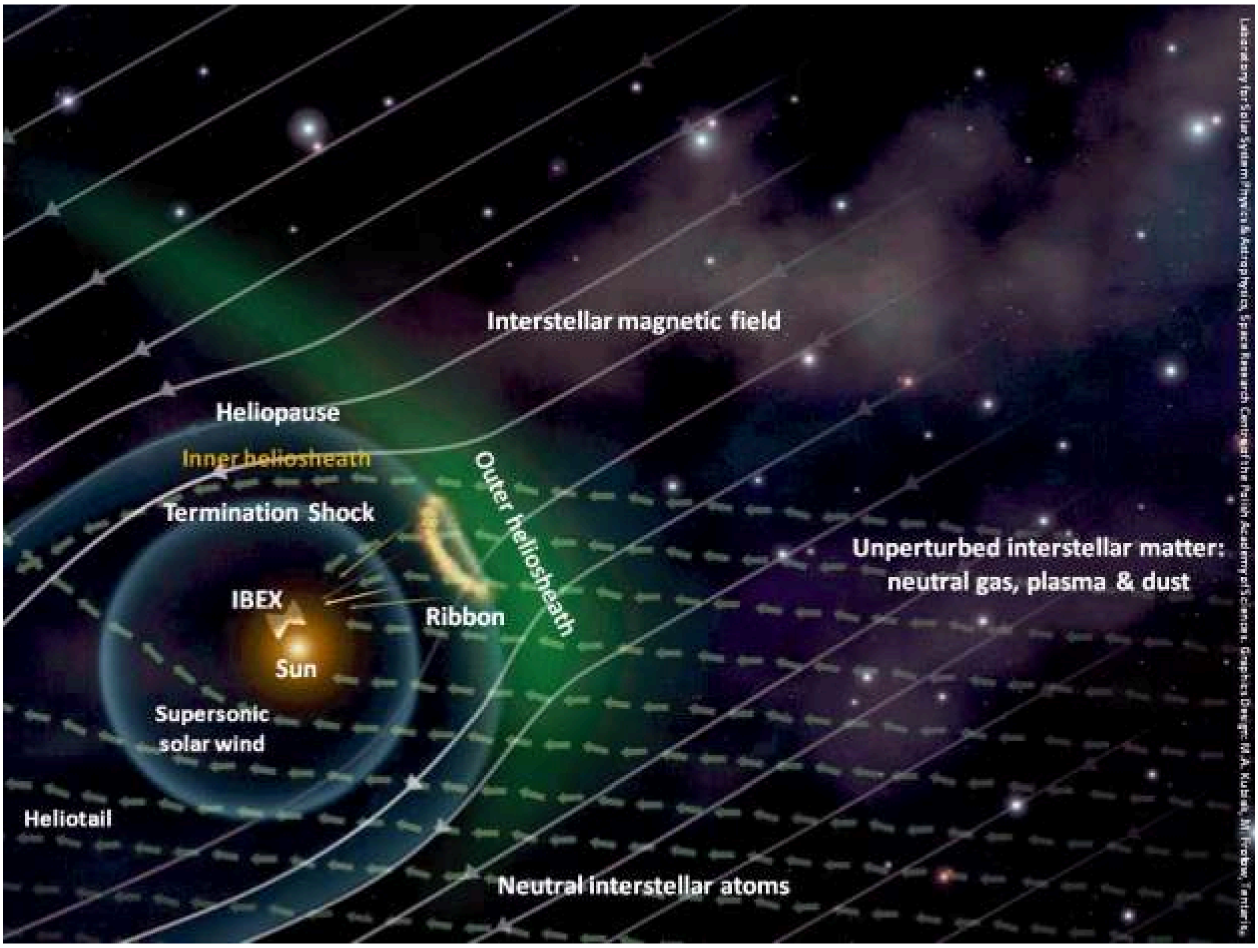
Heliospheric physics

(Laboratory for Solar System Physics and Astrophysics - LSSPA)

The hypersonic, ionised 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 magnetised. 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 Fig. 20.

The figure shows the Sun embedded in the local cloud of interstellar matter composed of ionised 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 as shown in , 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.20). The heliopause, impenetra-



Laboratory for Solar System Physics & Astrophysics, Space Research Centre of the Polish Academy of Sciences. Graphics Design: M.A. Kubiak, M. Frobow, Tentaris

Fig. 20. 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.

ble for charged particles except for cosmic rays, is transparent for neutral atoms, which thus freely enter the heliosphere. Inside the heliosphere, these 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 with-out being ionised 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 Fig. 20), 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 Fig. 20, schematically drawn close to the Sun).

Neutral atoms from the interstellar matter (whose streamlines are marked by the short arrows in Fig. 20) 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 slightly perturbed interstellar neutral atoms. Some of the atoms that are the product 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 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, 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.

In 2019, scientists from the Laboratory for Solar System Physics and Astrophysics (LSSPA) carried out studies of various aspects of the heliosphere and the surrounding interstellar medium. Our results were reported in seventeen scientific papers, published in international, peer-reviewed 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. 21).

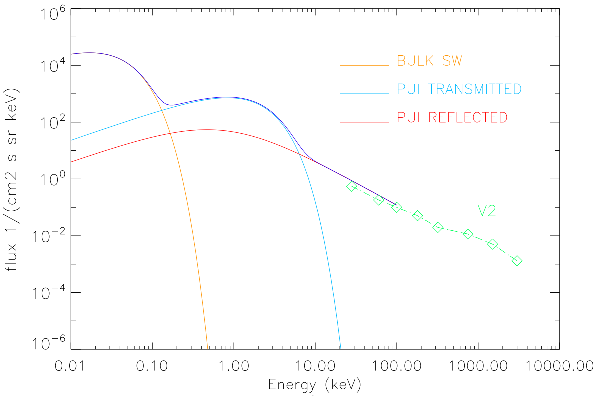


Fig. 21. A model spectrum of ions used to simulate the observed ENA flux. The model has three components: bulk solar wind (orange), pickup ions reflected off the termination shock (red), and pickup ions transmitted across the shock (blue). The three components add up to make the total spectrum (purple). 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.

