Annual Report 2013: Heliospheric physics[1]

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Studies of the Galactic neighborhood of the Sun

The journey of the Sun through the dynamically active local interstellar medium creates an evolving heliosphere environment. This motion drives a wind of interstellar material through the heliosphere that has been measured with Earth-orbiting and interplanetary spacecraft for 40 years. Recent results obtained by NASA's Interstellar Boundary Explorer mission during 2009 – 2010 suggest that neutral interstellar atoms flow into the solar system from a different direction than found previously. These prior measurements represent data collected from Ulysses and other spacecraft during 1992 – 2002 and a variety of older measurements acquired during 1972 – 1978. Consideration of all data types and their published results and uncertainties, over the three epochs of observations, indicates that the trend for the interstellar flow ecliptic longitude to increase with time is statistically significant. There is no obvious bias in the data that would explain the longitude trend, although possibly some uncertainties were underestimated. The variation in the interstellar wind longitude indicated by these historical data may be evidence for variations in the galactic environment of the solar system. These conclusions were published in the *Science* magazine by an international team of scientists led by P.C. Frisch, including M. Bzowski and J.M. Sokół from SRC PAS.

A new diagnosis of two different states of the local interstellar medium (LISM) near our solar system, in the form of a sensitivity study constrained by several distinct and complementary observations of the LISM, solar wind, and inner heliosphere, was carried out. Assuming the *Interstellar Boundary Explorer* (*IBEX*) He flow parameters for the LISM, the strength of the interstellar magnetic field in the Local Cloud equal to $\sim 2.7 \pm 0.2\ \mu G$ and the direction pointing away from the galactic coordinates (longituide, latitude) = (28°, 52°) ± 3° was found based on fitting the *Voyager 1* and *Voyager 2* in situ plasma measurements and the *IBEX* energetic neutral atoms ribbon. When using the *Ulysses* parameters for the LISM He flow, the same field direction, but a lower strength of 2.2 ± 0.1 μG was recently reported. It was pointed out that that with the *Ulysses* He flow, the solution obtained is in the expected hydrogen deflection plane (HDP). In contrast, for the *IBEX* He flow, the solution is ~20° away from the corresponding HDP plane. Second, the long-term monitoring of the interplanetary He flow speed shows a value of ~26 km s^{-1} measured in the upwind direction using the Doppler shift in the strong Lyα sky background emission line. All elements of the diagnosis seem therefore to support the *Ulysses* He flow parameters for the interstellar state. Based on these findings it was concluded that reliable discrimination between superfast, subfast, or superslow states of the interstellar flow should be based on in situ and remote observations carried out using various techniques and analyzed together with global modeling of the heliosphere. For the commonly accepted LISM ionization rates, a fast interstellar bow shock should be present upstream of the heliopause. These findings were published in *The Astrophysical Journal* by L. Ben Jaffel from Astrophysics Institute in Paris and R. Ratkiewicz, M. Strumik, and J. Grygorczuk from SRC PAS.

Studies of the distant heliosphere by in situ and remote-sensing observations

A new high-resolution 2.5-D numerical MHD model of the plasma at the heliospheric boundary was developed. Using this model, processes related to magnetic reconnection and plasma turbulence occurring in the presence of the heliopause (HP) and the heliospheric current sheet were studied. It was shown that

[1] Excerpt from the Annual Report 2013 of the Space Research Centre PAS, adapted from abstracts of papers authored or co-authored by members of the Lab personnel. The full list of papers published in 2013 by the members of the Lab is available at http://pfusia.cbk.waw.pl/files/pfusiaPubl.2013.html.

the interaction of plasmoids initiated by magnetic reconnection may provide connections between the inner and outer heliosheath and lead to an exchange of particles between the interstellar medium and the solar wind plasma previously shocked during the passage through the heliospheric termination shock (see Fig. 1). The magnetic reconnection may also cause plasma density and magnetic field compressions in the proximity of the HP. It was argued that these phenomena could possibly be detected by the *Voyager* spacecraft approaching and crossing the HP. These results seem to clarify the concepts of the "magnetic highway" and the "heliosheath depletion region" recently proposed to explain recent *Voyager 1* observations. The modeling results strongly support the hypothesis that the spacecraft has crossed the heliopause and is currently in the outer heliosheath. These conclusions were published in *The Astrophysical Journal Letters* by a team of SRC PAS scientists led by M. Strumik and including A. Czechowski, S. Grzędzielski, W.M. Macek, and R. Ratkiewicz.

