Heliospheric physics

(Laboratory for solar system physics and astrophysics)

The hypersonic, ionized solar wind 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 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's impression of the heliosphere is shown in Fig. 24.

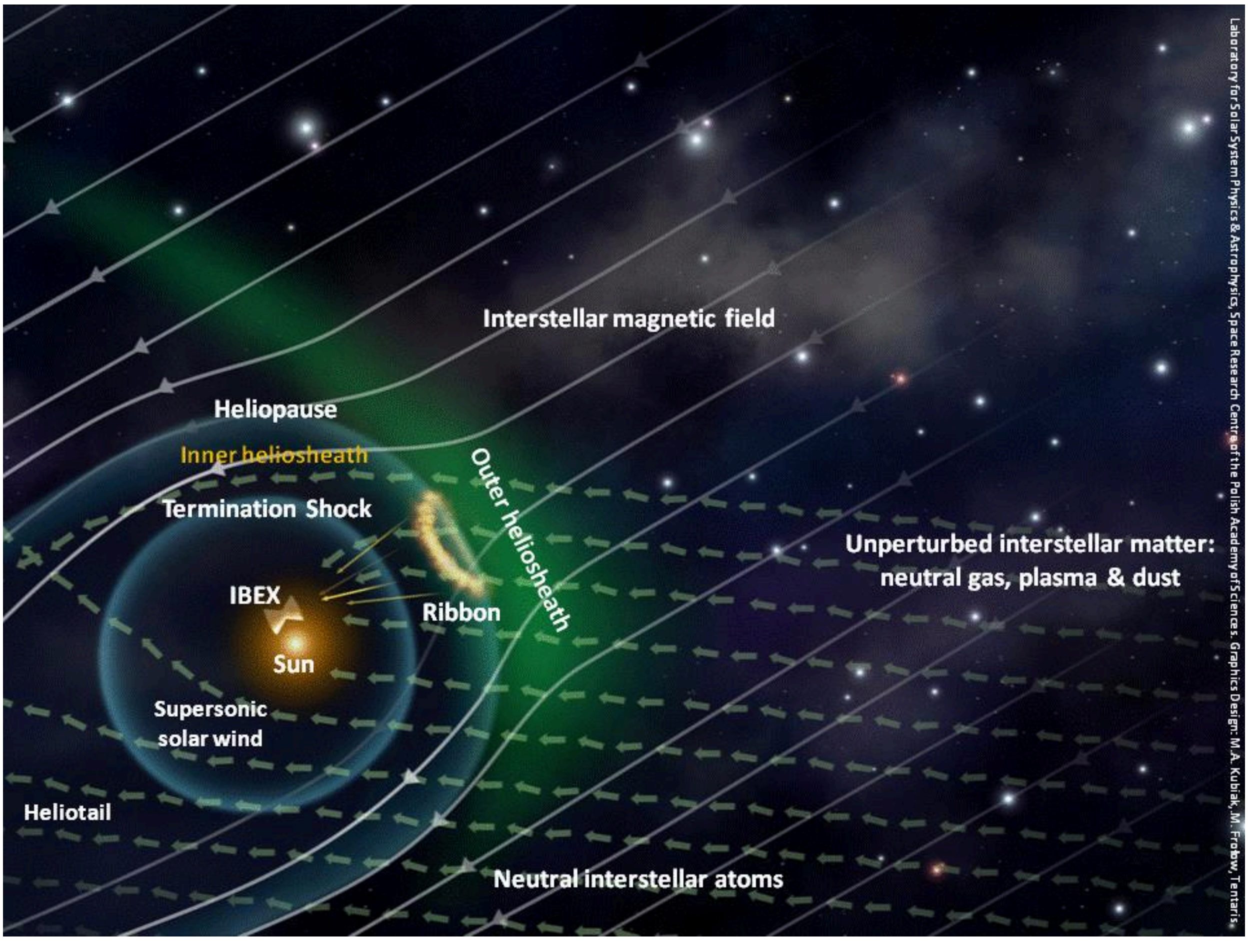

Fig. 24. Artist's impression of the heliosphere and its nearest Galactic neighbourhood as it emerges based on the analysis of recent IBEX observations and several years of research carried out in the Laboratory for Solar System Physics and Astrophysics. Graphics design: Marzena A. Kubiak, Maciej Frołow, Tentaris.

The figure shows the Sun 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 that happened 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—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 (bottom-left corner of Fig. 24). The heliopause, inpenetrable for charged particles except for cosmic rays, is transparent for neutral atoms. Energetic neutral atoms (ENAs) 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 (centre-left in Fig. 24), i.e., in the region between the termination shock and the heliopause. Some of those atoms freely escape from the heliosphere and, due to eventual collisions, slightly modify the inflowing interstellar gas.

