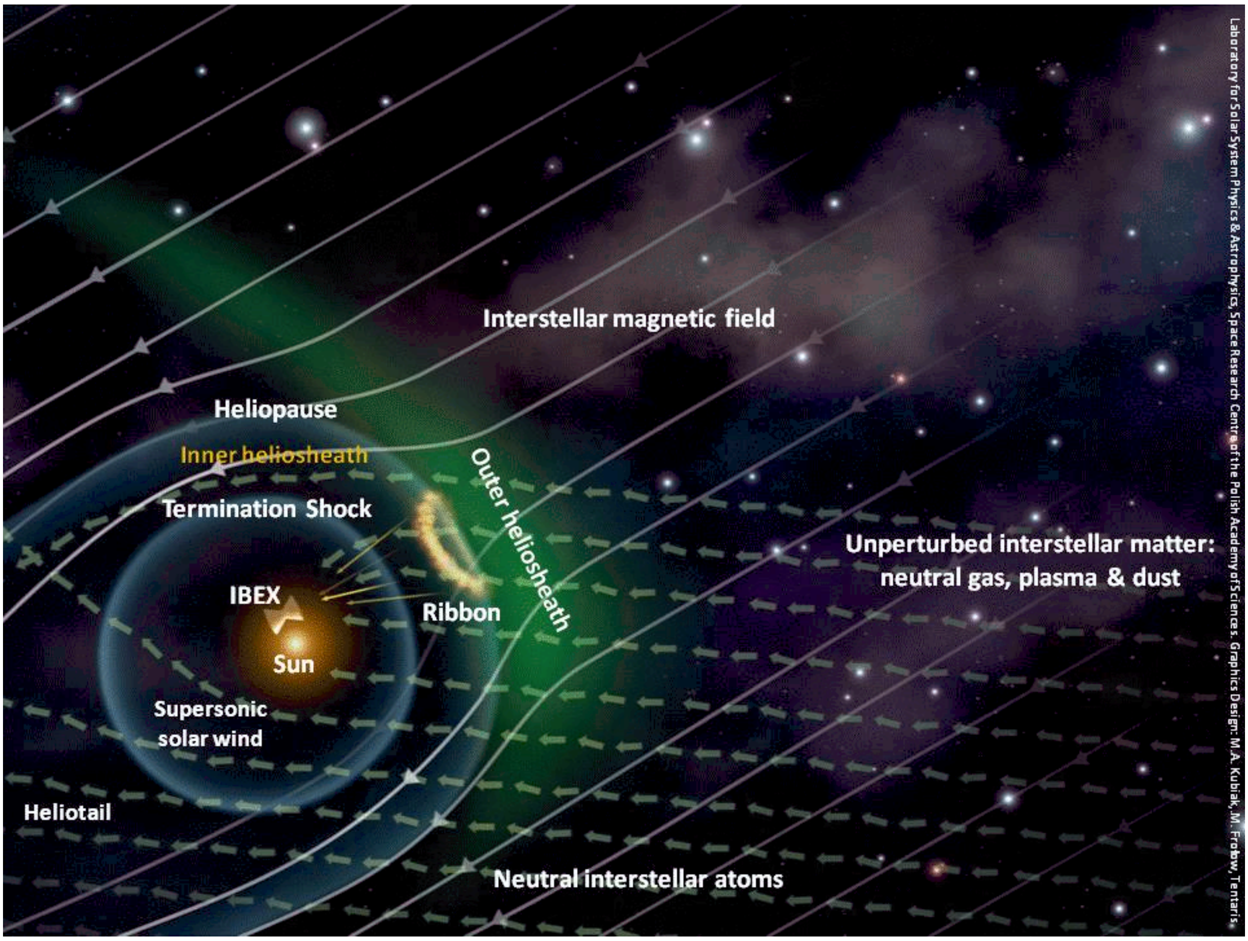
Heliospheric physics

(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 28.



Fig, 28. 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.

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 28, 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 28). 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 28), 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 28, schematically drawn close to the Sun).

Neutral atoms from the interstellar matter (whose streamlines are marked by the short arrows in Figure 28) 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 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. The Centrum Badań Kosmicznych 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.

The heliosphere is not round!

The solar wind expansion stops at a certain distance to the Sun. This happens in the locations where the solar wind pressure becomes equal to the pressure of the interstellar matter. The solar wind matter cannot accumulate infinitely inside the heliosphere and must find an exit path to the interstellar space. But where exactly is this path located? And is there just one evacuation path or more? These questions cannot be answered directly because up to now there have been just two active space probes – Voyager 1 and 2 – to reach the boundary regions of the heliosphere, and this happened in the regions least suspect of being anywhere close to the solar wind evacuation path. Therefore, the question of solar wind exhaust location can only be answered by means of remote-sensing measurements and theoretical modelling.

