Heliospheric physics

(Laboratory for Solar System Physics and Astrophysics - LSSPA)

The hypersonic, ionized solar wind carves out a cavity in the interstellar matter, called the heliosphere. The size of the heliosphere is determined by a balance between the pressures of the solar wind and the interstellar gas, both of which are 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 of interstellar matter, 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 Figure 16.

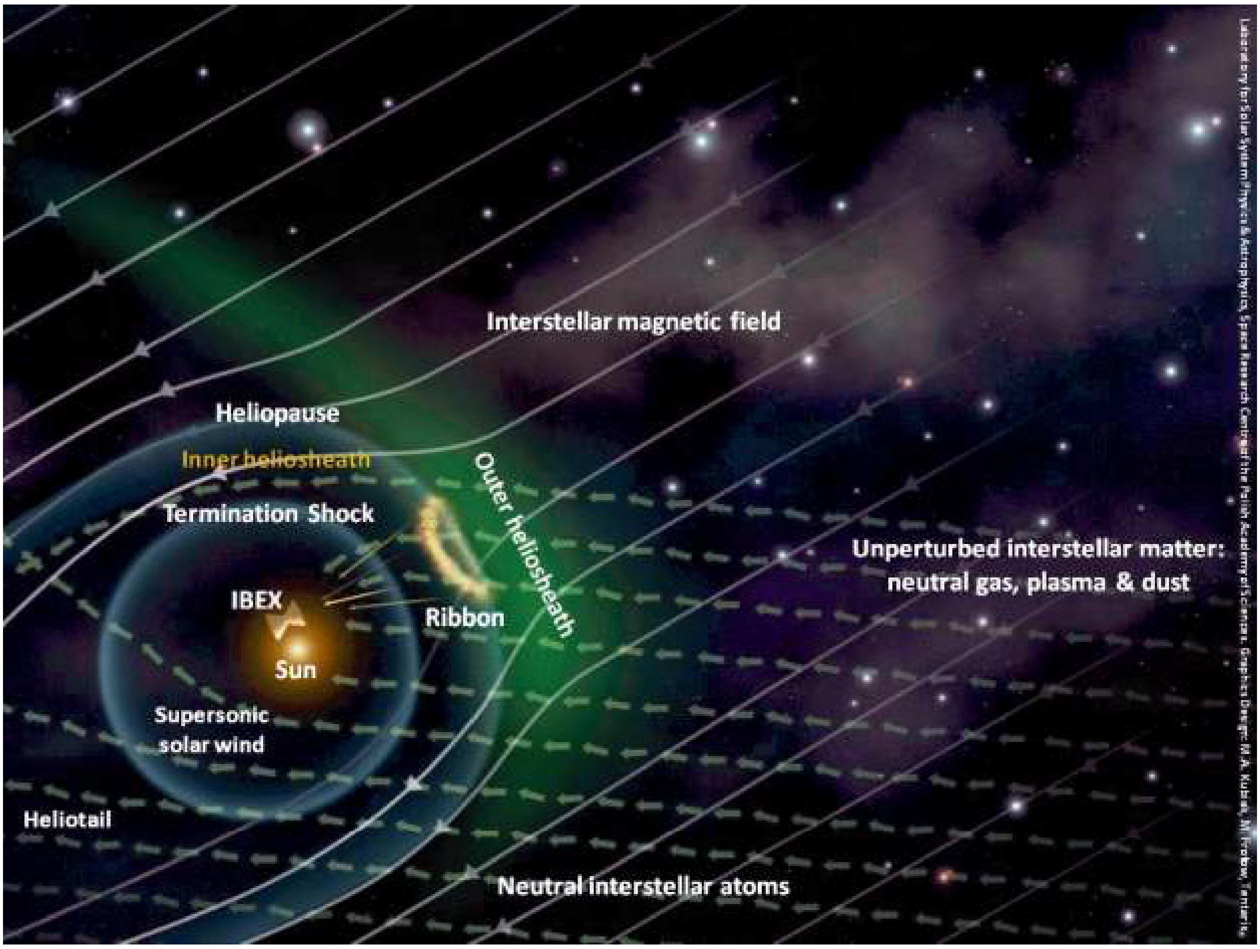

Fig. 16. Artist's impression of the heliosphere and its nearest Galactic neighborhood as it emerges based on the analysis of recent IBEX observations and several years of research carried out in the Laboratory for Solar System Physics and Astrophysics.

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. This cloud is one of many similar clouds within the Local Interstellar Medium—an astrophysical object spanning approximately 200 pc across that is a remnant of a series of Supernova explosions that happened a few million years ago. The Sun moves through the Local Interstellar Cloud from right to left in Figure 16, 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 Figure 12). The heliopause, impenetrable for charged particles except for cosmic rays, is transparent for neutral atoms, which thus freely enter the heliosphere. Inside the heliosphere, the interstellar atoms become the seed population for energetic neutral atoms (ENAs). ENAs are formed everywhere in the heliosphere due to the charge exchange reaction between the ions from local plasma and the neutral interstellar atoms. Once created, they travel without being ionized or absorbed at large distances, comparable to the size of the heliosphere.

The charge exchange process operates both in the supersonic solar wind and in the *inner heliosheath* (centre-left in Figure 16), i.e., in the region between the termination shock and the heliopause. Some of the ENAs created in these regions 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 Figure 16, schematically drawn close to the Sun).

Neutral atoms from the interstellar matter (whose streamlines are marked by the short arrows in Figure 16) typically have energies of between a few dozen and about 150 eV. Due to interaction between the heliosphere and the interstellar medium, a disturbed region called the *outer heliosheath* (the green haze in the figure) is formed in front of the heliosphere. In this region, the flows of interstellar plasma and interstellar neutral gas decouple from each other. This leads to the formation of another population of neutral atoms through charge exchange reactions between ions from the perturbed plasma flow past the heliopause and the hardly perturbed interstellar neutral atoms. Some of the atoms being products of this reaction 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 analysis of 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, Texas under the NASA Small Explorers program. It is managed by the Goddard Space Flight Center for the NASA Science Mission Directorate in Washington, DC. The research facilitated by IBEX is carried out by the IBEX Science Team of researchers from the United States, Poland, Switzerland, Germany, and Russia. CBK PAN has participated in the IBEX effort since the planning phase, at the Co-Investigator level.

During 2018, scientists from Laboratory for Solar System Physics and Astrophysics (LSSPA) carried out studies of various aspects of the heliosphere and the surrounding interstellar medium. All research results obtained in 2018 by LSSPA scientists were published in sixteen scientific papers in international, peer-reviewed scientific journals. Some of these results are presented below.