Others run in the opposite direction and reach detectors located in the Earth's orbit (in Fig. 24, schematically drawn close to the Sun). Neutral atoms from the interstellar matter (whose streamlines are marked by the short arrows in Fig. 24) typically have energies of between a few dozen, and about 150 eV, and freely enter the heliosphere, where some of them are detected by space-borne detectors. Due to interaction between the heliosphere and the interstellar medium, a disturbed region called the outer heliosheath (the green haze in the figure) forms in front of the heliosphere. In this region, the flows of interstellar plasma and interstellar neutral gas decouple. This leads to the formation of another population of neutral atoms (former outer heliosheath ions) through charge exchange reactions. Some of these atoms also enter the heliosphere and are detected as the so-called secondary population of neutral interstellar gas. Together with all the other populations of neutral atoms, they provide an important means for analysing the physical state of the distant regions that they originated from.

During recent years, a very important insight into the heliosphere, local interstellar medium and processes responsible for the coupling of these astrophysical objects was obtained based on observations by the NASA space probe Interstellar Boundary Explorer (IBEX). This mission was developed, and is being led by the Southwest Research Institute in San Antonio, TX under the NA SA 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. The Centrum Badań Kosmicznych Polskiej Akademii Nauk (CBK PAN) has participated in the IBEX effort, since the planning phase, at the Co-Investigator level.

Shortly after the start of IBEX observations, an arc-like, almost circular region of enhanced neutral atom emission was unexpectedly discovered in the sky. This was subsequently called the IBEX Ribbon. It appears that the IBEX Ribbon is formed somewhere close to the heliopause, probably in the outer heliosheath, where IBEX looks perpendicularly to the local direction of the interstellar magnetic field lines (marked by the long arrows neighbouring the heliopause in Fig. 24). Currently, the most probable hypothesis is that the centre of the IBEX Ribbon approximately points towards the direction of the interstellar magnetic field. The action of the interstellar magnetic field distorts the heliosphere from axial symmetry and probably pushes the heliotail to the side. Depending on the magnetic field strength and direction, and the relative speed between the Sun and the interstellar gas, the outer heliosheath at the upwind side 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, the character of the wave-like structures in front of the heliosphere is much more complex than previously thought.

Among the most important results obtained by scientists from the Laboratory of Solar System Physics and Astrophysics (LSSPA) of CBK PAN in 2017 is an understanding of the nature of the heliospheric Warm Breeze. The Warm Breeze, discovered by scientists from LSSPA in 2012, is an inflow of neutral helium into the heliosphere, which is different from the well-known inflow of interstellar neutral helium. When projected on the sky, the location of the Warm Breeze partly overlaps with the location of neutral interstellar gas. The region in the sky where the Warm Breeze and neutral interstellar gas are observed is shown in Fig. 25.

In earlier studies, scientists from LSSPA had determined the apparent direction and inflow speed of the Warm Breeze. A comparison of the inflow direction of the interstellar neutral gas and the location of the centre of the IBEX Ribbon (Fig. 25) suggested that the Warm Breeze is the secondary population of interstellar neutral gas, created in the outer heliosheath (shown previously in Fig. 24), which is due to charge exchange between the unperturbed interstellar helium and the compressed, heated and slowed-down He+ plasma flowing in the outer heliosheath past the heliopause.

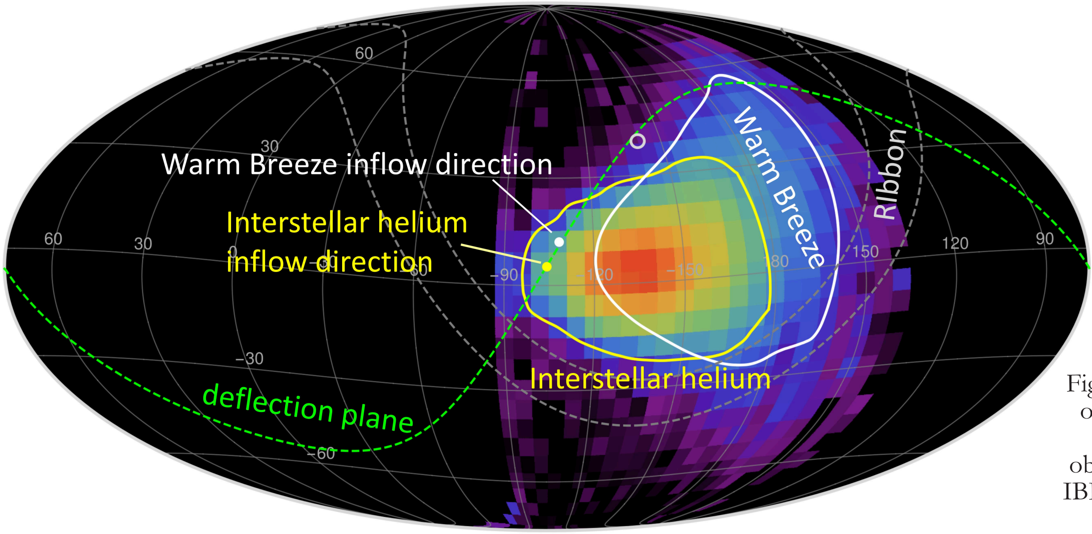

Fig. 25. Sky map of the neutral atom flux, observed by the IBEX-Lo sensor.