A study of expected signal from neutral energetic He atoms under various heliospheric scenarios was performed to check prospects for using He ENA as heliospheric information carriers. To that end, a model of heliosheath density and energy spectra of α-particles and He^+ ions carried by the solar wind was developed. Neutralization of heliosheath He ions, mainly by charge exchange with neutral interstellar H and He atoms, was calculated to give rise to ~0.2 – ~100 keV fluxes of energetic neutral He atoms (He ENA). Such fluxes, if observed, would give information about plasmas in the heliosheath and heliospheric tail. Helium ions after crossing the termination shock constitute suprathermal test particles, convected by hydrodynamically calculated background plasma flows. Locally, these test particles undergo some diffusion. Three versions of flows were employed. The He ions proceed from the TS towards the heliopause and finally to the heliospheric tail. Calculations of the evolution of α- and He+ particle densities and energy spectra include binary interactions with background plasma and interstellar atoms (radiative and dielectronic recombinations, single and double charge exchange, stripping, photoionization and impact ionizations), adiabatic heating (cooling) resulting from flow compression (rarefaction), and Coulomb scattering on background plasma. It was found that neutralization of suprathermal He ions leads to the emergence of He ENA fluxes with energy spectra modified by the Compton-Getting effect at emission and ENA loss during flight to the Sun. Energy-integrated He ENA intensities are in the range ~0.05 – ~50 cm^{-2} s^{-1} sr^{-1} depending on spectra at the termination shock (assumed kappa-distributions), background plasma model, and look direction. The tail/apex intensity ratio varies between ~1.8 and ~800, depending on model assumptions. Energy spectra are broad with maxima in the ~0.2 – ~3 keV range, depending on the look direction and model. It was concluded that expected heliosheath He ENA fluxes may be measurable based on the capabilities of the *IBEX* spacecraft. Data could offer insight into the heliosheath structure and improve understanding of the post-termination shock solar wind plasmas. The heliotail direction and extent could be assessed. These results were published in *Astronomy & Astrophysics* by S. Grzędzielski, P. Swaczyna, and M. Bzowski.

The signal of non-planetary energetic neutral atoms (ENAs) in the 0.4–5.0 keV range, measured with the Neutral Particle Detector (NPD) of the *ASPERA-3* and *ASPERA-4* experiments on board the *Mars* and *Venus Express* satellites, was reanalyzed. Owing to improvements in the knowledge of the sensor characteristics and exclusion of data sets affected by instrument effects, the typical intensity of the ENA signal obtained by *ASPERA-3* turned out to be an order of magnitude lower than in earlier reports. The ENA intensities measured with *ASPERA-3* and *ASPERA-4* now agree with each other. In the present analysis, we also correct the ENA signal for the Compton–Getting effect and for ionization loss processes under the assumption of the heliospheric origin of the signal. We find spectral shapes and intensities consistent with those measured by the *Interstellar Boundary Explorer* (*IBEX*). The principal advantage of *ASPERA* with respect to the *IBEX* sensors is the two-fold better spectral resolution. These observations are the only independent test of the heliospheric ENA signal measured with *IBEX* in this energy range. The

ASPERA measurements also allow to check for a temporal variation of the heliospheric signal as they were obtained between 2003 and 2007, whereas *IBEX* has been operational since the end of 2008. The results were published in *The Astrophysical Journal* by an international team of scientists led by A. Galli from the University of Bern, Switzerland, including M. Bzowski, J.M. Sokół, and M.A. Kubiak.