Structure of the heliosphere revealed by the spectrum of energetic neutral atoms

Energetic Neutral Atoms (ENAs) are an important tool for investigating the structure of the heliosphere and for diagnosing the enigmatic processes of acceleration of charged particles in the heliospheric boundary region. Observations of ENAs with energies below ~50 keV by the Cassini space probe, performed at the Saturn orbit, showed that ENA fluxes from the upwind and downwind regions of the heliosphere are similar in strength. This led the authors of these observations to hypothesise that the heliosphere is bubble-like rather than comet-like (i.e., it has no extended tail). An international team of scientists, led by A. Czechowski from the LSSPA investigated the hypothesis that these ENAs are created by charge exchange of solar wind pickup ions that have been accelerated at the solar wind termination shock, and subsequently advected with the plasma flow beyond the termination shock.

The research team simulated a directional distribution of ENAs within a wide energy range, from 3 to 88 keV, i.e., almost the entire energy range covered by available observations from IBEX, Cassini, and SOHO space probes (IBEX-Hi, INCA, and HSTOF instruments, respectively). The calculation of ENA fluxes was performed using a multi-tier simulation scheme. The global structure of the plasma flow inside and outside the termination shock was obtained using MS-FLUKSS – one of the most sophisticated global heliosphere models currently available. The PUI flux at the termination shock was calculated using the Warsaw Test Particle Model (WTPM) to simulate the spatial distribution of ISN H filling the space between the Sun and the termination shock, forming the seed population for PUIs. The PUI flux at the termination shock was calculated based on this density distribution and the most recent version of the LSSPA model of ionisation factors in the heliosphere (developed by the LSSPA during the past decade, see below).

An essential element of the simulation was a model of the acceleration of pickup ions at the termination shock. The research team applied a theory of acceleration developed several years ago by one of the team members (Gary Zank from the University of Alabama, Huntsville, USA) and his collaborators. In this theory, a fraction of the pickup ion population with energies below the electric potential threshold at the shock cannot penetrate this threshold and is reflected upstream of the solar wind. These ions are picked up and accelerated by the inflowing solar wind plasma, thus gaining energy. The reflection/ energisation cycle repeats until an ion has a sufficient energy to penetrate the potential threshold and enter the inner heliosheath. The energised ions are subsequently carried by the solar wind plasma in the inner heliosheath. While the kinetic energy of individual ions is large, the mean flow speed of their population is close to that of the bulk plasma, which leaves them enough time to exchange charge with ambient H atoms and produce a sufficiently large amount of ENAs.

The sequence of models used in the simulation drew upon the most-credible, currently-available values for relevant parameters obtained from observations. Equally important was adopting a proton spectrum just downstream of the termination shock, which on the one hand was in agreement with solar wind measurements and the Zank PUI acceleration theory, and on the other hand agreed with the Voyager LECP *in situ* measurements of the ion spectrum and of the termination shock strength (Fig. 17).

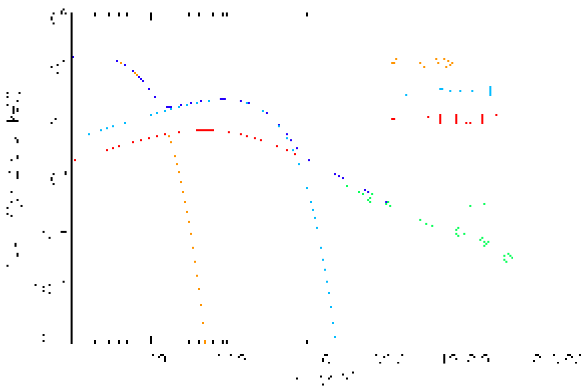

Fig. 17. A model spectrum of ions used to simulate the observed ENA flux. The model has three components: bulk solar wind (orange), pickup ions reflected off the termination shock (red), and pickup ions transmitted across the shock (blue). The three components add up to make the total spectrum (purple). This spectrum agrees very well with the spectrum of suprathermal ions measured by the Voyager 2 spacecraft in the corresponding energy ranges. Note that the energy of the reflected component is shown after energisation of these ions and their resulting penetration of the termination shock. Source: Czechowski et al., Ap. J. 888:1, 2020.

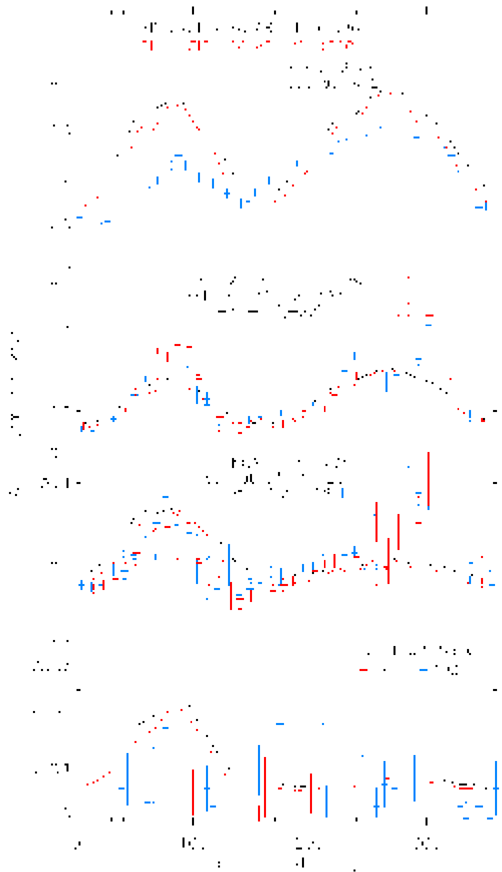

Fig. 18. Model of ENA flux (solid lines) for four energy bands (top–bottom panels), compared with actual observations from IBEX-Hi (first), INCA (second and third), and HSTOF (fourth). The data are presented by dots, and measurement uncertainties by error bars. There is relatively little difference between simulations performed separately for a maximum and a minimum of solar activity (red and black lines, respectively). Source: Czechowski et al., Ap. J. 888:1, 2020.

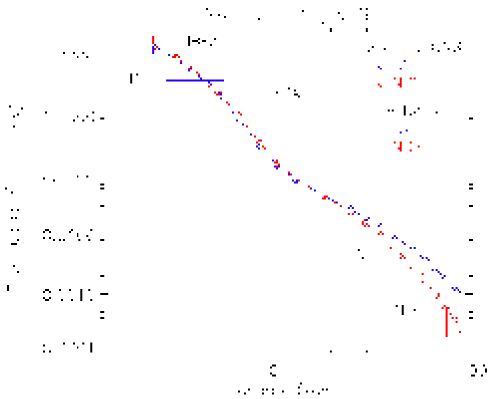

Fig. 19. Spectra of ENAs for the upwind (red) and downwind (blue) regions of the heliosphere, obtained from observations (points with bars) compared with the corresponding spectra obtained from simulations (diamonds). Horizontal bars mark the energy bands of the respective energy channels. Vertical bars represent uncertainties in observations. Source: Czechowski et al., Ap. J. 888:1, 2020.