The constituents of the neutral atom flux (Fig. 25) 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 (shown in black in Figure 25). The blue, yellow and red colours in Figure 25 correspond to a sequence of increasing intensities of the low-energy helium atoms observed by the IBEX-Lo sensor. The region corresponding to interstellar neutral (helium) atoms (ISN) lies inside the yellow contour. The region occupied by the Warm Breeze lies inside the white contour. The ISN and Warm Breeze regions partly overlap. The directions of inflow of ISN and Warm Breeze beyond the heliopause are marked by the yellow and white dots, respectively. The offsets of the centroids of the ISN and Warm Breeze regions from the unperturbed directions of ISN and Warm Breeze are due to the bending of the atom trajectories by the solar gravity force (the gravitational lensing effect). The green dashed line (bottom-left in Fig. 25) is a projection on the sky of the plane of deflection of the secondary populations of neutral interstellar gas. The grey arcs mark the location of the IBEX Ribbon in the sky. Note that the centre of the IBEX Ribbon, marked by the small white circle (right of centre in Fig. 25), lies within this plane.

During 2017, scientists from LSSPA (M. Bzowski, M.A. Kubiak, A. Czechowski, and J. Grygorczuk) verified the hypothesis that the Warm Breeze is the secondary population of interstellar neutral gas, by reproducing the observed signal through simulations, starting from first principles. The process of charge exchange between the plasma and neutral gas in the outer heliosheath was simulated along the orbits of the atoms that enter the IBEX-Lo detector by solving the atom gains and loss balance equation along the atom orbits. The plasma in the outer heliosheath was simulated using a magnetohydodynamics (MHD) model developed previously; the signal-synthesis portion of the simulation suite was also based on earlier work that had determined Warm Breeze parameters. Scientists from LSSPA demonstrated that: (1) in the absence of the assumed perturbation of the plasma in the outer heliosheath the Warm Breeze signal is not created; (2) the Warm Breeze signal appears whenever one assumes a perturbation for the plasma flow characteristic for the outer heliosheath; (3) characteristic discrepancies between observation and simulation results arise when the simulated outer heliosheath is axially symmetric, as expected in the absence of the interstellar magnetic field, and; (4) when the strength and direction of the interstellar magnetic field that are similar to those obtained from the analysis of the IBEX Ribbon are included in the background MHD modelling of the plasma, the simulated Warm Breeze qualitatively signal agrees with observations (see Fig. 26). This strongly suggests that the Warm Breeze is, in fact, the secondary population of interstellar neutral gas, and since details of this signal seem to depend on the assumed magnetic field and plasma parameters in front of the heliosphere, studying the Warm Breeze will likely bring important insights into both the physics of the outer heliosheath, and the physical state of the matter in the Local Interstellar Cloud.