Studies of neutral interstellar gas

The interaction of the local interstellar medium with the solar wind shapes our heliospheric environment. Hydrogen is the dominant component of the very local ISM. The H distribution observed at 1 AU is expected to be different from that outside the heliopause due to ionization, photon pressure, gravity, and filtration by interactions with heliospheric plasma populations. Interstellar hydrogen atoms move along trajectories that are quite different than those of heavier interstellar species such as helium and oxygen, which experience practically vanishing radiation pressure. Thus, a variation of the observed flux as a function of solar activity level is expected. Analysis of interstellar hydrogen sampled in situ by *IBEX* during the first four years of the mission was carried out and indeed, the hydrogen wind observed at 1 AU has decreased and nearly disappeared as the solar activity has increased over the last four years; the signal at 1 AU has dropped off in 2012 by a factor of ~8 to near background levels. The longitudinal offset of the observed inflow direction from the flow direction in the interstellar medium has also increased with time, presumably due to greater radiation pressure deflecting the interstellar wind. These observations provide an important benchmark for modeling of the global heliospheric interaction. They were published in *The Astrophysical Journal* by a team of *IBEX* researchers led by L. Saul and including M. Bzowski and M.A. Kubiak from SRC PAS.

Extending this analysis, a team of *IBEX* researchers, led by N.A Schwadron from the University of New Hampshire and including M. Bzowski from SRC PAS, demonstrated based on *IBEX* observations clear effects of radiation pressure in a large longitudinal shift in the peak of interstellar hydrogen compared with that of interstellar helium. Specifically, results from the Lee et al. interstellar neutral model were compared with *IBEX*-Lo hydrogen observations to describe the distribution of hydrogen near 1 AU. They provided new estimates of the solar radiation pressure: it was found that over the period analyzed from 2009 to 2011, radiation pressure divided by the gravitational force (μ) increased slightly from $\mu = 0.94 \pm 0.04$ in 2009 to $\mu = 1.01 \pm 0.05$ in 2011. The speed, temperature, source longitude, and latitude of the neutral H atoms were also derived. It was found that they are roughly consistent with those of interstellar He, particularly when considering the filtration effects that act on H in the outer heliosheath. Thus, this analysis shows that over the period from 2009 to 2011, signatures of neutral H consistent with the primary distribution of atoms from the LISM and a radiation pressure that increases in the early rise of solar activity were observed. These findings were published in a paper in *The Astrophysical Journal*.

The abundance of deuterium in the interstellar gas in front of the Sun gives insight into the processes of filtration of neutral interstellar species through the heliospheric interface and potentially into the chemical evolution of the Galactic gas. The possibility of detection of neutral interstellar deuterium at 1 AU from the Sun by direct sampling by *IBEX* was investigated by in-depth modeling studies. Using both previous and the most recent determinations of the flow parameters of neutral gas in the Local Interstellar Cloud and an observation-based model of solar radiation pressure and ionization in the heliosphere, the flux of neutral interstellar D at *IBEX* for the actual measurement conditions was simulated. The number of interstellar D atom counts expected during the first three years of *IBEX* operation was assessed. Also simulated were the observations expected during an epoch of high solar activity. In addition, the expected counts of D atoms from the thin terrestrial water layer covering the *IBEX-Lo* conversion surface, sputtered by neutral interstellar He atoms, were simulated to make basis for comparison with actual observations, which contain the terrestrial water deuterium foreground. This study was published in *Astronomy & Astrophysics* by an international team of researchers led by M.A. Kubiak from SRC PAS and including also M. Bzowski and J.M. Sokół.

Based on this modeling reconnaissance, the team identified interstellar deuterium atoms in the signal measured by *IBEX-Lo*. All data from the spring observation periods of 2009 through 2011 were analyzed. In the first three years of the *IBEX* mission time, the observation geometry and orbit allowed for a total LISM observation time of 115.3 days. However, the effects of the spacecraft spinning and stepping the observations through 8 energy channels reduced the effective observation time to 1.44 days. During this time, 2 counts for interstellar deuterium were identified. This number is conservatively assessed: because of a possibility of systematic error or additional noise in the data, though eliminated in our analysis to the best of our knowledge, the detection is supported only at a 1-sigma level. From these observations, the ratio D/H = $5.8 \pm 4.4 \times 10^{-4}$ at 1 AU was derived. After modeling the transport and losses of D and H from the termination shock to Earth's orbit, it was found that the result of $(D/H)_{LIC} = 1.6 \pm 1.2 \times 10^{-5}$ agrees with the abundance $(D/H)_{LIC} = 1.6 \pm 0.4 \times 10^{-5}$ for the Local Interstellar Cloud. This weak interstellar signal was extracted from a strong terrestrial background signal, consisting of sputtering products from the sensor's conversion surface. As a reference, the terrestrial D/H ratio in these sputtered products was accurately measured and then used to subtract this terrestrial background source. Because of the diminishing D and H signal at Earth's orbit during the rising solar activity due to photoionization losses and increased radiation pressure, this result demonstrates that in situ measurements of interstellar deuterium in the inner heliosphere require a sensor with a much higher collection power. This result was published in *Astronomy & Astrophysics* by an international team of researchers led by D.F. Rodriguez from University of Bern, Switzerland, and including M. Bzowski, M.A. Kubiak, and J.M. Sokół from SRC PAS.