The laws of physics suggest that the shape of the heliosphere depends on the speed of the Sun's motion through the interstellar gas, the density of this cloud, the intensity and direction of the interstellar magnetic field, as well as the spatial distribution of the total pressure of the solar wind. The key factor is the pressure balance between the solar wind and interstellar matter. The interstellar magnetic field exerts a certain stress force on the heliosphere, which can be conveniently represented as an additional pressure term known as the magnetic pressure. The magnitude of this pressure is proportional to the square of the strength of the component of the magnetic field vector perpendicular to the heliopause.

The ram pressure of the ionized component of interstellar matter is proportional to the total density of the interstellar plasma and to the square of Sun's speed relative to the surrounding interstellar plasma. If the interstellar magnetic field is so strong that the magnetic pressure is much larger than the ram pressure of the interstellar plasma, then the heliosphere is expected to be approximately spherical in shape, and the solar wind is evacuated via two channels parallel to the direction of the local interstellar magnetic field. If, however, the ram pressure is much larger than the magnetic pressure, then the heliosphere will take an elongated, comet-like shape (somewhat distorted from axial symmetry by the magnetic pressure), and the solar wind will be evacuated via one channel directed 'back-wards', i.e., along a long tail pointing approximately opposite to the Sun's motion. An extensive study on the shape of the heliosphere for various combinations of the ram and magnetic pressures was published in 2018 by two scientists from LSSPA team: Professor Andrzej Czechowski and Jolanta Grygorczuk Msc.

Based on available extensive insights from experimental and modelling studies using various measurement techniques, it had been concluded that most likely, the interstellar dynamic pressure is much larger than the magnetic pressure, and consequently the heliosphere has a comet-like form. However, in 2017, a team of US scientists published a hypothesis that the heliosphere is round in shape (in *Nature Astronomy*). They considered measurements of the flux of energetic neutral atoms (ENAs) with energies of several dozen keV (an order of magnitude larger than typical energies of solar wind protons), performed by the INCA instrument onboard the Cassini space probe. They found that: (1) variations in time of the flux are unexpectedly rapid; (2) they are strongly correlated with each other, with the phase of the 11-year cycle of solar activity, and with time variations of *in situ* point measurements of energetic ions in the outer heliosheath (the parent population for ENAs observed by INCA); and (3) the fluxes of these ENAs from the upwind and downwind sides of the heliosphere have similar magnitudes, and their variations are correlated in time. On this basis, the team of US researchers concluded that the distances to, and the dimensions of, the source region of these ENAs must be very similar for all directions. Consequently, the heliosphere must be approximately round and, if so, then it must be shaped by a strong interstellar magnetic field.

This hypothesis is at odds with previous views on the shape of the heliosphere because the strength of the interstellar magnetic field, the plasma density, and the speed of Sun's motion through the Local Interstellar Medium have been measured with a sufficiently good accuracy and suggest that interstellar magnetic pressure is lower than the plasma ram pressure. However, the INCA observations used by the aforementioned team of scientists are an enigma that must not be ignored. Professor Nathan Schwadron from the University of New Hampshire and Professor Maciej Bzowski from the LSSPA suggested that the INCA observations can be understood based on the conventional, comet-like paradigm of the heliosphere. In a paper published in *The Astrophysical Journal* (http://iopscience.iop.org/ article/10.3847/1538-4357/aacbcf) they suggested some reasons for the correlation between observed fluctuations of INCA ENAs, fluctuations of the charged particles observed by Voyager, and the phase of solar activity.

Schwadron and Bzowski pointed out that the ENA fluctuations are related to the ENA production rate, which is strongly dependent on fluctuations in the temperature and density of the solar wind plasma penetrating the solar wind termination shock. This is a quasi-stationary shock wave structure that separates the hypersonic and subsonic regimes of the solar wind outflow. When a portion of plasma with an increased density and speed crosses the termination shock, the plasma just downstream of the termination shock is heated and, before cooling, for some time propagates with the plasma flow in the inner heliosheath. The temperature of such plasma flow is much larger than that of the shock-processed 'regular' solar wind plasma. Therefore, the charge exchange rate between protons in the heated plasma and the ambient interstellar neutral H atoms increases rapidly and, consequently, an enhanced flux of ENAs is produced for a certain time before the heat dissipates. Since the occurrence of fast and dense gusts of the solar wind increases during high solar activity and, on the one hand, thesegusts have a global range and, on the other hand, the difference in arrival times between various locations along the shock is relatively small (a few months) a strong spatial correlation eventually appears between time fluctuations of the ENA flux from various regions of the termination shock, and a time correlation between the charged energetic particles processed by the termination shock, measured by the Voyagers, and the ENA fluxes from the heliosheath, measured (with a well-understood time delay) by INCA.