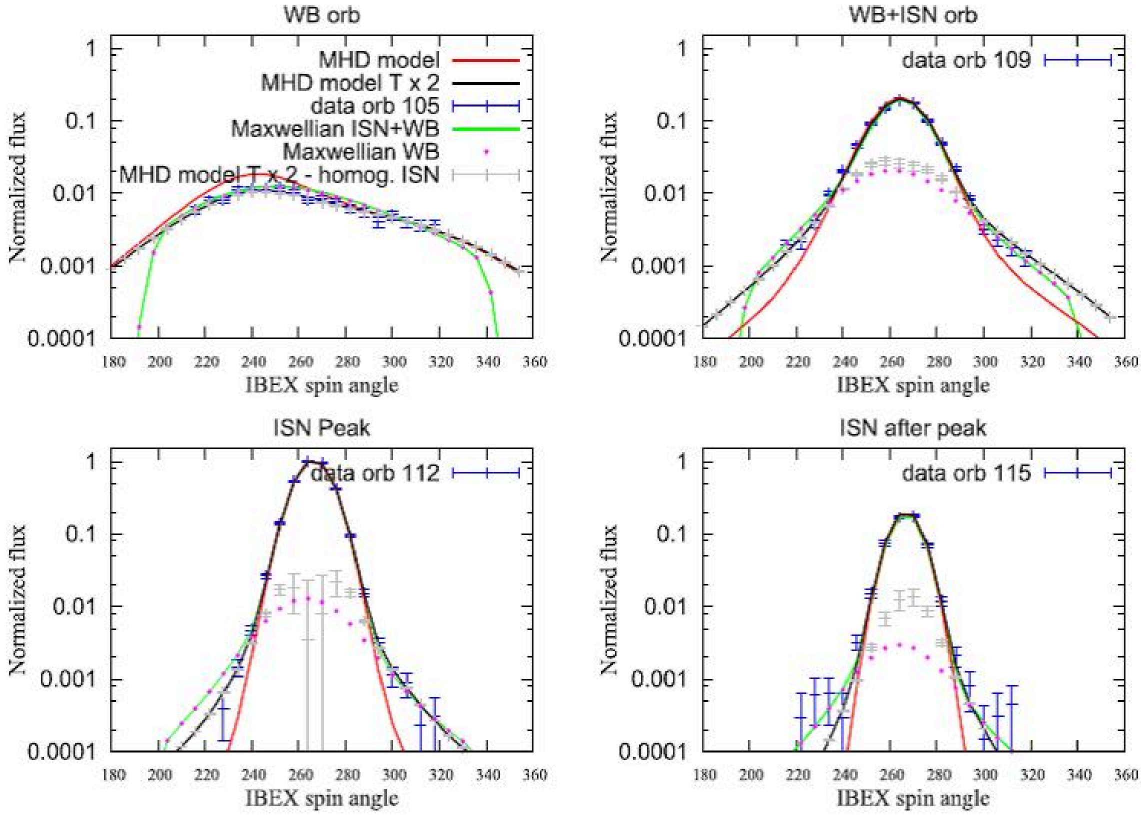

Fig. 26. Comparison of observations of neutral He by IBEX-Lo in selected orbits (105, 109, 112, and 115; blue dots with error bars) with models (solid lines). The green line represents a simplified model of two independent populations of neutral He, fitted in an earlier analysis. The red line illustrates the present model, where the signal is composed of a mixture of atoms penetrating the outer heliosheath without any interaction with the ambient plasma and those created in the outer heliosheath due to the charge exchange reaction between He atoms from interstellar gas and He+ ions from the compressed interstellar plasma flowing past the heliopause. The grey and purple dots represent the secondary population of interstellar gas, i.e., atoms originating from the outer heliosheath, obtained in the present model and the previous, simplified, approach. Simulated fluxes are normalized to the maximum of simulated flux for Orbit 112 and shown as a function of the IBEX spin angle, i.e., an angle in a plane close to perpendicular to the ecliptic plane (source: Kubiak et al., Ap. J. 845:15, 2017).

As a contribution to the debate on the shape of the heliosphere, A. Czechowski and J. Grygorczuk (J. Phys. CS 900, 012004, 2017) considered a model of an astrosphere surrounded by a partly ionized interstellar medium permeated by a magnetic field with intensities varying from the values typical for the Local Interstellar Cloud (~2 microgauss) up to a much stronger value of (20 microgauss). In addition to the plasma flow in the simulated astrospheres and their global shapes, they also simulated the expected sky distribution of the ENAs created due to charge exchange between neutral interstellar hydrogen and the plasma. They found that, in accordance with expectations, for the weak field, a comet-like heliosphere appears in the simulation, and its tail is not visible in the ENA signal because the lines of sight directed towards the tail are populated mostly by atoms that are created close to the termination shock, which obscure a much weaker signal from the ENAs created in the tail region. In contrast, for the strongest magnetic field considered, an astrosphere with two jets evacuating the stellar wind plasma appears, in agreement with predictions of the analytical model by Parker. When a moderate-velocity motion of the astrosphere through the interstellar medium is allowed for, the two jets are deflected backward, forming a split-tail phenomenon. For the case of a strong magnetic field and a split-tail, a strong ENA signal is expected from these regions in the sky because of the ENAs that are injected due to neutralization of energetic ions in the forward and flank parts of the termination shock and subsequently advected with the plasma evacuated through the tail. However, the observed distribution of ENAs in the sky would look qualitatively different under the two aforementioned hypotheses, as illustrated in Figure 27.