This successful reproduction of the observed flux distribution and spectrum by a simulation using a model of the heliosphere with a long tail strongly suggests that there is no need to deviate from the classical paradigm of the heliosphere. In other words, the heliosphere is not round!

The results of this work by the team led by Dr. A. Czechowski from LSSPA, including Dr. M. Bzowski, Dr. J. M. Sokół, Ms. M. A. Kubiak, and Ms. J. Grygorczuk from the LSSPA, and researchers from Princeton University, the University of Alabama in Huntsville, the University of New Hampshire, and the Max Planck Institute for Solar System Research were published in *The Astrophysical Journal* 888:1, 2020, in a paper by Czechowski et al. (https://doi.org/10.3847/1538-4357/ab5b14).

(A. Czechowski, M. Bzowski)

Density of interstellar H measured by means of pickup ions observed in the outer heliosphere

The density of interstellar neutral H, which is the dominant component of the interstellar matter in the Sun's vicinity, had been established in 2008 using several complementary observation data sets and analysis methods. One of the was observation of pickup ion flux observed by the Ulysses spacecraft on its circumsolar polar orbit, another was measuring the slowdown of the solar wind due to the "friction" of the solar wind plasma against the inflowing interstellar H atoms. This "friction" is a complex process involving exchanging charge and momentum between the interacting components, involving as a by-product creation of pickup ions. It seems, then, that pickup ion observations are the key to the density of interstellar H.

An international team of scientists led by Dr. Paweł Swaczyna from the Princeton University analyzed observations of pickup ion spectra obtained from the SWAPI experiment on-board the NASA New Horizons mission to Pluto. Observations were collected during the cruise in the solar wind before and after the close encounter with Pluto. Analysis of the ion spectra resulted in determination of the density of pickup ions along the trajectory of the New Horizons spectra on one hand, and of the density of the solar wind protons on the other hand. Combined with the knowledge of other ionization processes responsible for the production of pickup ions, mostly photoionization by the solar EUV radiation, and models of the density distribution of interstellar H along the New Horizons trajectory enabled determining the density of interstellar H at the termination shock of the solar wind, which turned out to be 40% larger than thought before. Consequently, the density of neutral H in the unperturbed interstellar gas is likely to be larger by this factor.

Since this change is large and potentially has important consequences for the views on the interaction of the heliosphere with the interstellar gas, the team led by Paweł Swaczyna re-analyzed the original observations, reported back in 2008 and 2009. They found that the measurement of the solar wind slowdown observed by the Voyager spacecraft is compatible with the present result when a more accurate formula for the velocity-dependent cross section for charge exchange is used in the analysis. For the Ulysses pickup ion measurement, repeating the analysis using an updated radiation pressure (Kowalska-Leszczyńska et al. 2018b, 2020a) and ionization rate models (Sokół et al. 2019a, 2020) resulted in an increase of the density obtained from this experiment by 10%. While the agreement with the result obtained from New Horizons is not perfect, the two determinations agree now within the uncertainty ratio.

The research team included Dr. M. Bzowski, Dr. I. Kowalska-Leszczyńska and Ms. M.A. Kubiak from LSSPA, CBK PAN. The results were published in a paper Swaczyna et al., ApJ 903:48, 2020.

(M. Bzowski)

Ionization rates of neutral gas species inside the heliospheric termination shock revised

The model of the evolution of ionization rates of neyutral species inside the termination shock with time and as a function of heliolatitude has been developed by LSSPA staff for more than twenty years now. Dr. Justyna M. Sokół and Dr. Maciej Bzowski from the LSSPA, together with Dr. Munetoshi Tokumaru (ISEE, Nagoya, Japan) and Dr. David McComas from the Princeton University overviewed the current state of knowledge about solar ionization rates for heliospheric atoms inside the termination shock. They compiled a list of ionization processes relevant for the ISN H, O, Ne, and He inside the heliosphere. The team focused on modulations with heliocentric distance, heliolatitude and time over the last three solar cycles. Three reactions: charge exchange with solar wind particles (protons and alpha particles), photoionization, and electron impact ionization were considered. Similarities and differences bet-ween ionization processes for the given species, as well as a comparison of the total ionization rates between the four species in the ecliptic plane and in the polar regions were presented. The ioniza-tion rates were considered within a consistent and homogeneous system of calculation, based on multi-source data from direct and indirect measurements of the solar wind and the solar EUV flux.

The study showed that ionization at 1 au is the strongest for H and O and, thus, the resulting modulation of the H and O fluxes of heliospheric particles is expected to be strongest. Modulation due to solar factors is weakest for He – it is almost an order of magnitude smaller than that for H and O at 1 au in the ecliptic plane. For He and Ne, the main source of ionization losses is photoionization. Consequently, modulation for these species is well correlated with variation in the solar activity. ISN H atoms are prone to solar wind variations both in time and in latitude. In the case of ISN O, both charge exchange and photoioni-