Consequently, the seemingly strange observations reported by the team of US researchers can be explained on the basis of the conventional heliospheric paradigm and the heliosphere, which, as the title of Schwadron and Bzowski's paper claims, is not round!

Conclusions from ENA observations from the HSTOF: The heliosphere has a tail and is asymmetrical

Since the speed and direction of motion of heliospheric ENAs reflect the speed and direction of motion of their parent ions, ENA observations offer a good insight into the energy distribution of cosmic plasma located far away from the observation site.

The High energy Suprathermal Time Of Flight sensor (HSTOF) instrument onboard the Solar and Heliospheric Observatory (SOHO) space probe has been carrying out ENA observations since 1996. The instrument is sensitive to ENAs with energies from 55 to 88 kiloelectronvolts (keV), i.e., to atoms traveling at 3250 to 4100 km/s. Other instruments observing ENAs (in different energy bands) include INCA, onboard the Cassini Saturn probe (observations between 2005–2013), the ASPERA instruments onboard the planetary probes Mars Express and Venus Express (also presently inactive), and the IBEX satellite (carrying out observations from 2009 until present).

The implications of HSTOF observations carried out from 1996 to 2010 were studied by a team of scientists from LSSPA: Professors Andrzej Czechowski, Maciej Bzowski, and Stanisław Grzędzielski, Dr Justyna M. Sokół and Jolanta Grygorczuk MSc., in collaboration with Professor K.C. Hsieh from the University of Alabama, who formulated the concept of the HSTOF experiment and Dr M. Hilchenbach from the Max-Planck-Institut für Sonnensystemforschung in Göttingen, Germany, who processed the data. The researchers found a clear downward trend in observed ENA intensities, which seems to be correlated with the secular systematic decrease in the solar wind flux observed *in situ* at the Earth's orbit, but not with periodic variation in the solar wind related to the solar activity cycle. A similar downward trend in ENA observations was found by INCA and IBEX. The correlation of the ENA flux with the solar wind flux supports the hypothesis that observed ENAs originate from the aforementioned charge exchange reactions between protons from the shocked solar wind plasma and interstellar hydrogen atoms in the boundary regions of the heliosphere.

Furthermore, these observations corroborate the hypothesis that the heliosphere's axial symmetry is distorted due to the action of the interstellar magnetic field. This is because the observed ENA flux in the "starboard flank" (ecliptic longitudes from 120° to 210°) is larger than the flux from the "portside flank" (ecliptic longitudes from 300° to 30°). The observed asymmetry is in agreement with recent estimates of the direction of interstellar magnetic field.

Finally, HSTOF observations lend strong support to the existence of the heliospheric tail: the flux observed from the upwind region of the heliosphere, i.e., from the direction of Sun's motion through the local interstellar matter, is much lower than the flux from the opposite direction. This behavior is expected if the heliosphere has a long tail. The upwind to downwind ratio of the ENA fluxes observed by HSTOF differs from the ratios observed by INCA and IBEX. Researchers from the demonstrated that this difference is a natural consequence of the larger energies observed by IBEX: 55 to 88 keV in comparison with 5 to 55 keV observed by INCA and 0.7 to 4.3 keV observed by IBEX, and the resultant difference in reaction cross sections. This result is another confirmation that "The heliosphere is not round!".

In addition to the data from the HSTOF, the research team used results of earlier determinations of the densities of interstellar hydrogen and helium at the termination shock of the solar wind, based on data from the Voyager and Ulysses spacecraft, with an important contribution from scientists from LSSPA as well as the Warsaw Test Particle Model of the density distribution of interstellar H and He in the heliosphere developed in LSSPA, and the Warsaw MHD model of the heliosphere.

The results and conclusions were presented by the team led by Professor A. Czechowski in a paper published in Astronomy & Astrophysics (https://www.aanda.org/articles/aa/abs/2018/10/aa32432-17/aa32432-17.html).