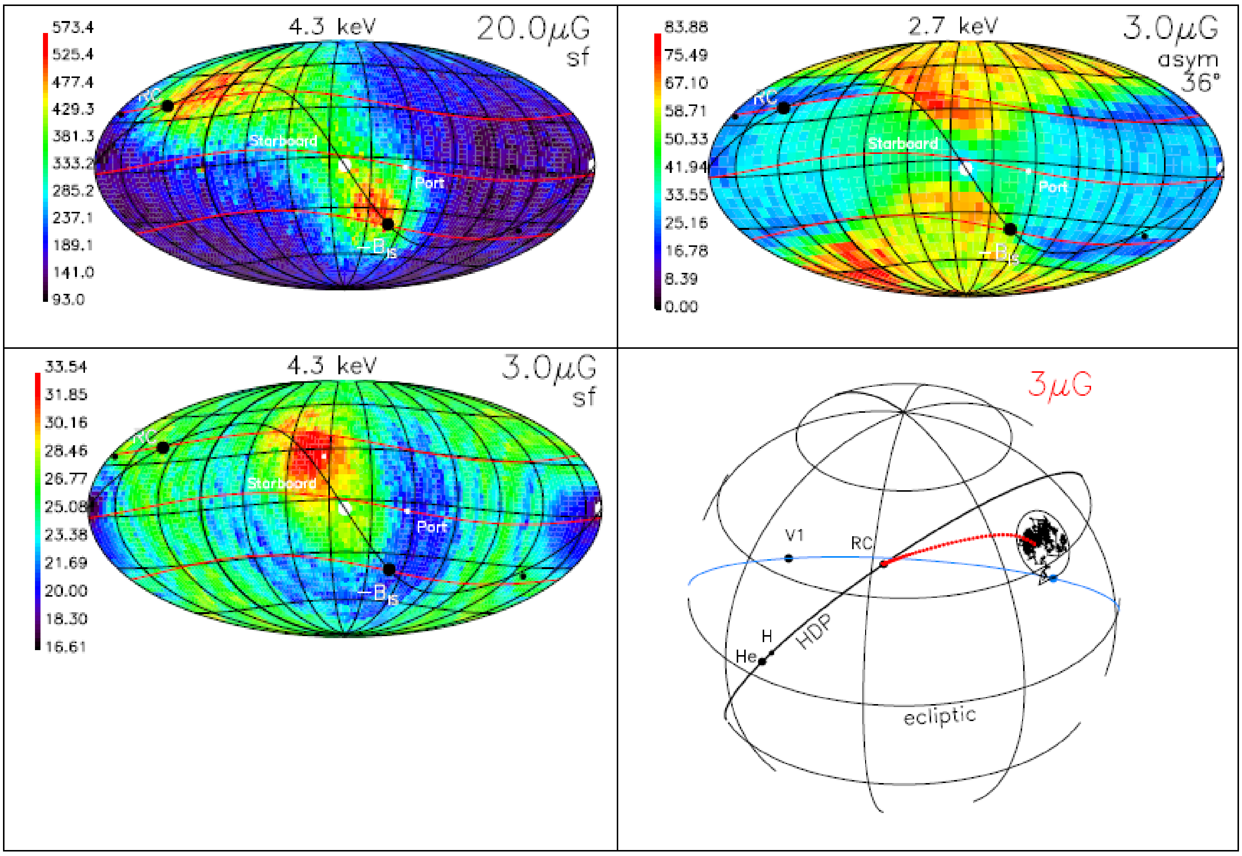

Fig. 27. Comparison of the intensity distribution of H ENAs for a strong interstellar magnetic field of 20 microgauss (upper-left) with that simulated for a low field strength equal to 3 microgauss (lower-left), for a spherically symmetric solar wind. Note the profound differences between these two maps. The upper-right panel illustrates the role of the latitudinal structure of the solar wind in the creation of the global distribution of H ENAs for the realistic case of a 3 microgauss interstellar field. The lower-right panel shows the unfolding direction of the interstellar magnetic field in the outer heliosheath (red line) from the unperturbed direction towards the IBEX Ribbon centre and in situ observations from Voyager 1 for parameters corresponding to those used in the simulation shown in the upper-right panel (adapted from Czechowski & Grygorczuk, J. Phys. CS 900, 012004, 2017).

In the split-tail scenario with a strong magnetic field, the location of the tail regions in the sky should be marked with local maxima of the flux, and not by flux depletion regions, as suggested by researchers who believe that the heliosphere is a croissant shape. The distribution of the ENA flux in the sky, as shown by Czechowski & Grygorczuk (see Fig. 27), depends on the strength and direction of the interstellar magnetic field as well as the latitudinal structure of the solar wind. Since the solar wind is latitudinally structured, with higher-energy flow in the polar regions, the ENA flux distribution for the energies that are characteristic of polar flows (3 keV and larger) is expected to be larger in the polar regions, in line with the observed data. The simulation for the low-strength interstellar magnetic field directed towards the IBEX Ribbon centre, and the latitudinally-structured solar wind predicts a draping of the magnetic field in the outer heliosheath, increasing with the decrease in solar distance. This means that for the geometric location of the Voyager 1 spacecraft, this direction and field strength agree with those observed, as shown in the lower-right panel in Fig. 27.