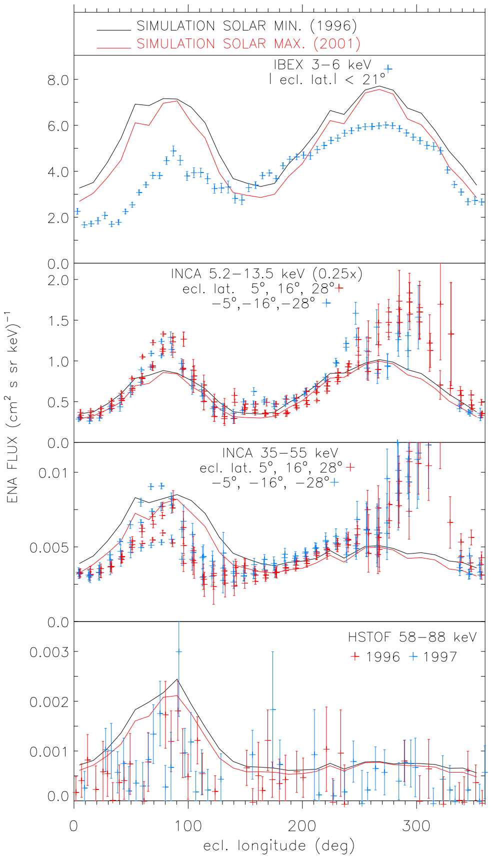


Fig. 22. Model of ENA flux (solid lines) for four energy bands (top–bottom panels), compared with actual observations from IBEX-Hi (first), INCA (second and third), and HSTOF (fourth). The data are presented by dots, and measurement uncertainties by error bars. There is relatively little difference between 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.

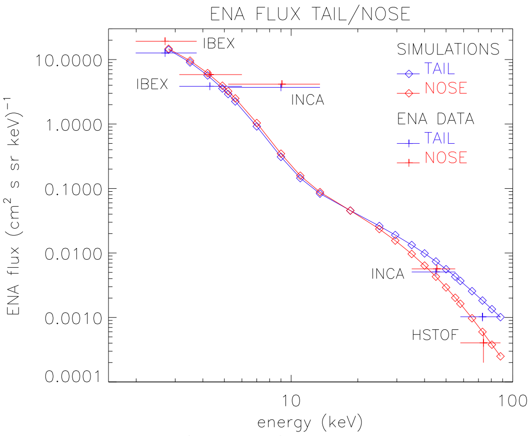


Fig. 23. Spectra of ENAs for the upwind (red) and downwind (blue) regions of the heliosphere, obtained from observations (points with bars) compared with the corresponding spectra obtained from simulations (diamonds). Horizontal bars mark the energy bands of the respective energy channels. Vertical bars 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 He$^+$ ions and the ionisation state of the Very Local Interstellar Medium

The physical state of the interstellar medium surrounding the Sun is the subject of extensive research. The Sun is penetrating a cloud of warm, partly ionised gas, but the ionisation state, temperature, and other physical parameters of this cloud are believed to be controlled to a large extent by ambient EUV radiation emitted by several relatively nearby stars that are very bright in this spectral region. Differential absorption, and the resulting ionisation of various ions of interstellar species and heating of interstellar matter by radiation from these stars make it challenging to determine the physical state of interstellar matter near the Sun. The ionisation state and mean density of interstellar neutral and ionised components can be approximately determined by averaging over lines of sight to nearby stars, i.e., on spatial scales exceeding the size of the heliosphere by many orders of magnitude. However, to understand the interaction of the solar wind with the interstellar medium, an understanding of the local interstellar conditions, within several thousand au from the Sun is necessary. This insight was discovered in 2019 by an international team of researchers led by Dr M. Bzowski from the LSSPA.

The heliosphere is created as a result of a pressure balance between the magnetised solar wind and the magnetised interstellar plasma. Interstellar neutral atoms mediate the interaction via charge exchange. The interstellar plasma is composed mostly of protons and He$^+$ ions. While the number abundance of He$^+$ ions in the plasma is on the order of 10%, its contribution to the plasma ram pressure acting on the heliosphere is fourfold bigger, because He$^+$ ions are fourfold heavier than protons. Therefore, determining the absolute density of He$^+$ ions in the unperturbed interstellar medium is important for heliospheric studies. However, up to now it has proved challenging because of the lack of available observables.

The flow of neutral interstellar helium through the perturbed interstellar plasma in the outer heliosheath (OHS) results in the creation of a secondary population of interstellar He atoms, the so-called Warm Breeze, which is due to charge exchange with perturbed He$^+$ ions. This secondary population brings an imprint of the OHS conditions to the IBEX-Lo instrument, and was discovered in 2010 by a research team led by CBK PAN scientists M. Bzowski and M. A. Kubiak.

In 2019, an international team of researchers led by Dr M. Bzowski, including Ms M. A. Kubiak, Dr J. M. Sokół, Dr A. Czechowski and Ms J. Grygorczuk from the LSSPA determined the number density of the interstellar He$^+$ population in the unperturbed interstellar medium in front of the Sun. This finding was based on IBEX-Lo observations (for the years 2010–2014) of neutral He atoms fitted using a global simulation of the heliosphere, and a detailed kinetic simulation of the filtration of He in the OHS. This density was found to be $(8.98\pm0.12)\times10^{-3}$ cm^{-3}. From this, they obtained the absolute density of interstellar H$^+$ as 5.4×10^{-2} cm^{-3} and that of electrons as 6.3×10^{-2} cm^{-3}. Consequently, the ionisation degree of H was found to be equal to 0.26 and that of He to 0.37. These conclusions agree with estimates of the parameters of the Very Local Interstellar Matter obtained from fitting observed spectra of diffuse interstellar EUV and the soft X-ray background.

These results were published in The Astrophysical Journal, in a paper by Bzowski et al. (Ap. J. 882:60, 2019, https://doi.org/10.3847/1538-4357/ab3462).