Direct sampling of neutral interstellar atoms by *IBEX* can potentially provide a complementary method for studying element abundances in the LIC and processes in the heliosphere interface. An extensive study of ionization processes was performed to set the stage for abundance-aimed in-depth analysis of measurements of NIS He, Ne, and O by *IBEX* and determine systematic differences between abundances derived from various calculation methods and their uncertainties. Using a model of ionization rates of the neutral interstellar species in the heliosphere, based on independent measurements of the solar wind and solar EUV radiation, a time-dependent method of calculating the survival probabilities of neutral interstellar atoms from the termination shock of the solar wind to IBEX was developed. Densities of these species along the Earth's orbit were calculated and the fluxes of NIS species as observed by *IBEX* were simulated. Ratios of survival probabilities, densities, and fluxes of NIS species at *IBEX* were pairwise computed to calculate correction factors for inferring the abundances at the termination shock. It was found that the previously used analytic method of calculating the survival probabilities gives acceptable results only for He and Ne during low solar activity. For the remaining portions of the solar cycle, and at all times for O, a fully time-dependent model should be used. Electron impact ionization is surprisingly important for NIS O. Interpreting the *IBEX* observations using the time-dependent model yields the LIC Ne/O abundance of $0.16 \pm 40\%$. The uncertainty is mostly due to uncertainties in the ionization rates and in the NIS gas flow vector. This value is in agreement with astrophysically-derived abundance of species in the solar Galactic neighborhood. These results were published in *Astronomy & Astrophysics* by a team of SRC PAS scientists M. Bzowski, J.M. Sokół, and M.A. Kubiak.

Recently Sokół et al. (2012) presented a reconstruction of the heliolatitudinal and time variations of the solar wind speed and density. The method of the reconstruction was based on (i) measurements of the interplanetary scintillations, (ii) OMNI-2 solar wind data in the ecliptic plane, and (iii) Ulysses solar wind data out of the ecliptic plane. To verify these findings, hydrogen charge exchange rates derived from these results were used as input parameters to calculate the interstellar hydrogen distribution in the heliosphere in the frame of our 3-D time-dependent kinetic model. The hydrogen distribution was then used to calculate the backscattered solar Lyman-α intensity maps. The theoretical Lyman- α maps were subsequently compared with the *SOHO/SWAN* measurements during the maximum and minimum of the solar cycle activity. It was found that in the solar minimum there is a quite good agreement between the model results and the *SWAN* data, but in the solar maximum the sky maps of the Lyman-α, the intensities are qualitatively different for the model results and observations. The study was published in *Journal of*

Geophysical Research by an international team led by O. Katushkina, including J.M. Sokół from SRC PAS.

Studies of multifractal scaling properties of interplanetary magnetic field

Continuing studies carried out during recent years, the multifractal scaling of the fluctuations in the interplanetary magnetic field strength , measured onboard *Voyager 2* in the entire heliosphere were analyzed in greater detail. Specifically, spectra observed by *Voyager 2* in a wide range of solar activity cycles during the years 1980 – 2009 at various heliospheric latitudes and distances from 6 to 90 astronomical units (AU) were analyzed. Focus was put on the singularity multifractal spectrum before and after crossing the termination heliospheric shock by *Voyager 2* at 84 AU from the Sun. In addition, parameters of the model that describe the asymmetry of the spectrum, depending on the solar cycle, were investigated. It was pointed out that the spectrum is prevalently right-skewed inside the whole heliosphere. Moreover, a change in the asymmetry of the spectrum at the termination shock was probably observed. It was shown that the degree of multifractality is modulated by the solar activity. Hence these basic results also bring significant support to some earlier claims suggesting that the solar wind termination shock is asymmetric. These findings were published in *Nonlinear Processes in Geophysics* by W.M. Macek and A. Wawrzaszek.