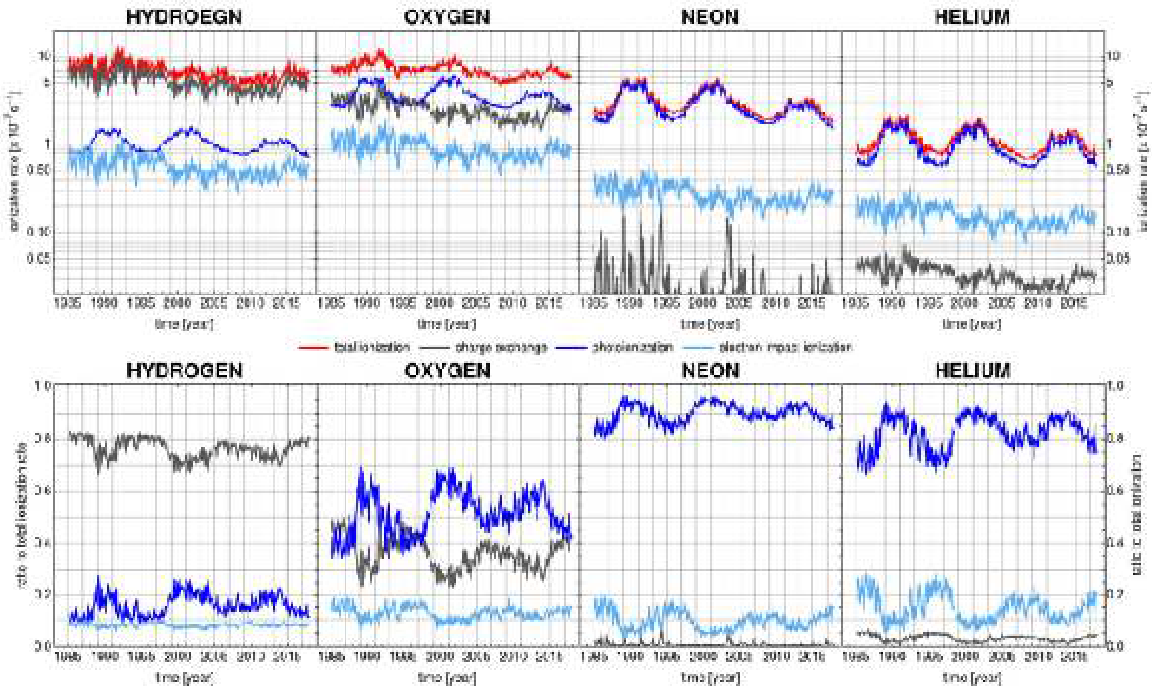

Fig. 20. Time series of ionization rates of neutral hydrogen, oxygen, neon and helium at 1 au in the ecliptic plane, presented for the time interval 1985–2019, with a time resolution corresponding to the solar rotation period (upper row). Red corresponds to the total ionization rate, which is a sum of the rates of charge exchange (grey), photoionization (dark blue), and electron impact ionization (pale blue). The lower row presents the percentage contribution of the three reaction rates to total rates for the four species, and its variation with time. Source: Sokół et al., Ap. J. 872:57, 2019.

zation losses can be a dominant ionization source, depending on the phase of solar activity and long-term changes in the solar wind. Total ionization rates are highest outside the ecliptic plane for O. Solar ionizing factors act differently on different heliospheric particles, which results in different modulation of these particles throughout the heliosphere. Total ionization rates for He and Ne vary in time with solar activity, whereas the rates for H and O follow variation in the cyclic solar wind outside the ecliptic plane, and aperiodic variations within it. This has important consequences for the study of heliospheric particles such as ISN gas, PUIs and ENAs, as well as physical processes in the inner and outer heliosphere.

These results were presented in papers by J.M. Sokół, M. Bzowski, M. Tokumaru, and D. McComas published in *The Astrophysical Journal* 872:57, 2019 and 897:179, 2020.

(J.M. Sokół, M. Bzowski)

A “forgotten” population of neutral gas inside the heliosphere

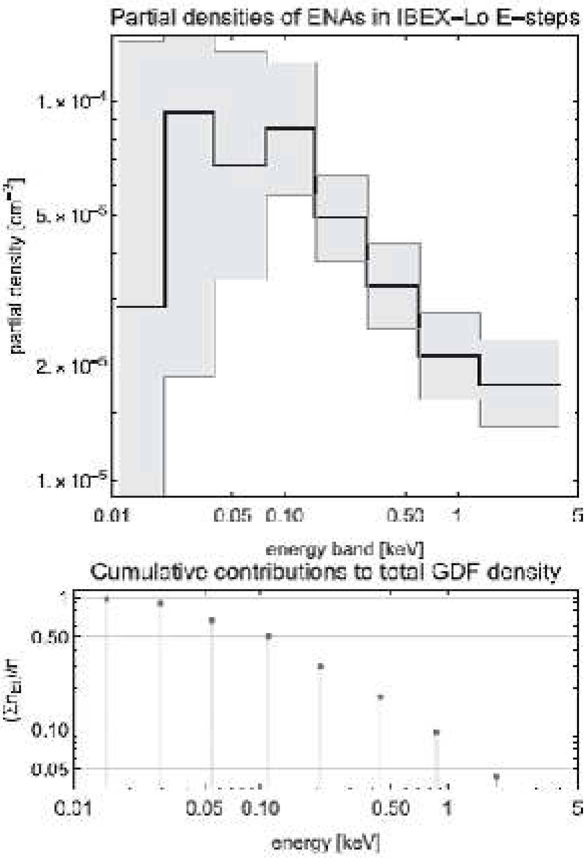

Fig. 21. Partial densities of H ENAs observed by IBEX-Lo in its eight energy steps (upper panel) and a plot of cumulative density of the H ENA population from highest to lowest energies (lower panel). Densities are marked with a black line, and their uncertainties by grey shading. Most of the atoms forming the ENA population at 1 au from the Sun have energies less than 0.1 keV. Consequently, their speeds relative to the Sun are sufficiently low to locate their Doppler shifts inside the spectral range of the solar Lyman-α line. Hence, these atoms are illuminated by solar Lyman-α radiation, which they re-emit by the fluorescence mechanism. This ENA glow is one of the components of the Lyman-α helioglow observed from Earth-orbiting spacecraft. Source: Bzowski & Galli, Ap. J. 870:58, 2019.

Interstellar neutral H penetrates the heliopause and continues its flow towards the Sun. On the way, it is strongly depleted inside the termination shock. Nevertheless, fractions of both primary and secondary populations of this gas reach the Earth's orbit. In these regions of the heliosphere, ISN H is the source population for interstellar pickup ions and the heliospheric backscatter glow. The globally distributed flux (GDF) of ENAs, created by charge exchange in the inner heliosheath, has been sampled directly by the Interstellar Boundary Explorer for almost a full cycle of the solar activity. Usually, these ENAs are treated as test particles bringing information on remote regions of the heliosphere. However, in fact, these atoms form a separate non-thermal population of neutral H atoms deep inside the heliosphere.

The energy spectrum of ENAs measured by IBEX is approximately described by a power law function, i.e., partial densities of atoms with energies corresponding to increasing energy channels of IBEX detectors rapidly decrease. Therefore, to assess the total density of ENAs at the Earth orbit, it is sufficient to analyze observations from the low-energy part of the spectrum, observed by the IBEX-Lo detector.

Based on available measurements from IBEX-Lo, Dr. M. Bzowski from the LSSPA and Dr. A. Galli from Bern University, Switzerland, calculated the number density of the GDF ENA population at the Earth's orbit. They found that this density is between 10^{-4} and 10^{-3} cm^{-3}, i.e., comparable in magnitude to the density of ISN H in the downwind portion of the Earth's orbit. Half of this atom population has energies less than ~80 eV. Consequently, this GDF population of neutral hydrogen is likely to provide a significant contribution to the intensity of heliospheric glow in the downwind hemisphere. It may also be the seed population for the ambiguous inner source of hydrogen pickup ions, and may be responsible for the excess production of pickup ions found in the analysis of magnetic wave events induced by the proton pickup process in the downwind region 1 au from the Sun, which was discovered in 2018 by a research team that included scientists from the LSSPA.