To date, most observations of ENAs have only considered hydrogen. P. Swaczyna, S. Grzędzielski, and M. Bzowski from LSSPA, however, have been investigating the observation of He ENAs and ENAs of selected heavier elements, including N, Ne, and O. For He, ENA fluxes resulting from neutralization of solar wind alpha particles and He+ pickup ions in the inner heliosheath were calculated, as well as ENAs originating in the outer heliosheath in the secondary-ENA emission mechanism, which is most likely responsible for the creation of the IBEX Ribbon. It was found that the dominant source of He ENAs in the heliosphere should be the inner heliosheath, and the magnitudes of the simulated spectra suggest that He ENA will be observable by NASA's planned Interstellar Mapping and Acceleration Probe. The most promising energy band is from a few to a few dozen keV/nucleon. Due to the long integration path, the largest signal is expected from the heliospheric tail. This means that observations of He ENA could be an important tool for diagnosing the global shape of the heliosphere, and help to resolve the ongoing debate about whether the heliosphere is comet-like, croissant-like, or bubble-like. It is hard to use existing H ENA observations for this purpose because energetic protons, which provide the seed population for H ENAs, become neutralized before they progress deeper in the heliospheric tail and consequently it is not possible to see the heliospheric tail (or two tails, in the croissant hypothesis). The sky image simulated for selected energies of He ENAs is shown in Fig. 28. These results were published in Swaczyna et al., Ap. J. 840:75, 2017.

Analysis of the expected fluxes of Ne, N, and O ENA by P. Swaczyna and M. Bzowski (Ap. J. 846:128, 2017) are a continuation of the He ENA study. The treatment of these species had to be simplified because of a much larger number of charge exchange reactions involved. Atoms of heavy species are much less abundant than H and He, so expected fluxes are much lower than these of H and He, and detection is much more challenging (see Fig. 29). Potentially, however, heavy ENAs may help in understand the details of the processes operating in different regions of the heliosphere. This is because they have different charge exchange cross sections across species, and consequently different extinction lengths. This means that they contain information from different distances from the Sun.