(M. Bzowski)

Interstellar neutral gas species and their pickup ions inside the heliospheric termination shock

The expected distribution of interstellar neutral (ISN) gas and PUI density of H, He, Ne, and O inside the heliosphere has been revised. Dr Justyna M. Sokół and Dr Maciej Bzowski from the LSSPA, together with Dr Munetoshi Tokumaru (ISEE, Nagoya, Japan) overviewed the current state of knowledge about solar ionisation rates for heliospheric atoms inside the termination shock. They compiled a list of ionisation 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), photoionisation, and electron impact ionisation were considered. Similarities and differences between ionisation processes for the given species, as well as a comparison of the total ionisation rates between the four species in the ecliptic plane and in the polar

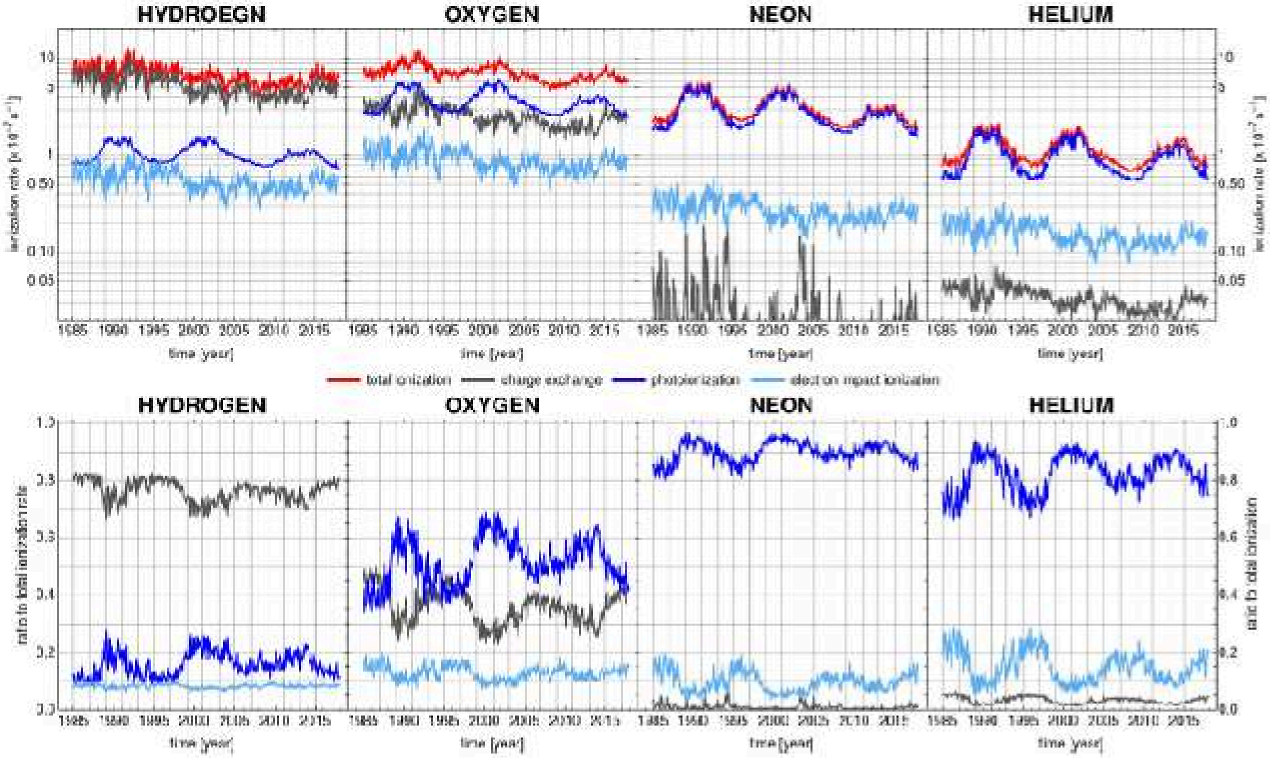


Fig. 24. Time series of ionisation rates of neutral hydrogen, oxygen, neon and helium at 1 au in the ecliptic plane, presented for the time interval 1985–2019, with a time resolution corresponding to the solar rotation period (upper row). Red corresponds to the total ionisation rate, which is a sum of the rates of charge exchange (grey), photoionisation (dark blue), and electron impact ionisation (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.

regions were presented. The ionisation 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 ionisation 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 ionisation losses is photoionisation. 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 photoionisation losses can be a dominant ionisation source, depending on the phase of solar activity and long-term changes in the solar wind. Total ionisation rates are highest outside the ecliptic plane for O. Solar ionising factors act differently on different heliospheric particles, which results in different modulation of these particles throughout the heliosphere. Total ionisation 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 a paper by J.M. Sokół, M. Bzowski and M. Tokumaru published in The Astrophysical Journal 872:57, 2019 (https://doi.org/0.3847/1538-4357/aafdaf).