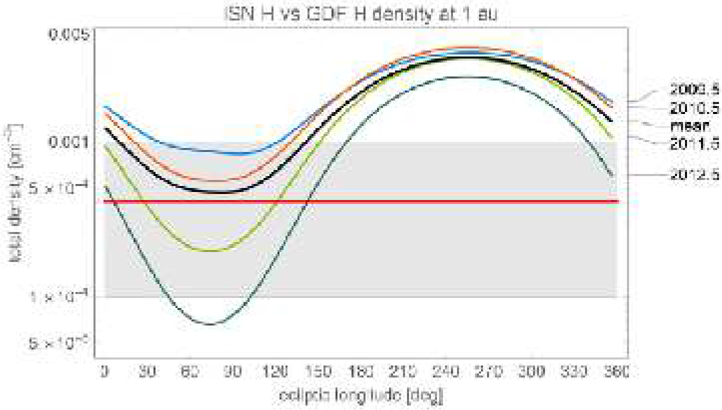

Fig. 22. Comparison of mean ENA density at 1 au (the thick orange line) with the density distribution of ISN H along the Earth orbit, simulated using the WTPM model for four dates in the solar activity cycle. While in the upwind portion of the Earth orbit (ecliptic longitudes 165–345°) the ENA density is lower than the ISN density by almost an order of magnitude during all phases of the solar cycle, in the downwind hemisphere they become comparable and, in certain years, ENA density may exceed that of ISN H gas. Source: Bzowski & Galli, Ap. J. 870:58, 2019.

The uncertainty of this density is high, and the spatial distribution of GDF ENAs density remains to be established. However, the analysis performed by Bzowski and Galli clearly suggests that GDF ENAs, treated as a gas population, deserve further analysis. These results were published in *The Astro-physical Journal* in a paper by Bzowski & Galli (870:58, 2019).

(*M. Bzowski*)

Uncertainty of the cross section for charge exchange in the outer heliosheath

Models play an important role in our understanding of the global structure of the solar wind and its interaction with the interstellar medium. A critical ingredient in many types of models is the charge-exchange collisions between ions and neutrals. Some ambiguity exists in the charge-exchange cross-section for protons and hydrogen atoms, depending on which experimental data is used. The differences are greatest at low energies and, for the plasma-neutral interaction in the outer heliosheath, may exceed 50% (Fig. 23).

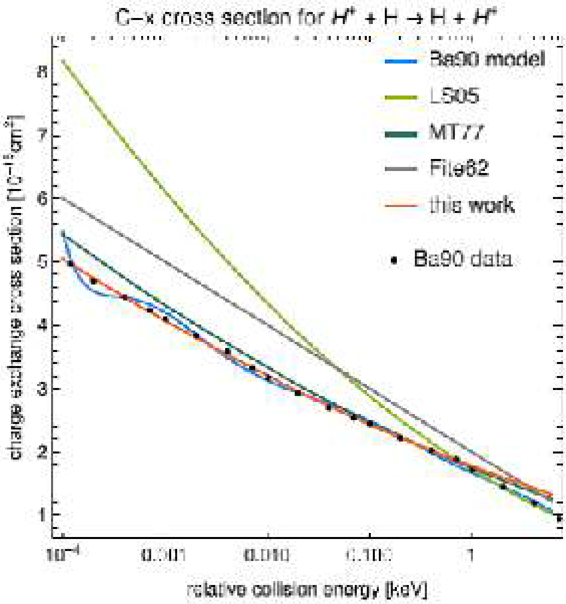

Fig. 23. Measurements of the charge-exchange cross-section between protons and H atoms shown as a function of the kinetic energy of particle collision (black dots), compared with various model formulae. The selected measurement data were chosen based on a review of the literature. Three models are in a very good agreement with the selected dataset, while two others are not. Model LS05 agrees with a different subset of experimental data (not shown) and has been widely used in the modelling of the heliosphere, becoming a de facto standard. It seems, however, that it is not appropriate in the context of the outer heliosheath. Source: Bzowski & Heerikhuisen, Ap. J. 888:24, 2020.

The charge-exchange cross-section is important because it directly affects the intensity of coupling between neutral gas and plasma in the outer heliosheath. A larger cross-section implies stronger heating and a slowdown of the plasma, on the one hand, and more intense production of the secondary H component and attenuation of the primary component, on the other hand. A smaller cross-section implies weaker mass-loading of the plasma, less intense production of the secondary component, and a different ratio between thermal and ram pressures in the plasma.

Dr. M. Bzowski from the LSSPA and Dr. J. Heerikhuisen from the University of Waikato, New Zealand, assessed a number of existing datasets and formulae for proton–hydrogen charge-exchange. They used a global simulation of the heliosphere to quantify differences between the currently-favored cross-section (the green line in Figure 23) and suggested a formula for the charge-exchange cross-section that most closely matches the majority of available data.

The two researchers also sought to identify uncertainty in the model of the heliosphere stemming from different cross-section models. To do this, they performed simulations of the heliosphere that only differed with respect to the adopted cross-section. They used the same model of the heliosphere that was used in the determination of the density of interstellar He^{+}, presented in this report. They found that in order to make the resulting two model heliospheres the same size, interstellar proton and hydrogen densities needed to be adjusted by 10%–15% (Figure 24). This observation provides a way to link uncertainty in the cross-section to uncertainty in the parameters of the pristine interstellar plasma.

This study was reported in a paper by Bzowski & Heerikhuisen published in *The Astrophysical Journal* (888:24, https://doi.org/10.3847/1538-4357/ab595a).

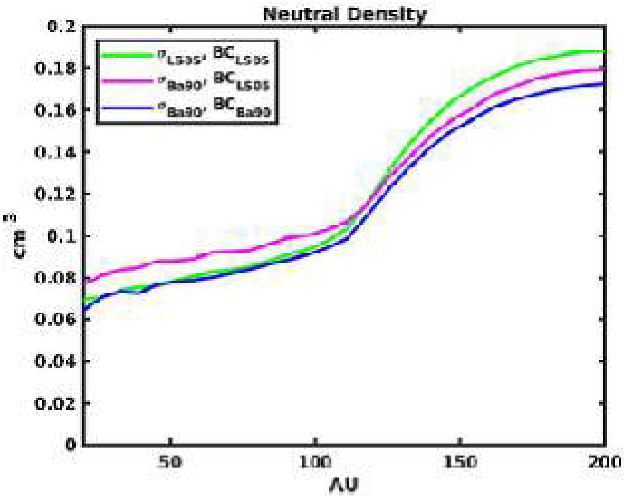

Fig. 24. Comparison of density profiles of neutral H in model heliospheres, simulated assuming two alternative cross-sections for charge exchange (LS05 vs Ba90), and different densities of interstellar plasma. Simulations based on identical plasma densities and different cross-sections are shown by green and blue lines. The purple line corresponds to the case where the preferred cross-section (Ba90) was used, and the density of interstellar plasma was adjusted. This figure illustrates the level of uncertainty in the model's results (or, in other words, the model's sensitivity) to the magnitude of the adopted charge-exchange cross-section. Source: Bzowski & Heerikhuisen, Ap. J. 888:24, 2020.