Interstellar neutral helium atoms observed in three IBEX-Lo energy channels

Interstellar neutral atoms of helium from the Local Inter-stellar Medium are observed by the Interstellar Boundary Explorer (IBEX) spacecraft in the Earth orbit. Researchers from LSSPA, Dr Paweł Swaczyna, Professor M. Bzowski, Marzena A. Kubiak MSc, Dr Justyna M. Sokół, and their international collaborators analysed these observations to determine the Sun's motion with respect to the Local Interstellar Medium and the temperature of this medium. From a broader perspective, the results of these analyses provide an important insight into how the heliosphere interacts with its surroundings. In a paper published in The Astrophysical Journal (https://doi.org/10.3847/1538-4357/aaabbf), they analysed data from two energy channels of the IBEX-Lo detector previously not used, in addition to the data from the channel previously used, and obtained a better assessment of these quantities.

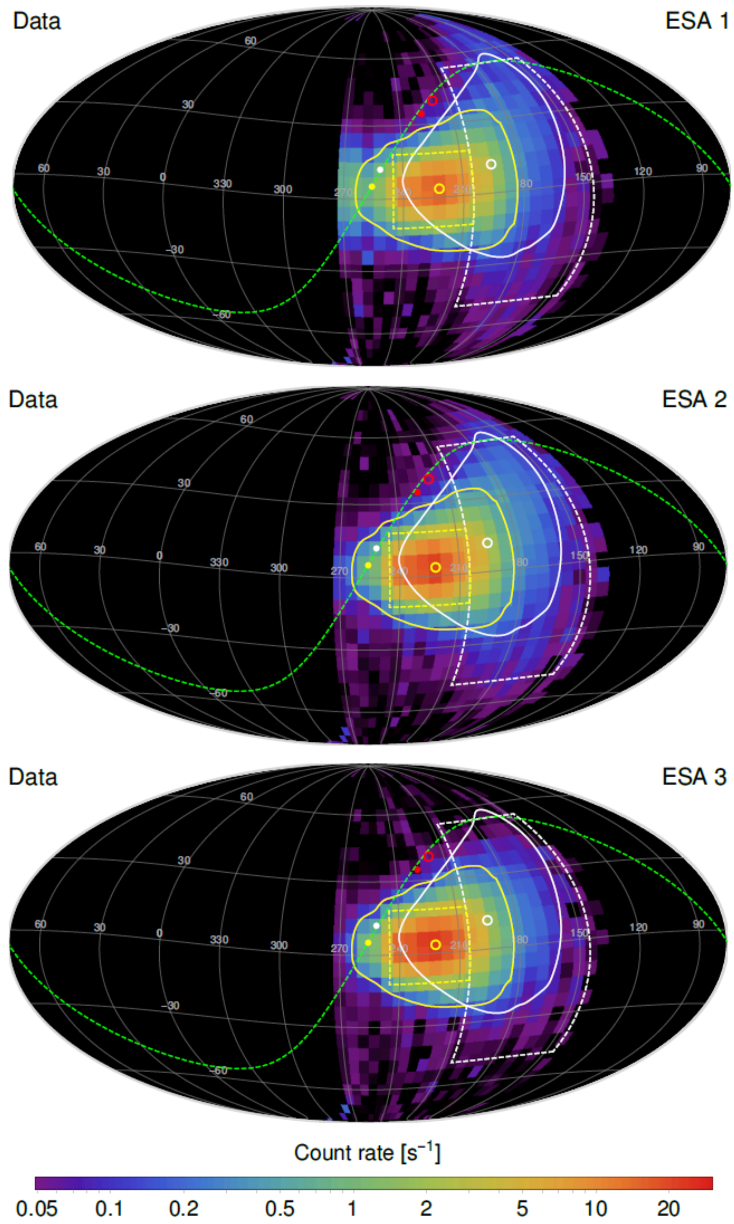
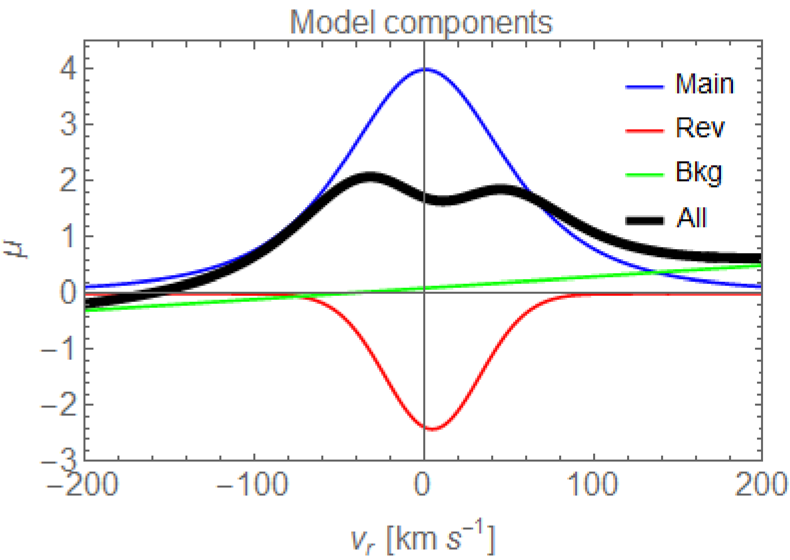


