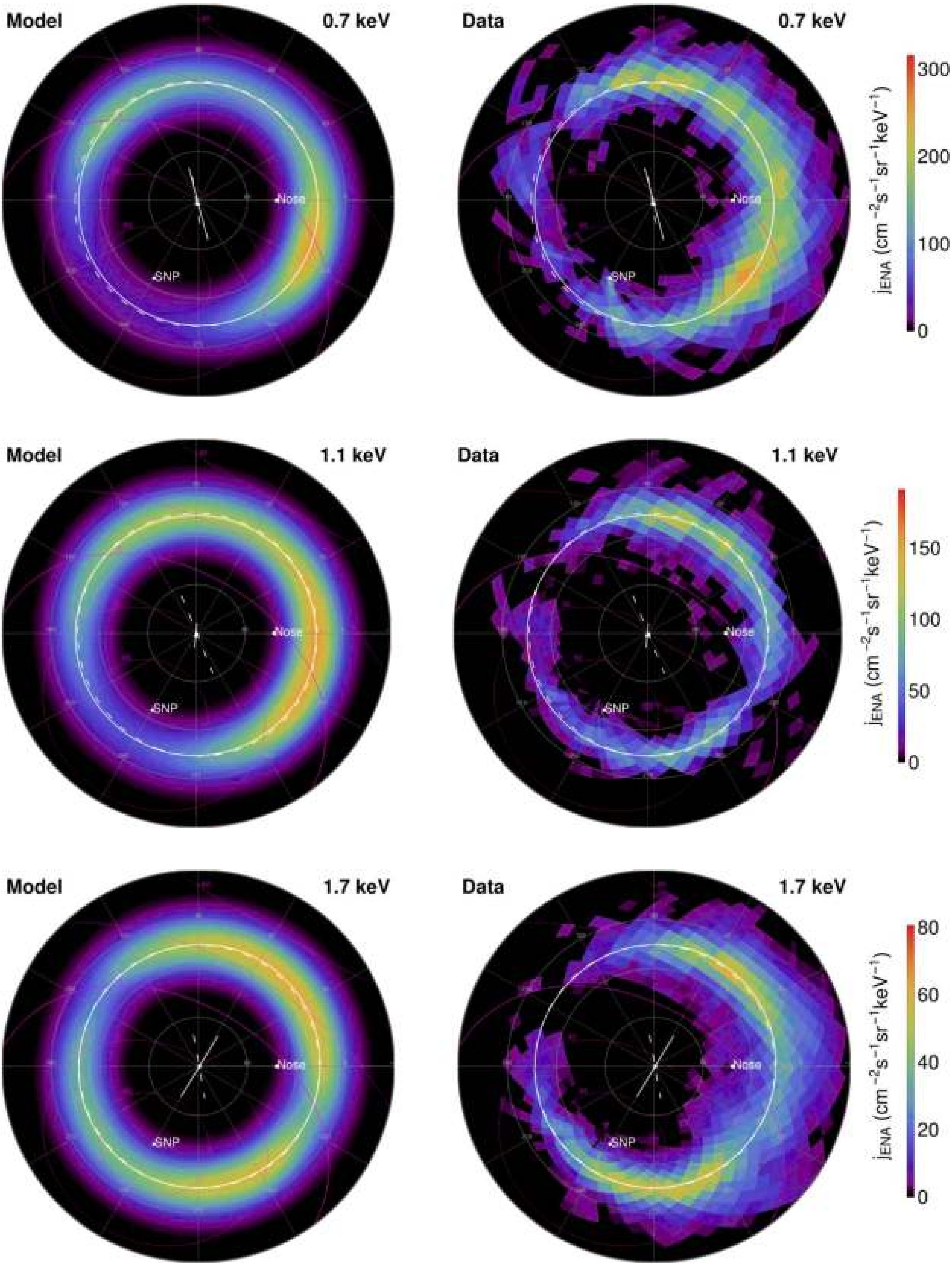

Figure 12. IBEX Ribbon observed using the IBEX-Hi detector of ENA in energy steps 2, 3, and 4 (from top to down, right-hand column) and the corresponding predictions of the model developed by scientists from SRC PAS. The scale of the ENA flux magnitude is shown at the side of the panels. Based on these simulations, the centres of the model Ribbon were calculated. A comparison of the model and actually observed Ribbon centres for various energies is presented in Figure 13. Adapted from Swaczyna et al., *Astrophysical Journal* Vol. 827:71, 2016.