What epoch do we probe when observing interstellar neutral He atoms?

In situ measurements of the heliospheric particle populations by the Voyager spacecraft can only be put in an appropriate context with remote-sensing observations of energetic and interstellar neutral atoms (ENAs and ISN, respectively) at 1 au when the time delay between the production and the observation times is taken into account. ENA times of flight from the production regions in the heliosheath are relatively easy to estimate because these atoms follow almost constant speed, force-free trajectories. For the ISN populations, dynamical and ballistic selection effects are important, and times of flight are much longer. But how long are they?

Dr. M. Bzowski and Ms. M. A. Kubiak, MSc, estimated these times for ISN He and H atoms observed by IBEX and in the future by IMAP using the WTPM model with synthesis method. This model calculates individual trajectories of interstellar atoms and estimates the production an d loss rates of the secondary atoms, that are created due to charge exchange between interstellar ions and interstellar atoms in the perturbed region in front of the heliopause. The researchers showed that for the primary population atoms, the times of flight are on the order of three solar cycle periods, with a spread equivalent to one solar cycle. For the secondary populations, the times of flight are on the order of ten solar cycle periods, and during the past ten years of observations, IBEX has been collecting secondary He atoms produced in the outer heliosheath during almost the entire 19th century. ISN atoms penetrating the heliopause at the time of Voyager crossing will become gradually visible about 2027, during the planned IMAP observations. Hypothetical variations in the ISN flow in the Local Interstellar Medium are currently not detectable. Nevertheless, it is expected that steady-state heliosphere models used with appropriately averaged solar wind parameters are suitable for understanding the ISN observations.

These findings were published by M. Bzowski and M. A. Kubiak in ApJ 901:12, 2020.

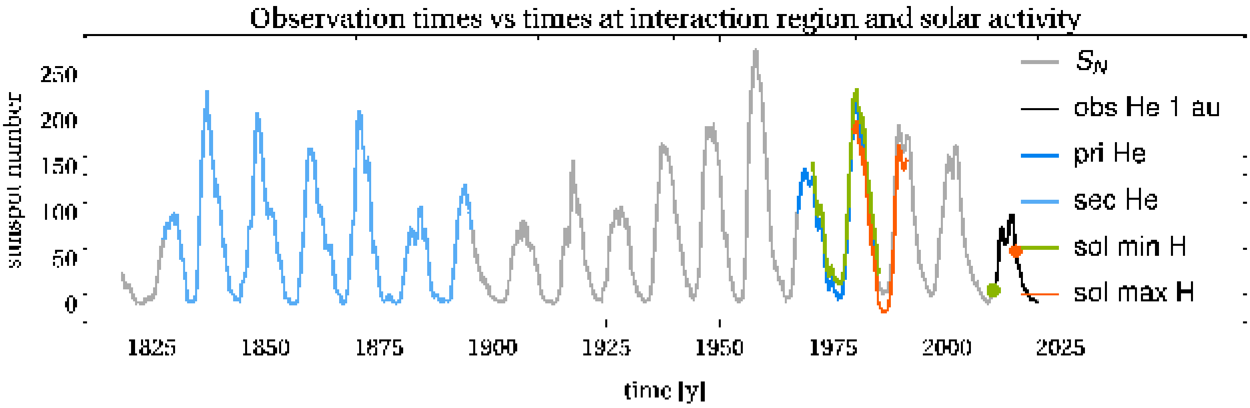

Fig. 25. Sunspot number is shown for a time interval from the early 19-th century until present to illustrate variations in the solar activity level (gray line). Color lines illustrate the time intervals when various populations of interstellar atoms observed nowadays by IBEX were traversing the outer heliosheath, where the charge exchange interaction responsible for the creation of the secondary interstellar atoms operates. The figure illustrates that the presently observed atoms belonging to the primary and the secondary populations originate from epochs separated in time by several solar cycle. Therefore, the conditions in the outer heliosheath at the times of their creation differed from each other and from those being probed nowadays by the Voyager spacecraft.

(M. Bzowski)

Evolution of the solar Lyman-α profile line and radiation pressure for interstellar hydrogen

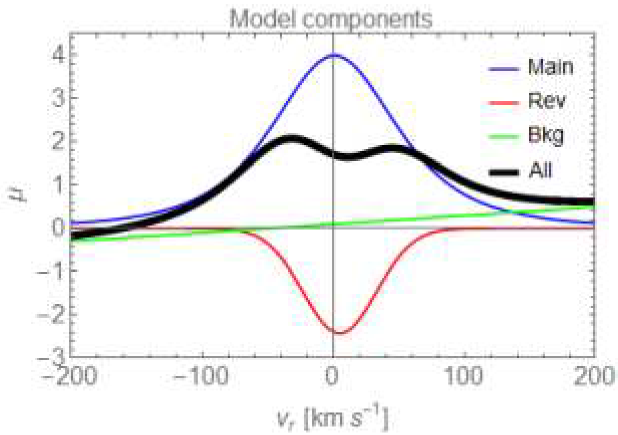

Fig. 26. Schematic illustration of building-blocks of the model of the profile of the solar Lyman-α spectral line. The blue line represents the main Gaussian-like shape, the red line the central self-reversal, and the green line the spectral background of the line. The actual profile is a superposition of these building-blocks; it is represented by the black line.

The Lyman-α line is one of the most prominent features in the UV part of the solar spectrum. It is responsible for the resonance radiation pressure acting on hydrogen atoms in the heliosphere, i.e., for an effective anti-solar force that is exerted on these atoms by photons from the Sun. Next to the solar gravity force, radiation pressure is the main factor that determines the trajectories of neutral hydrogen and deuterium atoms inside the heliosphere. Accurate knowledge of the dynamics of these atoms is necessary to calculate the density of interstellar neutral hydrogen inside the heliosphere and, consequently, to investigate derivative populations of H atoms important for heliospheric physics, including pickup ions and energetic neutral atoms. To that end, one needs a model of the spectral shape of the solar Lyman-α line and its evolution during the cycle of solar activity.