Fig. 29. Sky maps of counting rates of interstellar neutral atoms observed by IBEX in the analysed energy channels. The maps are centered at the direction of the Sun's motion with respect to the interstellar medium. Atoms are deflected by the Sun's gravity and thus observed predominantly away from this direction. Differences between observed counting rates in these energy channels are caused by the contribution of hydrogen atoms (not considered in this analysis) and the different energy-dependent sensitivities of the IBEX-Lo detector in these channels.

The structure of the interstellar medium at scales of tens and hundreds of parsecs around the Sun is not homogeneous. The Sun is within a system of multiple, partially-ionized, warm (5000–8000 K) and dense (~0.2 cm^{-3}) clouds, embedded in a very hot (~10^{6} K), completely ionized and rarefied (~0.005 cm^{-3}) region. Telescopic observations of the absorption lines towards the closest stars show that the Sun is located either in one of two clouds known as the Local Interstellar Cloud and G Cloud, or − more likely − in a boundary region between them. However, the ultimate determination is not possible from telescopic observations. The results of the IBEX mission may make it possible to resolve this enigma and answer the question of how conditions in the interstellar medium along the Sun's path will change during forthcoming millennia.

Previously, only data from one of the energy channels of the IBEX-Lo detector had been used in the analysis of the local interstellar gas. This was due to limited knowledge of the sensitivity of the detector to incoming atoms with various velocities (i.e., with various kinetic energies). As a first approximation, the energy channel that had been used in previous analyses was assumed to have a sensitivity independent of the atom energy. In this study, scientists from LSSPA analysed observations from the three energy channels of the IBEX-Lo detector in which interstellar neutral helium is visible, and abandoned the assumption of uniform energy sensitivity. The analysis aimed to determine the temperature and velocity vector of interstellar neutral helium simultaneously with the determination of the velocity-dependent sensitivity. Researchers found that the previously-obtained parameters of the interstellar medium did not need revision. This is important because this analysis lends more credence to earlier analyses of interstellar neutral gas and its secondary component, the so-called Warm Breeze, and to conclusions stemming from these analyses concerning the orientation of the interstellar magnetic field.

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



Fig, 30. 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-a 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-a line and its evolution during the cycle of solar activity.

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, Professor Maciej Bzowski, 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 30 (the main line – blue line, the self-reversal in the centre – 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 31, 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* (http:// iopscience.iop.org/article/10.3847/1538-4357/aa9f2a).

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 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,

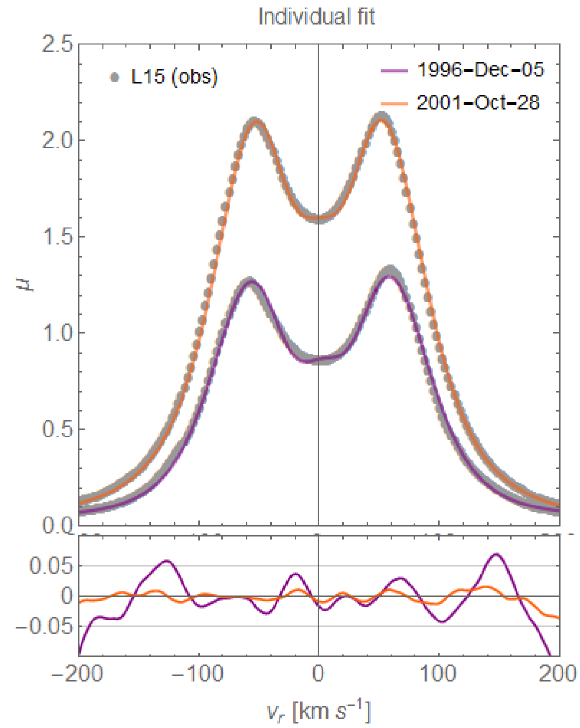


Fig. 31. Example solar Lyman-α line profiles obtained from the newly-developed model for the solar maximum (orange) and solar minimum epochs (purple). The bottom panel presents relative differences between model predictions and actually-measured profiles.

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.

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.