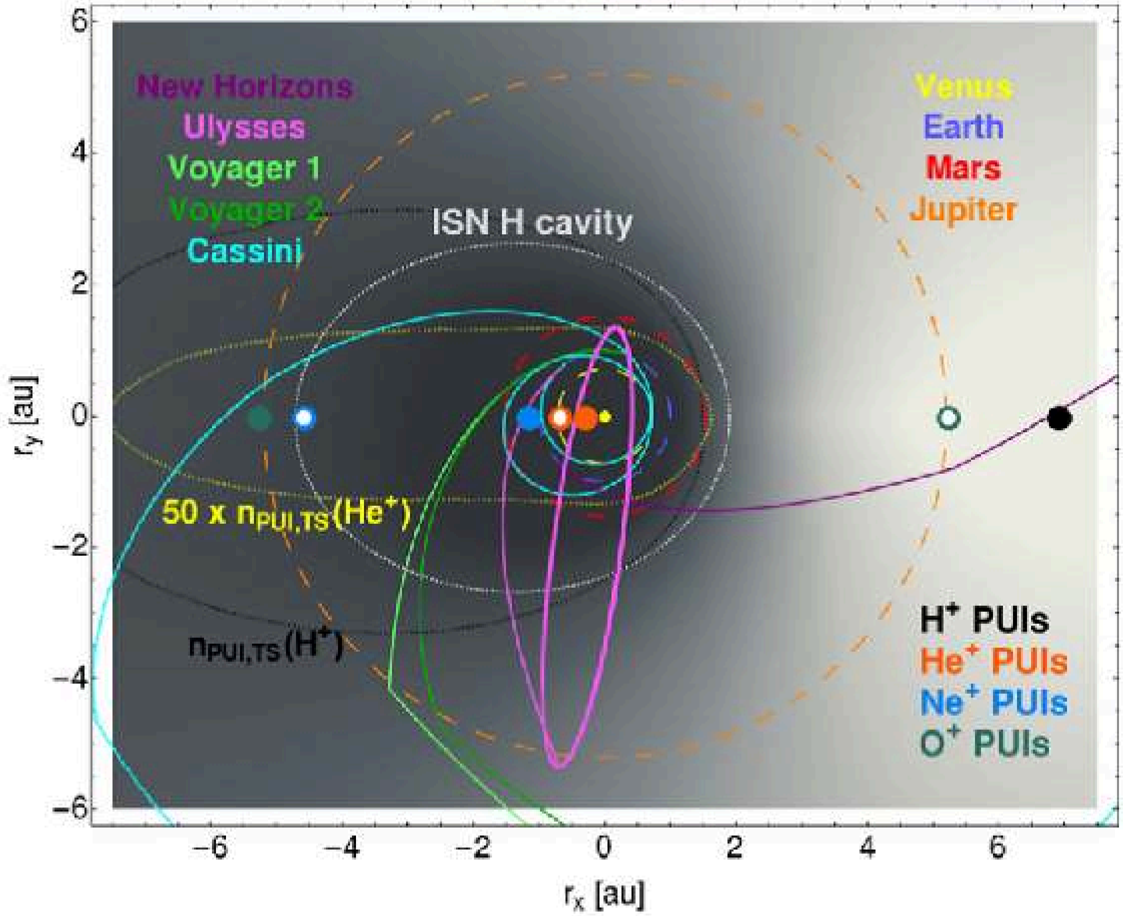


Fig. 25. The density distribution of H^+ pickup ions in the ecliptic plane is shown as a background for the locations of the maximum pickup ion densities of H^+ (black), He^+ (orange), Ne^+ (blue), and O^+ (green) in 1996 (full circles) and 2001 (empty circles). The upwind direction is shown on the right-hand side. For comparison, orbits of Venus, Earth, Mars, and Jupiter are shown as broken lines. Also shown are portions of the trajectories of selected spacecraft: Ulysses, Voyagers 1 and 2, New Horizons, and Cassini. The boundary of the cavity in the density distribution of ISN H in 1996 is marked by the grey dotted line. The yellow dotted line marks a region where the He^+ PUI density exceeds by a factor of 50 the upwind density of He^+ at the termination shock. Source: Sokół et al., Ap. J. 879:24, 2019.

These revised solar ionisation rates were used by scientists from the LSSPA (Dr J. M. Sokół, Dr M. Bzowski, and Ms M. A. Kubiak) to study the spatial distribution of ISN gas density for H, He, Ne, and O and the PUI density for H^+, He^+, Ne^+, and O^+ in the region between 1 au and the termination shock of the solar wind, both in and out of the ecliptic plane, during minimum and maximum solar activity. The study focused on similarities and differences in the large-scale structures of ISN gas and PUI densities between various species that formed in the heliosphere.

These results show that different species have different ISN and PUI density structures. This is due to differences in modulation by solar ionising factors, even though the inflow direction, speed and temperature of these species are identical (except for H). The latitudinal anisotropy of the ionisation rates causes anisotropy in ISN gas and PUI densities measured along the ecliptic plane. Because this anisotropy is different for different species, relative abundance ratios of ISN and PUI densities vary non-uniformly in space and time. The study, performed for the first time for a homogeneous system of ionisation rates for the species in question, showed that while the ISN density maxima are expected outside 1 au, the PUI density maxima are expected to be found closer to the Sun. The PUI densities, throughout the heliosphere, are expected to be highest for He^+ PUIs, then H^+ PUIs, Ne^+, and O^+ PUIs. The optimal location for the detection of He^+ PUIs is downwind, within 1 au. For Ne^+ PUIs, during the solar minimum detection is optimal at 1 au, while during the solar maximum the peak is shifted almost to Jupiter's orbit, with a density reduction of over 50%. Although O^+ PUIs can be searched for in both upwind and downwind regions (as intensities are expected to be similar), acceptable locations are found at distances starting from the Jupiter orbit, up to a few tens of au. The upwind hemisphere is confirmed as the best location to detect H^+ PUIs.

The research team identified the location of the cavity in ISN gas density for the four species, and variation of the size and shape of the cavity with time. The greatest cavity is expected for ISN H, while the smallest cavity is expected for ISN He. The study also discussed relative abundance ratios of Ne/O, H/He, Ne/He, and O/He for ISN gas and PUIs densities, together with their variation with location in the heliosphere, and their modulation along the TS. For relative abundance ratios of ISN gas densities of the species in question, the distribution at the TS is uniform up to about 40° off the downwind direction, where an increase in the ab solute density is expected. For PUIs, the variation at the TS is not uniform in time and is a function of the angle off the upwind-downwind axis and heliolatitude; it also varies with the phase of solar activity.

These results were presented in a paper by Sokół et al. published in The Astrophysical Journal 879:20, 2019 (https://doi.org/10.3847/1538-4357/ab21c4).

(J. M. Sokół)

Science opportunities from observations of interstellar neutral gas with an adjustable detector boresight direction

The interstellar neutral (ISN) gas that has entered the heliosphere can be detected at a few au from the Sun, as demonstrated by Ulysses and the Interstellar Boundary Explorer (IBEX) space probes. Ulysses observed the ISN gas from a set of vantage points distributed along its solar polar orbit from 1994 to 2007, while IBEX has been observing from the Earth's orbit in an almost fixed direction relative to the Sun since 2009. A follow-on mission for IBEX will be NASA's Interstellar Mapping and Acceleration Probe (IMAP), which will be launched in 2024. Researchers from the LSSPA are involved in the preparation of this mission. In particular, Dr M. Bzowski, Dr J. M. Sokół, and Ms M. A. Kubiak are Co-Investigators in the IMAP Science Team. During 2019, LSSPA scientists were deeply involved in the science development of the IMAP-Lo instrument, which draws its heritage from the IBEX-Lo detector. One of the significant improvements in this new instrument will be an ability to vary the angle of the boresight relative to the Sun. This capability will enable IMAP-Lo to track ISN flux in the sky during almost the entire year and, consequently, significantly lengthen the observation time.