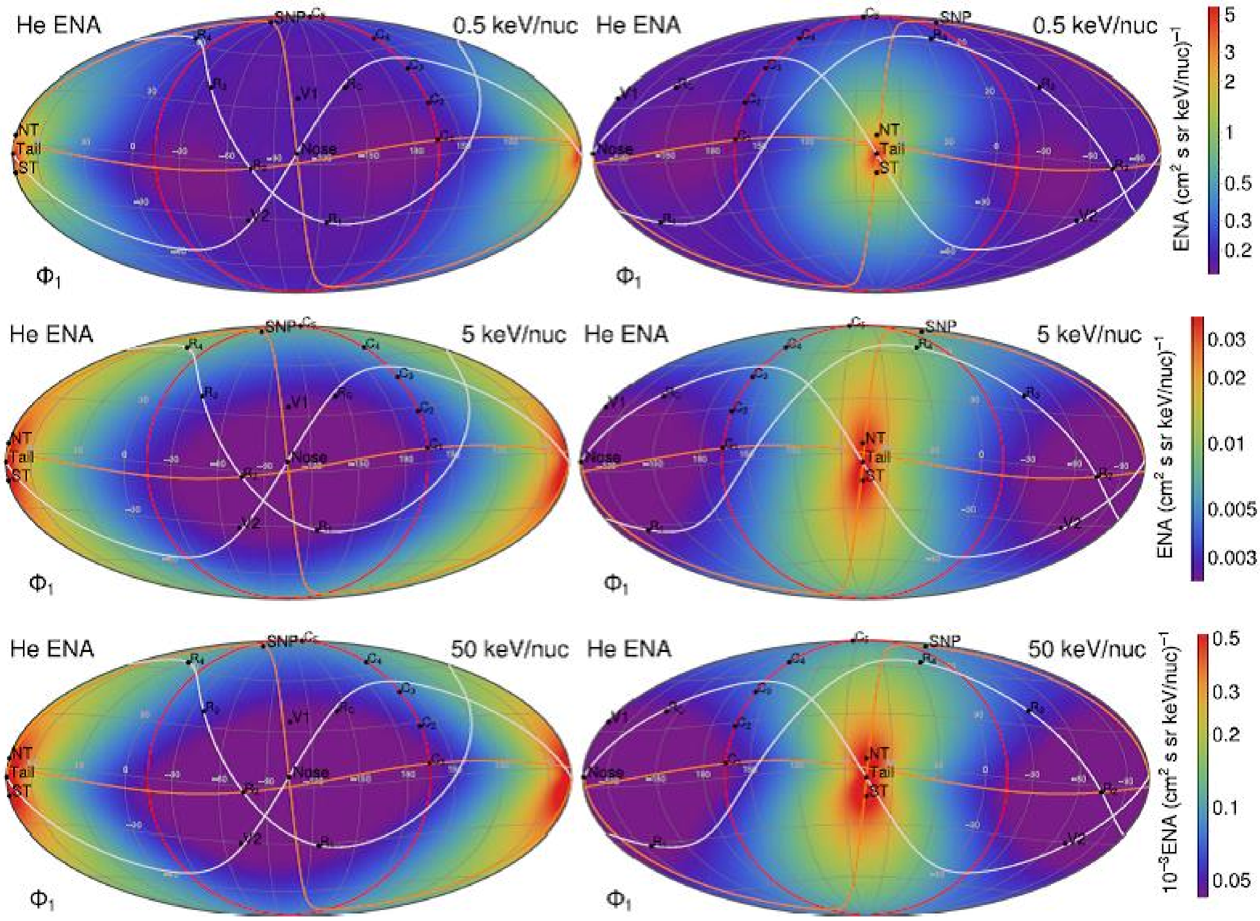

Fig. 28. Maps of the flux of He ENAs for selected energy bands 0.5, 5, and 50 keV/nuc, simulated using potential-flow models of the heliosphere and latitudinally-structured solar wind. The left-hand column shows the sky centred at the heliospheric nose (in the middle for the plots), and the right-hand column the same flux distribution in a projection centred at the heliospheric tail direction. The grey lines represent the IBEX Ribbon centreline (the R1–R4 line) and the neutral gas deflection plane. The red circles represent the crosswind plane (i.e., the plane perpendicular to the direction of motion of the Sun through the Local Interstellar Cloud), and the plane perpendicular to the latter (adapted from Swaczyna et al. Ap. J. 840:75, 2017).

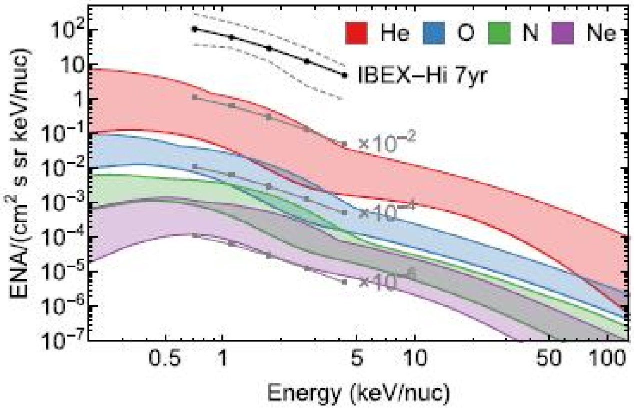

Fig. 29. The range of simulated ENA intensities of He, O, N, and Ne, marked with the colours shown in the panel. Intensity ranges are compared with the mean spectrum of H ENAs observed by IBEX (black dotted lines). The grey lines are eye-guides and represent the IBEX spectrum scaled down by the factors indicated at the respective guidelines (adapted from Swaczyna & Bzowski, Ap. J. 846:128, 2017).

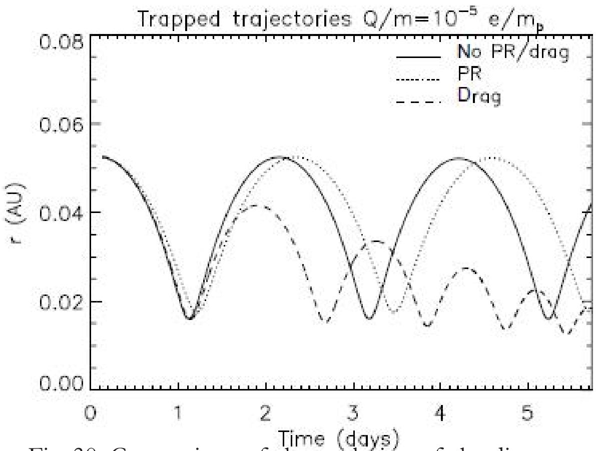

Fig. 30. Comparison of the evolution of the distance from the Sun of a nanodust grain with no drag effects (solid line, stable orbit), under the influence of Poynting–Robertson drag (dotted line, very ineffective decay of the perihelion), and under drag due to momentum transfer from CME plasma (broken line), which results in a rapid decay of the perihelion, eventually leading to the loss of the grain in the heat of the Sun (source: Czechowski & Kleimann, Ann. Geophys. Vol. 35, pp. 1033–1049, 2017).

Nanodust grains—the tiniest grains of interplanetary dust—are composed of just hundreds or thousands of atoms. Stationary models of the dynamics of nanodust grains inside the Earth's orbit suggest that these grains hover unrealistically long in their orbits, which should lead to a build-up of their density distribution; however, this is not supported by observations. Based on extensive modelling by A. Czechowski from LSSPA and J. Kleimann, the key to resolving this enigma is momentum transfer (drag force) from plasma particles to nanodust grains during coronal mass ejections (CMEs). CMEs are strongly dynamic, transient phenomena that involve eruptions of high-speed, high-density plasma from the solar corona that propagate away from the Sun in the solar wind. The momentum imparted to nanodust grains by CME ions creates an effective force that results in a reduction in the aphelia of dust grain orbits. Eventually, this brings nanodust particles close to the Sun for sufficiently long to sublime. The evolution of the distance of a nanodust grain from the Sun in the absence and in the presence of a CME is illustrated in Fig. 30. CMEs appear to be responsible for elimination of nanodust particles from their bound orbits inside 1 AU (astronomical unit), which probably prevents an excessive build-up of their density.