Studies of various space plasma processes

The behavior of finite magnetic field lines during reconnection processes was studied. The field line motions were portrayed using the Euler potentials representation. A new insight into plasma flow fields related with magnetic reconnection was proposed. In this approach, reconnection is treated as a breakage of magnetic topology, which results in deviation from the line preserving flow regime. Constraints and general equations for these flows were derived. In this approach, the flux preserving flows are treated as a special case of the line preserving regime. Also derived was a constraint on the non-ideal term in Ohm's Law within diffusion regions, which relates plasma flow with resistivity, and which must hold for non-reconnective diffusion. A new method of detecting magnetic reconnection was proposed. These results were published by a SRC PAS PhD student P. Figura and a SRC scientist W.M. Macek in *Annals of Physics*.

Analysis of measurements from the ESA/NASA *Cluster* mission showed in situ acceleration of ions to energies of 1 MeV outside the terrestrial bow shock. The observed heating can be associated with the presence of electromagnetic structures with strong spatial gradients of the electric field that lead to ion gyro-phase breaking and to the onset of chaos in ion trajectories. It results in rapid, stochastic acceleration of ions in the direction perpendicular to the ambient magnetic field. The electric potential of the structures can be compared to a field of moguls on a ski slope, capable of accelerating and ejecting the fast running skiers out of piste. This mechanism may represent the universal mechanism for perpendicular acceleration and heating of ions in the magnetosphere, the solar corona and in astrophysical plasmas. This is also a basic mechanism that can limit steepening of nonlinear electromagnetic structures at shocks and foreshocks in collisionless plasmas. These findings were published in *European Physics Letters* by an international team of scientists led by K. Stasiewicz from SRC PAS, including M. Strumik.

The velocity distribution of interstellar pickup ions (PUIs) has typically been described as evolving through fast pitch angle scattering, followed by adiabatic cooling while being transported radially outward with the solar wind. The slope of the observed pickup ion distributions is determined by a combined action of ionization processes, which control the radial profile of interstellar neutrals being the source population for PUI, and the PUI cooling processes. In the past, a cooling index of 3/2 for the PUI velocity distributions has been used in almost all studies. This value is based on the implicit assumptions of immediate PUI isotropization due to pitch angle scattering and solar wind expansion with the square of the distance from the Sun. In a study by an international team of scientists led by Ph.D. student J.H. Chen from the University of New Hampshire, including M. Bzowski and J.M. Sokół from SRC PAS, the observed PUI cooling index was determined for He^+ PUI distributions observed with ACE SWICS at a ~30° interval in the upwind direction each year from 1999 through 2010, i.e., over the past solar cycle. The results were compared with an isotropic PUI model with the cooling index treated as a free parameter. The ionization rate was obtained for the actual observation time from independent observations. To extract effects of slow PUI pitch angle scattering, the comparison was repeated for the intervals when interplanetary magnetic field (IMF) was perpendicular to the solar wind expansion direction. When averaged over the entire data set, the cooling index turned out to be very close to 3/2. However, it varies substantially from 1.1 to 1.9 between samples, shows a distinct variation with solar activity, and has a significant correlation with the sunspot number, when data are restricted to nearly perpendicular IMF ($\theta_{B,vSW} > 60°$), excluding the slow pitch angle scattering in the radial IMF direction. These findings were published in *Journal of Geophysical Research*.