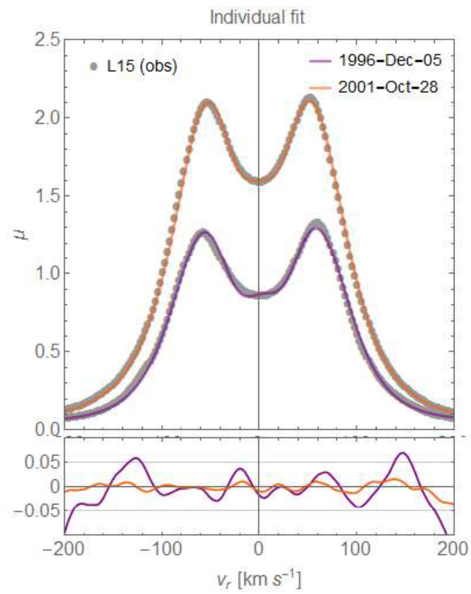

Fig. 27. Example solar Lyman-α line profiles obtained from the newly-developed model for the solar maximum (orange) and solar minimum epochs (purple). The bottom panel presents relative differences between model predictions and actually-measured profiles.

Previous models of the Lyman-α line profile were based on just a few observations, and therefore they were not able to reproduce the evolution related to variations in solar activity with sufficient accuracy. A team of scientists from LSSPA: Dr. Izabela Kowalska-Leszczyńska, Dr. Maciej Bzowski, Ms. Marzena A. Kubiak MSc, and Dr. Justyna M. Sokół developed a new model of the evolution of the solar Lyman-α line profile based on new observations from the SOHO satellite that have been available since 2015. Based on these observations, the researchers proposed an analytical formula composed of three parts. Each describes a different feature of the line profile, shown in Figure 26 (the main line - blue line, the self-reversal in the center - red line, and a slight slope of the whole line with respect to the vertical axis - green line). It turned out that by using the proposed formula, the team could reproduce solar line profile observations collected over several years (covering almost a full cycle of solar activity) with very good accuracy. An example is shown in Figure 27, where two observed profiles (dots) are compared with fitted functions (lines). Furthermore, the team of researchers found that the parameters of the proposed function (e.g., the widths of component functions, the depth of the self-reversal, and the shifts of the profile component relative to each other) can be expressed as linear functions of total solar irradiance in the Lyman-α line. The evolution of the latter quantity is closely related to the level of solar activity. The results of this analysis were presented in a paper published in *The Astrophysical Journal* (Kowalska-Leszczyńska et al., 2018a).

Subsequently, the team from LSSPA examined how the new radiation pressure model affects the interstellar neutral hydrogen distribution in the heliosphere, and distributions of its derivative populations of particles. The analysis started with a comparison of the densities of interstellar hydrogen inside the heliosphere predicted by the old and new models. It turned out that during periods of low solar activity the new model predicts more hydrogen close to Earth's orbit than the old one, but during high solar activity, the new model predicts less gas. The largest differences between the two considered models are in a region located opposite to the direction of inflow of the interstellar gas to the heliosphere, i.e., in the downwind region.

Another aspect considered by the research team was the value of the density of interstellar neutral hydrogen at the termination shock. In 2008, scientists from the CBK PAN carried out estimates using the old model of radiation pressure and the flux of pickup ions observed by the Ulysses mission. The new value of hydrogen density calculated using the new model of radiation pressure turned out to be statistically consistent with the old one due to the large measurement uncertainty, which was 25% of the measured value.

Another question was the influence of the new radiation pressure model on the hydrogen atom flux seen by the IBEX-Lo detector. Several years ago, scientists from the USA and Russia discovered that the ratios of fluxes of hydrogen atoms observed by IBEX-Lo in different energy channels are inconsistent with models. They had suggested that the reason for this may be an insufficient understanding of the radiation pressure acting on hydrogen atoms in the heliosphere. Simulations performed by scientists from LSSPA showed that indeed, expected fluxes of hydrogen atoms are very sensitive to details in the radiation pressure model, but even using the newly-developed model does not remove the observed discrepancy.

Therefore, researchers from LSSPA challenged the existing paradigm regarding how the radiation pressure in the heliosphere actually works. It had been assumed that if the flux of photons from the Sun decreases with the square of solar distance, then the force due to the radiation pressure should behave in the same way. This is because the gravity force also decreases with the square of solar distance. Consequently, the ratio of the gravity and radiation pressure forces acting on hydrogen atoms should be constant, regardless of where it is measured. But is that assumption true, if some of the solar photons are scattered by hydrogen atoms? Scientists from LSSPA calculated how many of the original photons emitted by the Sun are scattered from the beam of hydrogen atoms located between the Sun and a given location in the heliosphere. They found that even at relatively small distances (within approximately 10 astronomical units - around Saturn's orbit) scattering losses can reach 30% of the original Lyman-α photons emitted by the Sun within the spectral sensitivity band of hydrogen. Thus, the force caused by radiation pressure decreases much faster with distance than previously thought.