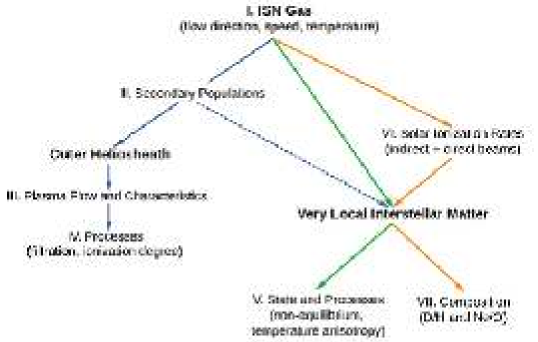


Fig. 26. Graphic representation of science opportunities for a study of the local interstellar medium by direct sampling of interstellar neural H, He, Ne, O, and D using a scanning instrument located at the Earth's orbit that is able to vary the angle between the Sun and the instrument boresight. This configuration is similar to that planned for the IMAP-Lo experiment. Source: Sokół et al., Ap. J. S. 245:26, 2019.

A team of LSSPA scientists (J. M. Sokół, M. A. Kubiak, M. Bzowski) in collaboration with the IMAP-Lo Lead Professor N. Schwadron and Professor E. Möbius from the University of New Hampshire studied the science opportunities afforded by this new capability. This study identified alternative advantageous ISN gas observation geometries for the detector moving along the Earth orbit over the course of a year, and suggested a multi-choice, annual ISN observation scheme. Science opportunities provided by these alternative schemes were identified as a function of time of year and phase of solar activity. Observation geometries and seasons were determined separately for various ISN species and populations.

The researchers found that using an adjustable viewing direction allows to perform sampling ISN gas in the upwind hemisphere, where the signal is not distorted by gravitational focusing. However, ISN species can be sampled almost throughout the year, which enables improving the observation statistics. They demonstrated that with appropriately-adjusted observation geometries, primary and secondary populations can be fully separated. Additionally, they showed that atoms of ISN gas on indirect trajectories can be detected, and pointed out the impact of this capability on the study of ionisation rates of ISN species.

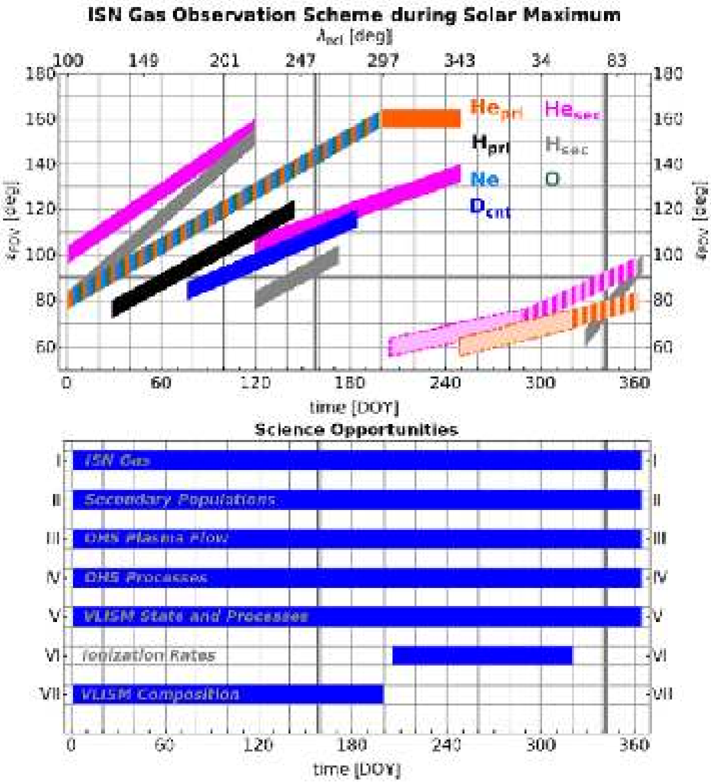


Fig. 27. Timeline for science opportunities stemming from the ability to adjust the boresight in the planned IMAP-Lo experiment (lower panel). Alternative schedules are presented in the upper panel. The ?$_{\text{FOV}}$ angle is the angle between the spacecraft's rotation axis, directed towards the Sun, and the boresight of the mounted instrument. Source: Sokół et al., Ap.J.S. 245:26, 2019.

The results of this study, which may be regarded as a yearly observation plan for such an experiment, were published in a paper by Sokół et al. in *The Astrophysical Journal Supplement Series* 245:26, 2019 (https://doi.org/10.3847/1538-4357/ab21c4).

(*M. Bzowski*)

A "forgotten" population of neutral gas inside the heliosphere

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 remo-te regions of the heliosphere. However, in fact, these atoms form a separate non-thermal popula-tion of neutral H atoms deep inside the helio-sphere.

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 analyse 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.