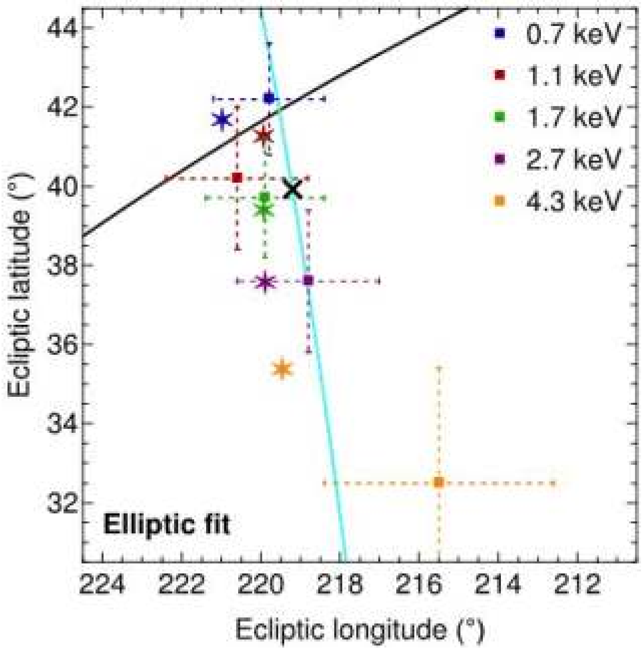

Figure 13. Comparison of the centres of the Ribbon for various ENA energies, obtained from observations (squares with error bars) with those obtained from the model presented in Figure 12. The cyan line represents the solar meridian, i.e., a great circle in the sky perpendicular to the solar equator, and the black line represents projection on the sky of the deflection plane of the secondary population of neutral interstellar gas, determined by scientists from SRC PAS based on analysis of observations of the Warm Breeze. See also Figure 14. Adapted from Swaczyna et al., Astrophysical Journal Vol. 827:71, 2016.

The action of the interstellar magnetic field is expected to break the axial symmetry of the heliosphere. As a result, the directions of inflow of neutral interstellar gas and of an additional population of neutral gas, expected to form behind the heliopause in the outer heliosheath due to interaction of the inflowing interstellar neutral gas and the interstellar plasma streaming past the heliopause, are expected to differ but remain in the plane defined by the direction of the Sun's motion with respect to interstellar matter and the direction of the interstellar magnetic field, embedded in this matter. This hypothetical additional neutral population, streaming into the heliosphere from the outer heliosheath, is called the secondary population of the interstellar gas, and until recently its existence was only a prediction based on models of the heliosphere. These models predicted that the secondary population of interstellar hydrogen should be comparable in abundance to that of the primary population, but the secondary population of interstellar neutral He was to be almost entirely missing.

Recently, while analysing IBEX observations, researchers from SRC PAS unexpectedly discovered that besides the inflow of neutral helium of interstellar origin, an additional "breeze" of neutral helium exists in the heliosphere. This new helium population was called the Warm Breeze, since it was slower, warmer and much more tenuous than the primary ISN gas. The origin of the Warm Breeze was unknown. In 2016, scientists from SRC PAS precisely determined the inflow direction and velocity of the Warm Breeze, its temperature, and the abundance with respect to the primary ISN population. Additionally, they helped in the analysis of observations of neutral interstellar oxygen, led by their US collaborators. Based on the results of these analyses they noticed that the directions of inflow of the Warm Breeze and the interstellar helium, hydrogen and oxygen are in the same plane, which additionally includes the centre of the IBEX Ribbon, as illustrated in Figure 14. Such a geometry is predicted by heliospheric models (regardless of the abundance of the secondary populations), when the action of interstellar magnetic field on the heliosphere is taken into account. Since the Ribbon centre was shown to be coincident with the direction of interstellar magnetic field, the scientists from SRC PAS concluded that the Warm Breeze is the secondary population of interstellar helium.

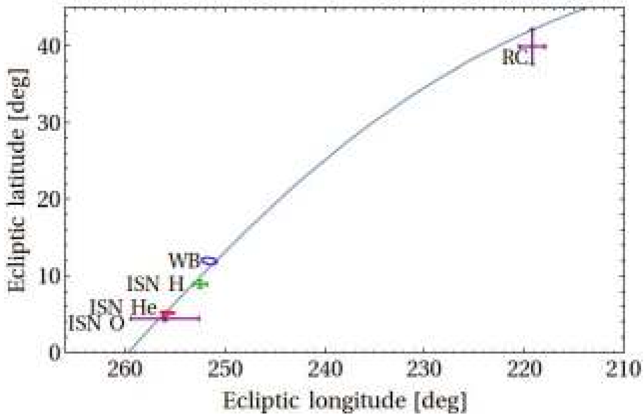

Figure 14. Ecliptic coordinates of the directions from which the interstellar neutral H, He, O, and the Warm Breeze flow into the heliosphere. These directions and their uncertainties are marked with the colour symbols ISN H, ISN He, ISN O, and WB. The line is a projection on the sky of the common plane, fitted to these directions. This plane is the so-called neutral gas deflection plane. Heliospheric models predict that the vector of interstellar magnetic field should be located in this plane. The centre of the IBEX Ribbon is also located in this plane (within the uncertainty of its determination), as illustrated by the RC symbol. Adapted from Kubiak et al., Astrophysical Journal Supplement Series Vol. 223:36, 2016.