Turbulence is a complex phenomenon and the driving mechanisms are still not clearly understood. It appears naturally in astrophysical plasmas, including planetary and interstellar shocks. The shocks in astrophysical plasmas are usually collisionless due to the very low density of the medium, and differ from those observed in fluids because they often result from the interaction of nonlinear structures. Investigating collisionless shocks and weakly collisional plasma is difficult under laboratory conditions, but given the plethora of past and current space missions, the solar wind appears to offer a natural laboratory for investigating these phenomena. Based on plasma measurements from several space probes within the THEMIS mission, W. M. Macek and A. Wawrzaszek from LSSPA, in collaboration with researchers from other Polish and American institutions, have shown that the plasma dynamics within the magnetosheath (i.e., behind the Earth's bow shock, when looking from the Sun) is intermittent, and turbulence is strongly anisotropic. More particularly, for very strong shock waves (i.e., for flow speeds much larger than the Alfven speed, which is the speed of sound in a magnetized medium) fluctuations in plasma parameters in the direction perpendicular to the local magnetic field strongly differ from the normal distribution. However, for the direction parallel to the local magnetic field, the plasma is close to equilibrium, i.e., normally distributed. This result, published in Macek et al., Ap. J. Lett. 851: L42, 2017, is potentially important for the development of a theory of turbulence.

Line-preserving flows in magnetized fluids are those where any fluid element on a given external field line remains on that line. The case of inviscid and incompressible fluids was described by Helmholtz in 1858. His description was later extended to barotropic compressible fluids by Thomson in 1869 and Nanson in 1874. In this same area, P. Figura from LSSPA has recently investigated the stability of line-preserving flows against certain perturbations introduced to the flow itself, and to the external field. He defined the deviation vector that describes a departure of a given system from the line-preserving regime. Examination of this vector will facilitate investigating departures of this given system from the line-preserving regime. These results, published in Figura, Geophys. Astophys. Fluid Dynamics 111, 508, 2017, offer a new view on magnetic reconnection processes.

In addition to leading several projects, researchers from LSSPA have also collaborated with international colleagues on several studies of the heliosphere. A. Czechowski contributed to a large-scale review paper (Pogorelov et al., Sp. Sci. Rev. 212, 193, 2017) on processes operating in the outer heliosheath.

J. M. Sokół and M. Bzowski assisted in the first analysis of observations of interstellar pickup ions in the solar wind, carried out during the cruise of the NASA New Horizons mission to Pluto (McComas et al., Ap. J. S. 238:18, 2017). They also formed part of the international team of scientists involved in identifying plasma wave signatures of the process of pickup of newly-injected ions due to ionization of interstellar atoms in the inner heliosphere. This ongoing, comprehensive research programme involves measurements taken at 1 AU from the Sun and outward. Results obtained so far were published by Argall et al. in Ap. J. 849:61, 2017, and by Smith et al. in J. Phys. CS 900, 012018, 2017.

M. Bzowski, M. A. Kubiak, and J. M. Sokół provided input to an overview of seven years of global imaging of heliospheric ENAs by IBEX (Mc Comas et al., Ap. J. S. 229:41, 2017), and J. M. Sokół, M. Bzowski, and M. A. Kubiak supported A. Galli and an international team of scientists in the analysis of the lowest-energy ENAs from the downwind hemisphere, i.e., from the tail region. This analysis was challenging on the one hand because the low observation statistics, and on the other hand because time-dependent losses of the observed atoms between the creation and detection sites had to be precisely accounted for. Results were published by Galli et al. in Ap. J. 851:2, 2017.

J. M. Sokół and S. Grzędzielski assisted O. Khabarova's effort to identify and understand evidence from the available observations to support the existence of high-latitude conic current sheets in the solar wind, published in Khabarova et al., Ap. J. 836:108, 2017.

J. M. Sokół helped E. Zirnstein and colleagues to analyse the imprint of the Sun's evolving solar wind on the ENA atoms observed by IBEX; the model of evolution of the latitudinal structure of solar wind (developed by J. M. Sokół, P. Swaczyna and M. Bzowski in 2016 and carefully maintained during 2017) was critical to this study. Results of the ENA study were published by Zirnstein et al. in Ap. J. 846:63, 2017.

(M. Bzowski)