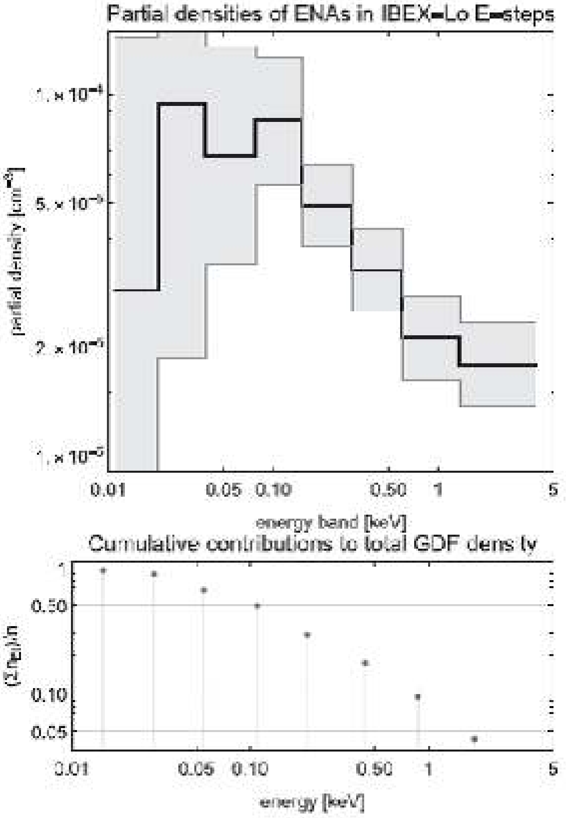


Fig. 28. Partial densities of H ENAs observed by IBEX-Lo in its eight energy steps (upper panel) and a plot of cumulative density of the H ENA population from highest to lowest energies (lower panel). Densities are marked with a black line, and their uncertainties by grey shading. Most of the atoms forming 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.

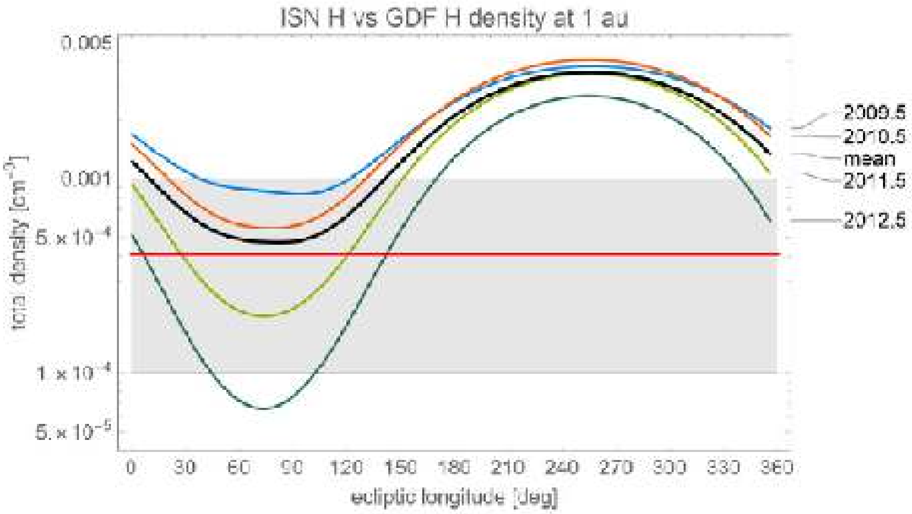


Fig. 29. Comparison of mean ENA density at 1 au (the thick orange line) with the density distribution of ISN H along the Earth orbit, simulated using the WTPM model for four dates in the solar activity cycle. While in the upwind portion of the Earth orbit (ecliptic longitudes 165–345°) the ENA density 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 Astrophysical Journal in a paper by Bzowski & Galli (870:58, 2019, https://doi.org/10.3847/1538-4357/aaf1b2).

(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. 30).

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-favoured cross-section (the

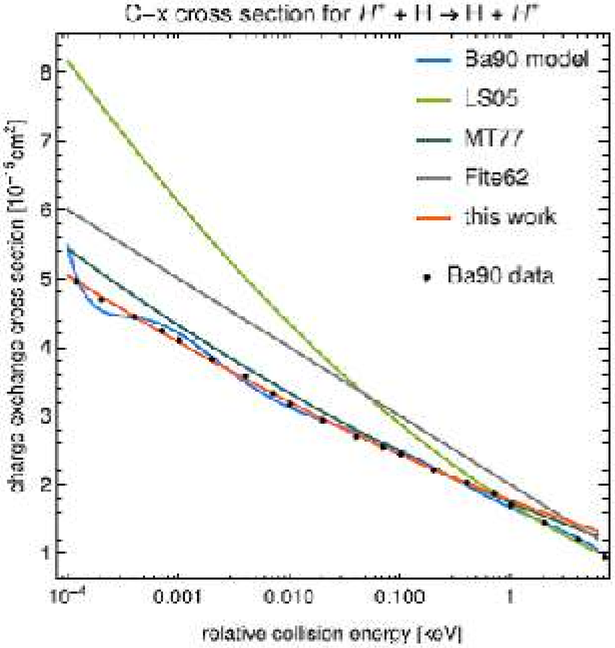


Fig. 30. Measurements of the charge-exchange cross-section between protons and H atoms shown as a function of the kinetic energy of particle collision (black dots), compared with various model formulae. The selected measurement data were chosen based on a review of the literature. Three models are in 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.

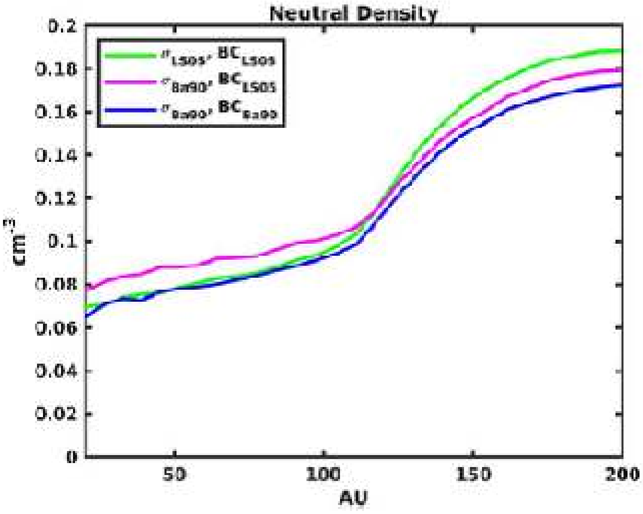


Fig. 31. Comparison of density profiles of neutral H in model heliospheres, simulated assuming two alternative cross-sections for charge exchange (LS05 vs Ba90), and different densities of interstellar plasma. Simulations based on identical plasma densities and different cross-sections are shown by green 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.

green line in Figure 30) 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 31). 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).