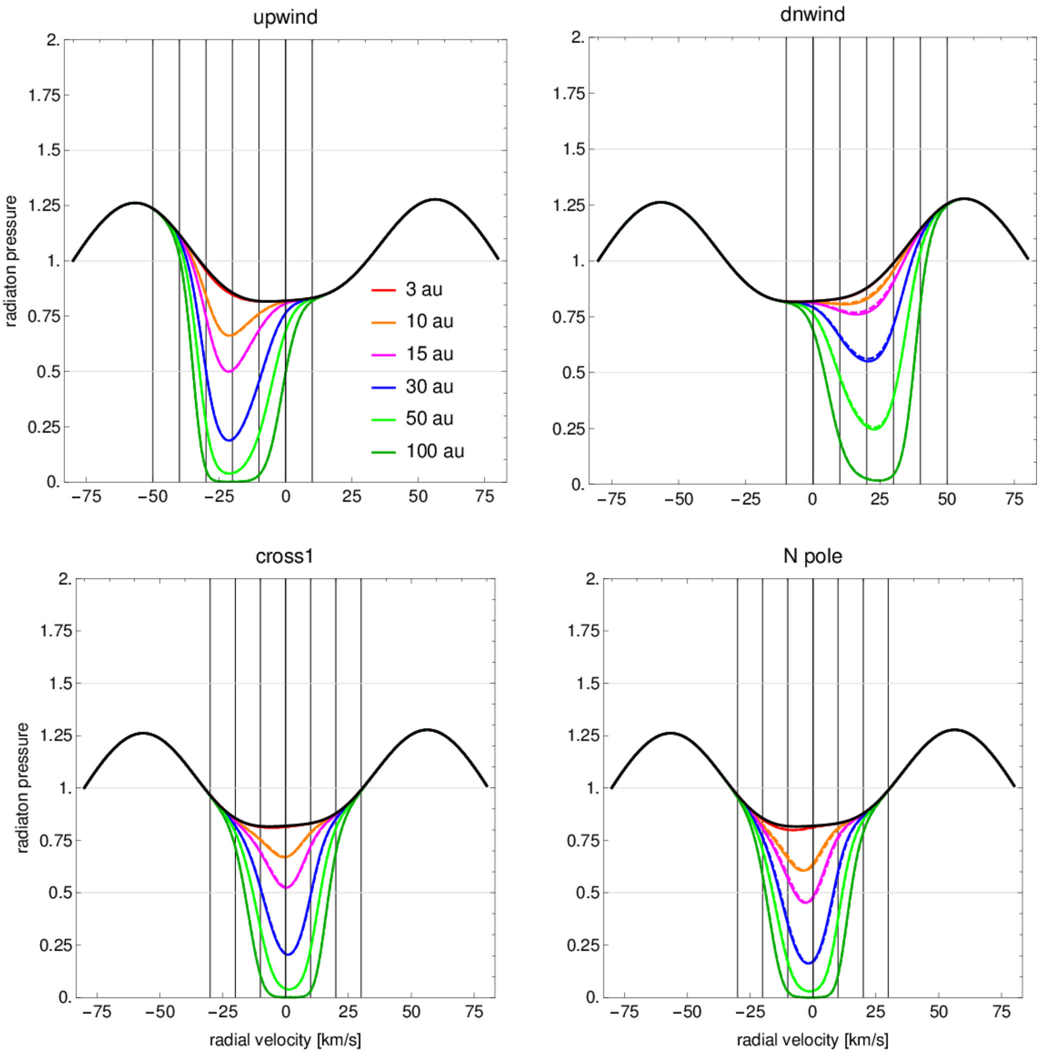


Fig. 32. Evolution of effective radiation pressure (expressed in units of solar gravity force) acting on hydrogen atoms in the heliosphere with distance from the Sun. Absorption of solar photons that are responsible for radiation pressure results in a gradual decrease of the effective spectral flux from 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 results of this analysis were presented by the team lead by Dr Izabela Kowalska-Leszczyńska in a paper published *The Astrophysical Journal* (http://iopscience.iop.org/article/10.3847/1538-4357/aae70b).

Magnetic waves excited by newborn interstellar pickup ions measured by the Voyager spacecraft up to Pluto's orbit

New ions in the solar wind are created by ionization of interstellar atoms that penetrate inside the heliosphere. They are called pickup ions because immediately after creation they are "picked up" by the Lorentz force from the magnetic field "frozen" in the solar wind and advected with the solar wind into the interplanetary space. Pickup ions gyrate in the magnetic field, producing characteristic magnetic waves. These waves can be detected via careful analysis of time series of the intensity and direction of the magnetic field, observed by the interplanetary probes.