Continuing studies of neutral interstellar gas and the derivative populations of pickup ions, researchers from SRC PAS explained the discrepancies between the direction of inflow of neutral interstellar gas inferred previously from direct-sampling observations of ISN He by IBEX and Ulysses on one hand, and from observations of pickup ions on the other hand. The direct-sampling observations had been presented in Annual Report 2015, the pickup ion observations had been analysed by researchers from US and Germany. In 2016, scientists from SRC PAS modelled the expected apparent direction of ISN gas, inferred from pickup ions taking into account the complex, time-and heliolatitude dependent model of ionization of interstellar gas inside the heliosphere. This latter model was developed in SRC PAS in 2013. The results of this analysis, illustrated in Figure 15, suggest that the reason for the aforementioned discrepancies is neglecting by the authors of the pickup ion analysis the latitudinal structure and temporal evolution of the ionization rates. These variations are relatively complex and most likely result in such variations of the pickup ion flux measured by spacecraft orbiting the Sun in orbits similar to that of the Earth that the apparent direction of inflow of interstellar neutral gas may vary by a few degrees from year to year. This effect is illustrated in Figure 15.

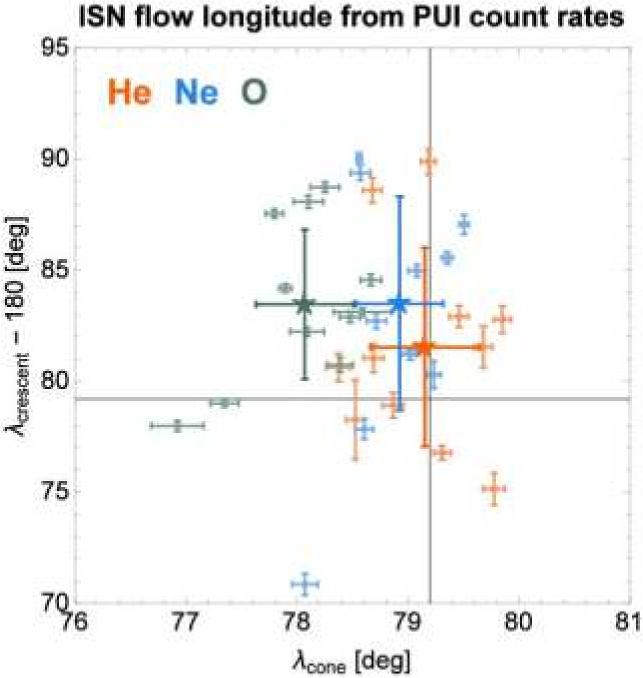

Figure 15. Ecliptic coordinates of the apparent longitude of inflow of interstellar neural gas, inferred from model of the flux of pickup ions created due to ionization of neutral interstellar oxygen, neon, and helium. These directions were obtained from analysis of model fluxes of pickup ions, calculated using the sophisticated model of ISN gas distribution and of its ionization rates, developed earlier by scientists from SRC PAS for the years 1998 – 2015. It is evident that on average, these directions differ from the direction marked by the black crosshairs, determined precisely by scientists from SRC PAS in 2015 based on direct-sampling observations of interstellar helium. The present analysis of the pickup ion model results was carried out using similar methods as those used by authors of analysis of actual pickup ion measurements that resulted in the biased results. The bias obtained now by scientists from SRC PAS is similar to that obtained in the original analysis. This suggests that the reason for the bias is neglecting the complex behaviour of the pickup ion production rate, related to the evolution of the ionization rate during the solar cycle. Adapted from Sokół et al., Monthly Notices of Royal Astronomical Society Vol 458 No 4, pp 3691-3704, 2016.

The conclusions drawn in 2016 by researchers from SRC PAS based on analysis of observations of interstellar neutral helium, hydrogen and oxygen atoms and on theoretical models are an important step forward in the understanding of the interaction of the solar wind with the interstellar matter surrounding the Sun, and considerably advance studies of the immediate environment of the Sun in the Galaxy. They form a coherent picture of the geometry of the magnetic field in the local interstellar matter, the flow of the interstellar plasma around the heliosphere, and the interaction of the solar wind with the interstellar matter within the boundary layer between the heliosphere and the interstellar matter as well as within the interstellar matter ahead of the heliosphere.

These results were presented in a series of scientific articles published in the Astrophysical Journal, Astrophysical Journal Supplement Series and the Monthly Notices of the Royal Astronomical Society. The research was carried out by scientists from SRC PAS and researchers from the IBEX science team from the US and Switzerland.

In addition to these results, scientists from SRC PAS supported their international colleagues in several other research activities. They helped in identification of plasma waves, excited in the solar wind during the process of picking up of newly-created ions by the magnetic field embedded in solar wind (Fisher et al. 2016). They participated in analysis of low-energy distributed flux of ENA observed by IBEX-Lo, which brought an estimate of energy of maximum flux of this component (Galli et al. 2016). They supported analysis of the inflow parameters of interstellar oxygen (Schwadron et al, 2016) and in detection by Park et al. (2016) of the secondary population of interstellar oxygen. They also helped in interpretation of observations of the flux of ENA coming to the IBEX detectors from the direction of ecliptic poles (Reisenfeld et al. 2016). The full list of papers authored or co-authored by Lab members is available in the Web at http://pfusia.cbk.waw.pl/files/pfusiaPubl.2016.html.

(M. Bzowski)