Distribution function of neutral helium in the heliospheric boundary region

Interactions between the solar wind and interstellar matter involve, among other processes, charge exchange between interstellar neutral atoms and plasma, which results in the creation of a secondary population of interstellar neutral (ISN) atoms. These secondary atoms are former interstellar ions from the perturbed plasma, flowing around the heliosphere. They inherit the kinematic parameters of their parent ions and move freely across large distances as they are no longer tied to the plasma by electromagnetic forces.

The secondary population of interstellar helium was detected by IBEX. However, the interpretation of these measurements was mostly based on an approximation which assumed that in the outer heliosheath, the primary interstellar neutral atoms and the secondary atoms form two non-interacting homogeneous Maxwell–Boltzmann populations. Although this approximation is incorrect from the fundamental viewpoint, it was able to explain observations with surprising fidelity. LSSPA scientists M. A. Kubiak, M. Bzowski and J. M. Sokół investigated this apparent contradiction and sought to understand the distribution function of interstellar neutral helium in the boundary region of the heliosphere, based on information about the physical state of interstellar matter in this region.

The researchers adopted the global model of the heliosphere used in the study of He^+ density in the VLISM, and simulated the distribution function in the outer heliosheath and inside the heliopause using the method of characteristics. The statistical weights used in this method were obtained from solutions of the production and loss equations for secondary atoms due to charge-exchange collisions in the outer heliosheath. This simulation method was developed by the LSSPA in 2017, and has been successfully used in the determination of He^+ density in the very local interstellar medium (these results are presented in this report).

Results of the simulation, performed using the aforementioned secondary population synthesis method, are shown in Figure 32. The intensity of the secondary population increases when going from the outside to the inside of the outer heliosheath. A left-right asymmetry of the secondary population appears approximately 300 au from the Sun and attains maximum magnitude between 200 and 115 au, where production of the secondary population is most intense. Moving closer to the Sun, inside the heliopause, the distribution function narrows but maintains a certain level of asymmetry, which is a signature of the presence of the secondary population in the sample. At 1 au, the only remaining asymmetry is at the fringe of the distribution function, in qualitative agreement with IBEX observations.

These results were compared with those obtained using the approximation of two Maxwell–Boltzmann populations. The researchers found that the two-Maxwellian approximation for the distribution function of neutral He is poor within the outer heliosheath, but reasonable inside the termination shock. This is due to a strong selection effect: He atoms able to penetrate the termination shock are a small, peculiar subset of the entire secondary He population. Nevertheless, the two-Maxwellian approximation is a good