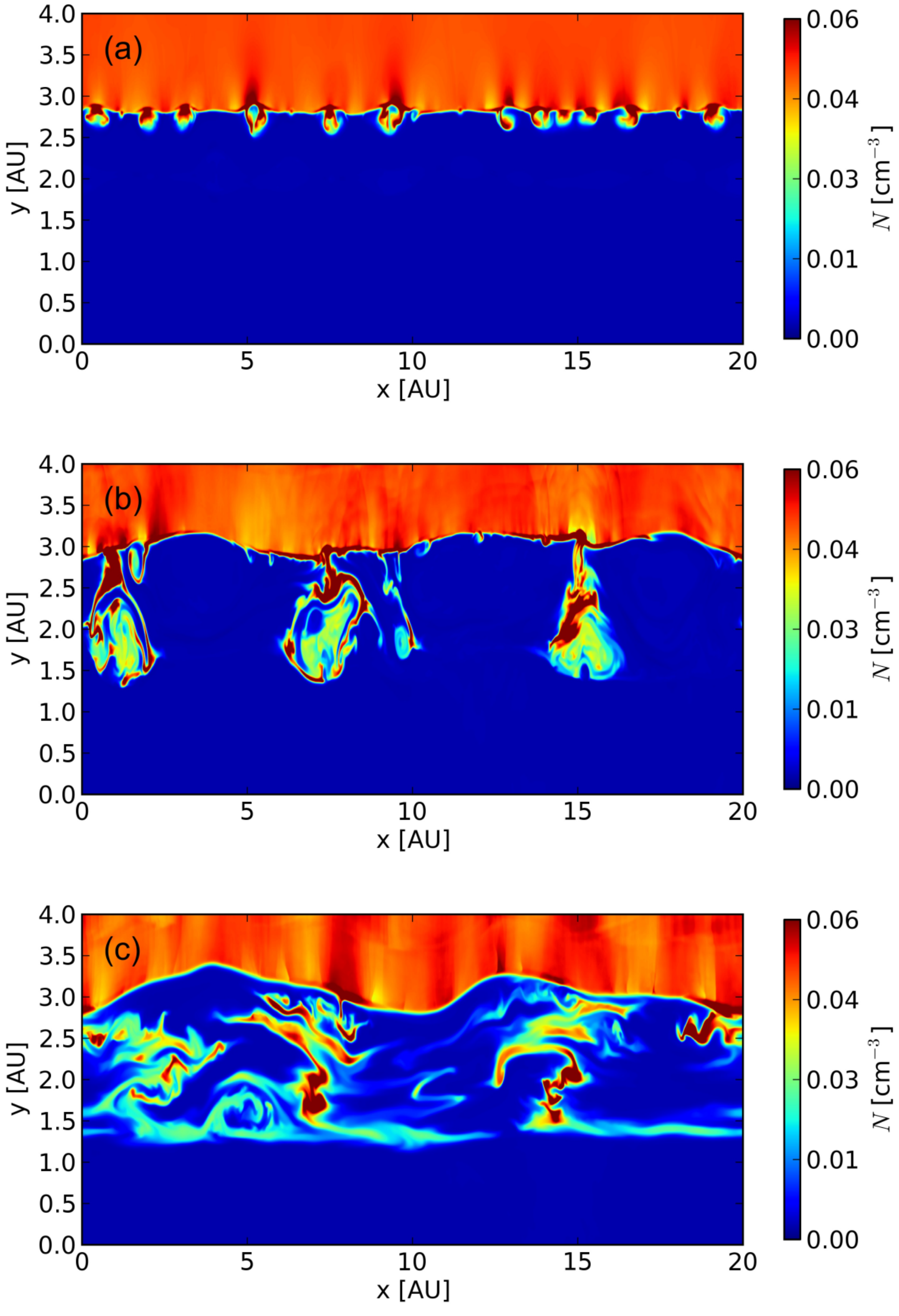

Fig. 1. Illustration of simulation results: Top panel: early phase of development of the phenomenon of plasma transport from the outer heliosheath inside the heliopause, initiated by magnetic reconnection and interaction between magnetic islands at the heliopause and the heliospheric current sheet. Only small intrusions of interstellar matter in the heliosphere are visible. Middle panel: the MHD equations used in the modeling lead to development of channels within which interstellar matter is transported covering large distances inside the heliosphere. Bottom panel: After some time, the transport of plasma through the heliopause ceases, but the interstellar matter intrusions remain inside the inner heliosheath, arranged in layers in the inner heliosheath.