Magnetic waves produced by ion pickup have characteristic signatures in observed time series of interplanetary magnetic field, and are different for each of the pickup ion species. However, these signatures can be detected only when the growth rate of the wave is greater than the turbulence level of the solar wind. Searching for wave-growth events is challenging, but very important, because it enables models of the distribution of neutral gas in the heliosphere, and the pickup ion creation processes in the solar wind magnetic field to be verified. The growth rate of magnetic waves depends, among other things, on the production rate of pickup ions. This rate is directly proportional to the density of the interstellar neutral gas in the interplanetary space, and ionization rates, which vary both temporally and spatially with heliographic latitude. The spatial distribution of interstellar neutral hydrogen and helium densities, and the rates of their ionization are totally different and, consequently, the resulting pickup ion production rates are significantly different. For solar distances smaller than three astronomical units, the production rate for helium pickup ions is much greater than that for hydrogen ions. Consequently, we can expect to find more magnetic wave events characteristic of the creation of helium than hydrogen pickup ions. Beyond 3 au, more hydrogen pickup ions are produced.

Magnetic waves excited by newborn interstellar pickup ions are observed within the supersonic solar wind from a few tenths to several dozens of astronomical units from the Sun. They were detected by instruments on the ACE (at 1 au) and Ulysses missions (from 1 to 5 au). Very important data were gathered by the Voyager spacecraft between 1 and 45 au. A team of researchers from the University of New Hampshire studied magnetic field data from Voyager 1 and Voyager 2 missions collected in the period from 1997 to 1990, and identified more than 600 events associated with magnetic waves excited by newly-born interstellar pickup ions, both helium and hydrogen.

Scientists from LSSPA (Dr Justyna M. Sokół, Professor Maciej Bzowski, and Marzena A. Kubiak MSc) studied pickup ion production rates for interstellar hydrogen and helium using the Warsaw Test Particle Model simulation code, models of the solar wind evolution in time and heliographic latitude, and solar wind extreme ultraviolet ionizing radiation. These research tools, developed by the team from LSSPA, were employed to calculate the distribution of interstellar neutral hydrogen and helium gas inside the heliosphere and production rates for pickup ions along Voyager 1 & 2 trajectories. The results of these studies were applied by the team at the University of New Hampshire in their research on magnetic wave creation. The study showed that magnetic waves due to pickup ions can be excited as far from the Sun as Pluto's orbit and beyond, i.e., up to 45 au from the Sun. Both teams of researchers found good agreement between the model's predictions and observed rates of magnetic waves due to pickup ion creation.

The results of the study were published in a series of three articles by Hollick et al. in The Astrophysical Journal and The Astrophysical Journal Supplement. The articles are available at: http://iopscience.iop.org/article/10.3847/1538-4357/aac83b, http://iopscience.iop.org/article/10.3847/1538-4357/aac839, http://iopscience.iop.org/article/10.3847/1538-4365/aac83a.

A corridor to the Sun for select nanodust particles

The smallest dust grains in the circumsolar dust cloud are nanodust particles, i.e., dust grains with sizes of a few, to a few ten millionth parts of a millimeter. They are so small they only include a few dozens of thousands of atoms. Like all dust grains in the Solar System, they are electrically charged, and their high charge to mass ratio makes the Lorentz force from the magnetic field in the solar wind similar in strength to the solar gravity force, or even larger. Therefore, the motion of nanodust grains significantly differs from the motion of typical dust grains, which resembles the motion of asteroids.

Nanodust is predominantly produced by collisional fragmentation of larger dust particles. Initial velocities of particles produced by this mechanism are close to the orbital velocities of their parent dust grains. The newly-created dust grains quickly become electrically charged, are picked up by the solar magnetic field, frozen in the solar wind, accelerated to velocities comparable to that of solar wind, and move away from the Sun. However, particles that are created sufficiently close to the Sun become "trapped" in bound orbits around it, due to an interplay between solar gravity and magnetic forces. Therefore, it is likely that a population of trapped nanodust particles is present in the vicinity of the Sun.

Another hypothetical source of nanodust is comets and, in particular, sungrazing comets. Such comets have perihelia deep inside Mercury's orbit and aphelia somewhere between the orbits of Mars and Jupiter. The initial velocities of nanodust particles released by these comets shortly before perihelion are much larger than those of collisional nanodust particles. If the release of a nanodust particle occurs inside the Mercury orbit, its speed may be comparable to that of the solar wind, but in the opposite direction. Therefore, it is expected that the orbital dynamics of these nanodust particles are different to those of collisional nanodust grains. This topic was investigated by Professor Andrzej Czechowski from LSSPA and Professor Ingrid Mann from the Arctic University of Norway in Tromsø, Norway, who created a particle motion model.