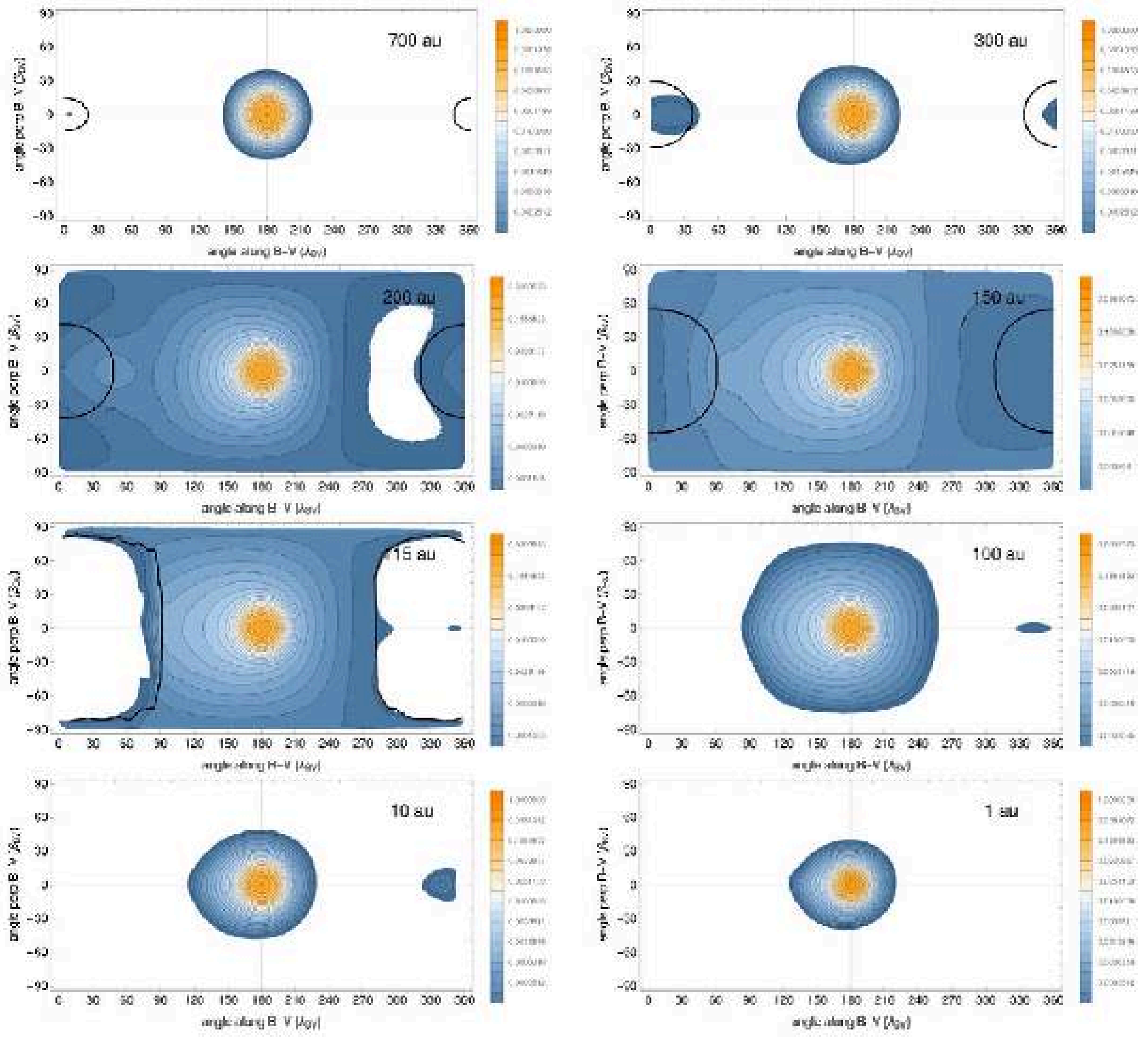


Fig. 32. Maps of the full distribution function of neutral He obtained from simulations for locations distributed along the direction of the Sun's motion through the interstellar medium (i.e., along the so-called upwind line). It starts from 700 au and 300 au, where the He population consists almost solely of primary interstellar atoms, runs through 200, 150 and 115 au, where the production of secondary atoms is most intense, ending at 100, 10 and 1 au from the Sun, where there is no secondary atom production and an increasing effect of ballistic selection is visible. The reference frame is based on the so-called B-V frame. The horizontal axis is the angle off the upwind direction along the plane defined by the upwind direction and the direction of the vector of the unperturbed interstellar magnetic field (the B-V plane). The vertical axis is the elevation angle with respect to this plane. This figure shows full distribution functions of neutral He, integrated over atom speeds and normalised to the peak value at 1000 au. Unperturbed interstellar atoms flow in from the centres of the panels and are represented by yellow disks. Secondary atoms are represented in blue and white. Source: Kubiak et al., Ap. J. 882:114, 2019.

reproduction of the density distribution of ISN He inside the termination shock, and provides a realistic reproduction of the orientation of the plane defined by the Sun's velocity vector through the local interstellar matter and the vector of the unperturbed interstellar magnetic field. Its temperature and velocity parameters, however, are not representative of those of the secondary population in the region where it is produced, or for the plasma in this region.

These conclusions were published in *The Astrophysical Journal* in a paper by Kubiak et al. (882: 114, 2019, https://doi.org/ 10.3847/1538-4357/ ab3462).

(M. Bzowski)

Trajectories of dust particles around stars

The motivation for this work was observations of excessive infrared emission in the vicinity of some stars. One proposed explanation is that the emission comes from small dust grains trapped by the stellar magnetic field. In the case of the Sun, trapped small dust particles (ranging from a few to a few ten nm) was theoretically predicted by A. Czechowski from the LSSPA and I. Mann.

In 2019, this hypothesis was tested. An international team of researchers, including A. Czechowski, applied the theory to the cases of Vega and Fomalhaut. Vega and Fomalhaut are young, hot stars of the A spectral type, with high rotation rates (20–40 times faster than that of the Sun). Theoretical arguments put forward by Czechowski and Mann imply that trapping of nanodust grains around these stars is unlikely, for two reasons. First, for a hot star, the high radiation pressure acting on dust grains overcomes the gravity force. Consequently, the attractive force, which is necessary for trapping, is absent and dust grains cannot be trapped. Second, for a rapidly rotating star, the outer limit of the trapping region contracts, consequently, the hypothetical trapped dust would have to survive the extreme conditions inside the stellar corona. These theoretical suggestions were confirmed by numerical calculations performed using simplified models of the stellar wind and the magnetic field for Vega and Fomalhaut. These conclusions were published in a paper by Stamm et al. in Astronomy & Astrophysics (626, A107, 2019, https://doi.org/ 10.1051/0004-6361/201834727).

An additional chapter in this paper discusses the effect of corotation of the coronal plasma (not included in earlier models developed by Czechowski and Mann) on the process of nanodust trapping. The conclusion is that including plasma corotation in dust trajectory simulations does not affect trapping, provided that the magnetic field and the plasma flow satisfy freezing-in equations. This observation lends credence to earlier conclusions.

(A. Czechowski)

Studies of the intermittent nature of the turbulence in magnetospheric plasma and solar wind out of the ecliptic plane

The solar wind is considered as a natural plasma laboratory to study turbulence and its intermittent nature. One approach uses the multifractal formalism, which is a generalisation of the fractal description and allows us to classify processes and data with a high level of heterogeneity.

Dr Anna Wawrzaszek from the LSSPA, in cooperation with scientists from Belgium and Italy conducted a multifractal analysis of magnetic field measurements obtained by the Ulysses space probe during two solar minima (1997–1998, 2007–2008) and one solar maximum (1999–2001), separately within the fast and slow solar wind regimes. These studies were based on a much larger number of cases than previous research, and showed that outside the ecliptic plane, the degree of multifractality/ intermittency slowly decreases with distance from the Sun (regardless of the component or reference system). The researchers concluded that this radial dependence may be explained by the slower evolution of turbulence outside the ecliptic plane, and the decreased efficiency of intermittency drivers with distance from the Sun. Additionally, the analysis showed that the greatest differences between magnetic field components are found close to the Sun, where intermittency is the strongest. Moreover, it was observed that the slow solar wind during the maximum of solar cycle 23 has a lower level of multifractality (intermittency) than the fast solar wind, which can be related to the idea of the existence of a new type of Alfvénic slow solar wind.

These results were published in The Astrophysical Journal in a paper by Wawrzaszek et al. (876:153, 2019, https://doi.org//10.3847/1538-4357/ab1750).

To better understand the process of hydromagnetic convection in space plasma, Dr Anna Wawrzaszek and a PhD student, Ms Agata Krasińska, performed systematic studies of the dynamics of a four-dimensional generalised Lorenz system. This model, which was proposed in 2010 by other scientists from the LSSPA (W. Macek and M.

Strumik), was supplemented by a fourth variable that described the profile of the magnetic field induced in a convected magnetised fluid. Analytical and numerical analyses of this system were performed in 2019.

They revealed several types of dynamical states, including nondegenerate and subcritical Hopf bifurcation, and forward and backward bifurcation structures (tangent, pitchfork, period-doubling). Moreover, they determined an analytic formula for control parameters at which Hopf bifurcation exists. This advance makes it possible to control the linear stability of the considered system. In particular, the two researchers found that magnetic field control parameters significantly influence the linear stability regime of the generalised Lorenz model. Moreover, the study showed the existence of several windows of non-chaotic variation (windows of order). In particular, period-3 windows were observed, at the edge of which the researchers identified new cases of type I intermittency.

These results were published in a paper in the *International Journal of Bifurcation and Chaos* (29 No 14, 1920042, 2019, https://doi.org/10.1142/S0218127419300428).

(A. Wawrzaszek)