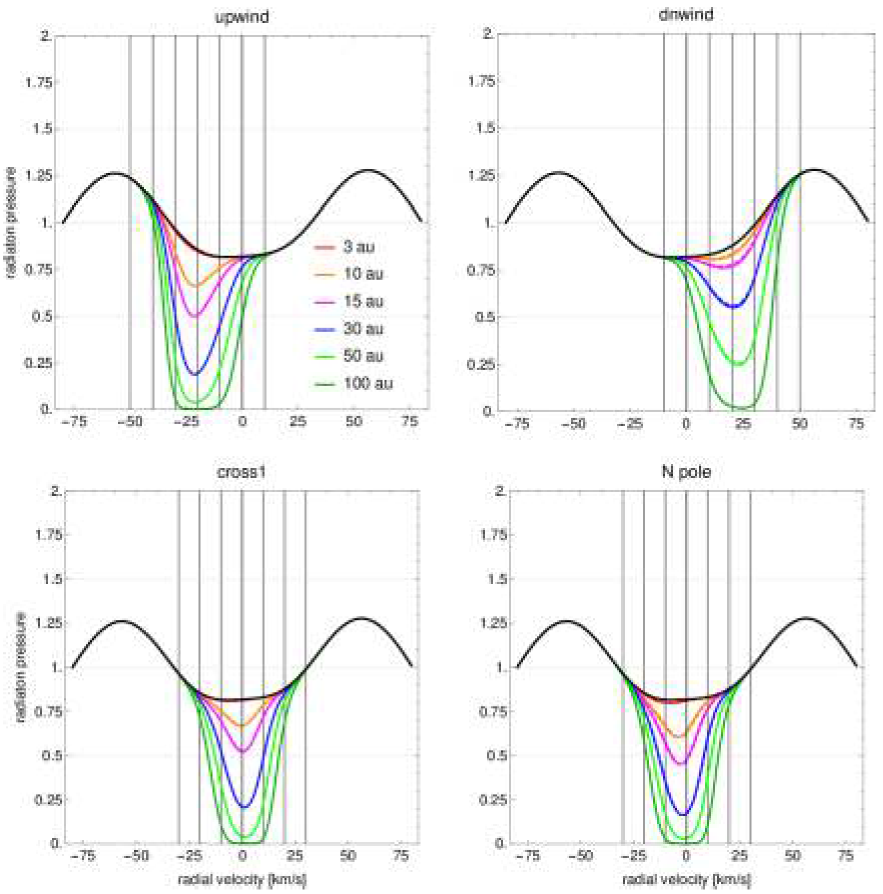

Fig. 28. Evolution of effective radiation pressure (expressed in units of solar gravity force) acting on hydrogen atoms in the heliosphere with distance from the Sun. Absorption of solar photons that are responsible for radiation pressure results in a gradual decrease of the effective spectral flux from the Sun in the frequency range corresponding (due to the Doppler effect) to radial velocities of interstellar neutral atoms in the heliosphere. As a result, the magnitude of radiation pressure effective for interstellar hydrogen atoms is closely related to the column density of interstellar hydrogen between a given location in space and the Sun. Hence, the approximation in which radiation pressure is just a factor that is scaled with the square of the distance to the Sun (represented by black profiles) is unlikely to be valid. The four panels present the evolution of spectral profiles of the solar Lyman-α line along upwind, downwind, crosswind and north-pole lines in the heliosphere at selected distances from the Sun.

The modification of the radiation pressure force due to the absorption effect is larger than the differences between the two radiation pressure models. Therefore, a new radiation pressure model in the heliosphere is needed, which should take absorption processes into account. However, this new model must also include the distribution of interstellar neutral hydrogen in the heliosphere as the two phenomena are closely related to each other.

The results of this analysis were presented by the team lead by Dr. Izabela Kowalska-Leszczyńska in Kowalska-Leszczyńska et al., ApJS 2018a,b, 2020).

A novel method of establishing the unresolved background in the EUV surveys of the sky

In observations of diffuse emissions like, e.g., the Lyman-a heliospheric glow, contributions to the observed signal from point sources (e.g., stars) are considered to be a contamination. There are relatively few bright point sources that are usually properly resolved and can be subtracted or masked. Others are unresolved partly due to the helioglow foreground, and partly due to resolution and sensitivity limitations of the detector. Nevertheless, the radiation from these sources is registered by the instruments and must be subtracted from the signal. Up to now, however, a suitable method to establish this contribution was lacking.

A team of scientists from LSSPA CBK PAN led by Dr. M. Strumik proposed such a method and applied it to observations of the helioglow performed by the Solar Wind Anisotropies (SWAN) experiment onboard the SOHO spacecraft. To estimate the unresolved EUV background, the team used spectroscopic observations of several thousand astrophysical objects available from databased of observations from International Ultraviolet Explorer (IUE).

The estimated distribution suggests that the number of these sources increases with decreasing intensity. Below a certain threshold, these sources cannot be resolved against the diffuse signal from the backscatter glow, that results in a certain physical background from unresolved point sour-

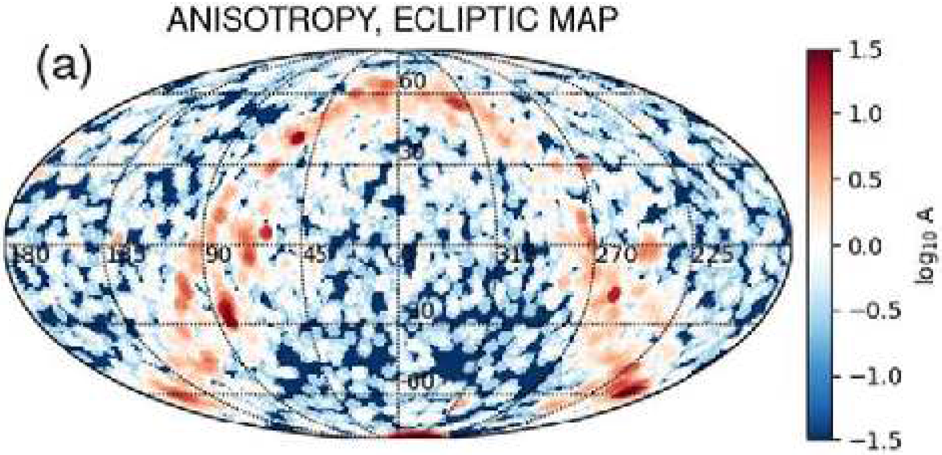

Fig. 29. The distribution in the sky of the unresolved EUV background for the sky survey by SOHO/SWAN, obtained by scientists from CBK PAN. The magnitude of the spatial fluctuations of the EUV radiation from spatially unresolved stars is presented in the logarithmic scale. Source: Strumik et al., ApJ 899:48, 2020

ces. Detection, understanding, and subtraction of the point-source background has implications for proper characterization of diffuse emissions and accurate comparison with models. Stars are also often used as standard candles for in-flight calibration of satellite UV observations, thus proper understanding of signal contributions from the point sources is important for the calibration process. The team proposed a general approach to quantify the background radiation level from unresolved point sources in UV sky survey maps. In the proposed method, a distribution of point sources as a function of their intensity is properly integrated to compute the background signal level. These general considerations were applied to estimate the unresolved-point-source background in the SOHO/SWAN observations that on average amounts to 28.9 R. The team found that, unsurprisingly, the distribution in the sky of the unresolved background is patchy.

These results were published by Strumik et al. in ApJ 899:38, 2020. The research team included Dr. M. Strumik, Dr. M. Bzowski, Dr. I. Kowalska-Leszczyńska, and Ms. M.A. Kubiak.

(M. Bzowski)

Ionospheric and magnetospheric group

(Plasma Physics Group)

Satellite Detection of Ionospheric ULF Magnetic Field Fluctuations Caused by Lightning (Strumik et al. 2021)

One can expect that electromagnetic fluctuations caused by lightnings can propagate from the lower atmosphere higher into the ionosphere, which is an ionized and electrically conducting medium. This process however requires conversion of the electromagnetic perturbation propagating in the neutral atmosphere into an ionospheric plasma wave, which for so-called ultra-low frequency (ULF) regime can attenuate strongly the wave amplitude. The attenuations are considered to be so significant that one could argue that it is virtually not possible to observe ionospheric magnetic field perturbations caused by lightnings using currently-available satellite magnetometers.

At present, there are many remote observations of lightnings and direct satellite measurements of ionospheric magnetic field fluctuations that can be analysed searching for a possible link between the two phenomena. Using two types of lightning observations and Swarm satellite measurements, we provide an evidence that lightnings can generate electromagnetic perturbations that propagate into the ionosphere, and can be measured with magnetometers onboard low-Earth-orbit satellites, e.g., by the Swarm constellation. We identify links between lightnings and ionospheric wave properties suggest a real causality relationship between the two phenomena. To our knowledge, this is the first direct experimental confirmation of such a relation in the ULF range.