Based on numerical simulations of the forces acting on nanodust particles, Czechowski and Mann concluded that unlike "regular" nanodust particles, particles from sungrazing comets cannot be trapped close to the Sun, even those released very close to the Sun. Therefore, sungrazing comets are unlikely to be an additional source of the trapped nanodust population. However, the two researchers identified an interesting phenomenon that they called a "corridor to the Sun".

Some nanodust grains, released in the inbound leg of the comet orbit, can enter peculiar trajectories leading them deep into the solar corona, i.e., the upper, hot part of the solar atmosphere, visible from Earth during solar eclipses. Due to electromagnetic forces, these grains approach the Sun at a distance much closer than the perihelion of the parent comet, which may lead to destruction of nanodust grains by sublimation or collisions with ions. Most nanodust grains are, however, picked up by the solar wind and ultimately escape the Sun.

The results of this study were presented in a paper published by Czechowski & Mann in *Astronomy & Astrophysics*, available at https://www.aanda.org/articles/aa/abs/2018/09/aa32922-18/aa32922-18.html.

Exact solutions and singularities of an X-point collapse in Hall magnetohydrodynamics

Magnetic reconnection is a topological rearrangement of the global magnetic field. It is believed to be responsible for fast conversions of magnetic field energy into other energy forms, like kinetic energy of the plasma flow, as well as thermal and radiation energies. Despite multiple, decades-long attempts to fully understand how some basic concepts can explain the overall picture of plasma dynamics in various environments, like the solar corona, the Earth's magnetosphere, relativistic astrophysical plasmas, or tokamak physics, the most fundamental questions have remained poorly understood, and magnetic reconnection continues to be one of the most challenging problems in plasma physics.

One of the many challenging aspects of magnetic reconnection is the question of its onset. Long ago, Dungey argued that neutral X-points in the magnetic field are unstable and collapse into thin, elongated regions of significantly-increased resistivity, called current sheets. In principle, the formation of current sheets requires a kinetic description of the process. Nonetheless, an acceptable understanding has been obtained using an appropriate magnetohydrodynamical approach. Various plasma fluid approximations have facilitated our understanding of the specific physical phenomena involved in the formation of current sheets. One of them is Hall magnetohydrodynamics (MHD), which is a monofluid approximation of a two-fluid description of plasmas that is much more detailed than more frequently-exploited ideal or resistive magnetohydrodynamics. In Hall magnetohydrodynamics, unlike classical magnetohydrodynamics, resistivity is non-zero; the magnetic field becomes fro-zen in the electron fluid, rather than the bulk plasma flow, and dispersive whistler waves appear due to the Hall effect. Such a theory is useful in the solar corona as well as in the Earth's magnetosphere.

To reduce the complexity of the global dynamics of magnetic collapse, Artur Janda MSc from LSSPA hypothesised a specific, self-similar structure for the magnetic field and incompressible plasma flow. Having reduced the Hall MHD equations for the case of an X-point collapse, and using an appropriate ansatz, he obtained a definition of a dynamic system that could be solved in terms of elliptic functions. He found that there are two possible classes of solutions. One consists of periodic regular solutions, and the other includes singular solutions. Surprisingly, it turned out that singular solutions are more physically relevant, because regular ones exhibit a superalfvenic plasma flow. An exact formula, based on initial conditions at the time when singularities form, was found. These results were published in a paper by Janda in the *Journal of Mathematical Physics* (https://doi.org/10.1063/ 1.5026876).

Exact solutions within Hall MHD are very rare. The solution obtained by Artur Janda seems to be the only one in the literature that is singular. It is very important to identify its physical meaning. Although self-similarity has to break down at a certain point, shock waves accompanying the current sheet are expected to appear. Moreover, intuitively, from the physical point of view, the emerging resistivity is unlikely to be homogeneous, and it can be expected that the reconnection rate will explosively increase. This picture seems to be complementary to the well-known secondary tearing instability of elongated current sheets, the so-called plasmoid instability that leads to the acceleration of magnetic reconnection.

The exact solutions found by Artur Janda are a convenient tool to derive appropriate initial conditions, leading generically to the formation of singularities, which in general is a challenging mathematical task. Another interesting task would be to extend this class of solutions to nonlinear magnetosonic waves forming singularities. Such solutions would clarify the outstanding problem of the heating of the solar corona.

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