Heliospheric physics

(Laboratory for Solar System Physics and Astrophysics SRC)

Studies of the Galactic neighborhood of the Sun by observations of neutral interstellar atoms.

Studies of the heliosphere and its Galactic neighborhood based on observations of neutral interstellar atoms onboard a NASA satellite Interstellar Boundary Explorer (IBEX) continued. In the effort to determine the flow parameters of neutral interstellar gas, the orientation of the satellite spin axis (and thus of the field of view of its instruments) was determined with a high accuracy and confidence by a careful comparison of the data from IBEX Star Sensor and Star Tracker. The consistency of the spin axis determination by the two instruments was established to be about 0.1 degree, which is sufficient for an accurate determination of the flow parameters of neutral interstellar gas. The result of this research, of key importance for further analysis of IBEX observations, is now in press in a paper in a special section in *The Astrophysical Journal Supplement Series*, scheduled for publication in the beginning of 2012.

(M. Hłond, M. Bzowski and a team of IBEX researchers)

With the issue of the boresight of the IBEX-Lo field of view solved, it was possible to reliably study the flow of neutral interstellar species. Neutral interstellar helium is almost unaffected at the heliospheric interface with the interstellar medium and freely enters the solar system. This second most abundant species provides excellent information on the characteristics of the interstellar gas in the Local Interstellar Cloud (LIC). The IBEX Science Team completed analysis of neutral interstellar helium observations, carried out using two independent analysis methods. One of them was developed in SRC. It is based on a very sophisticated numerical model of the gas flow and in the heliosphere and of the

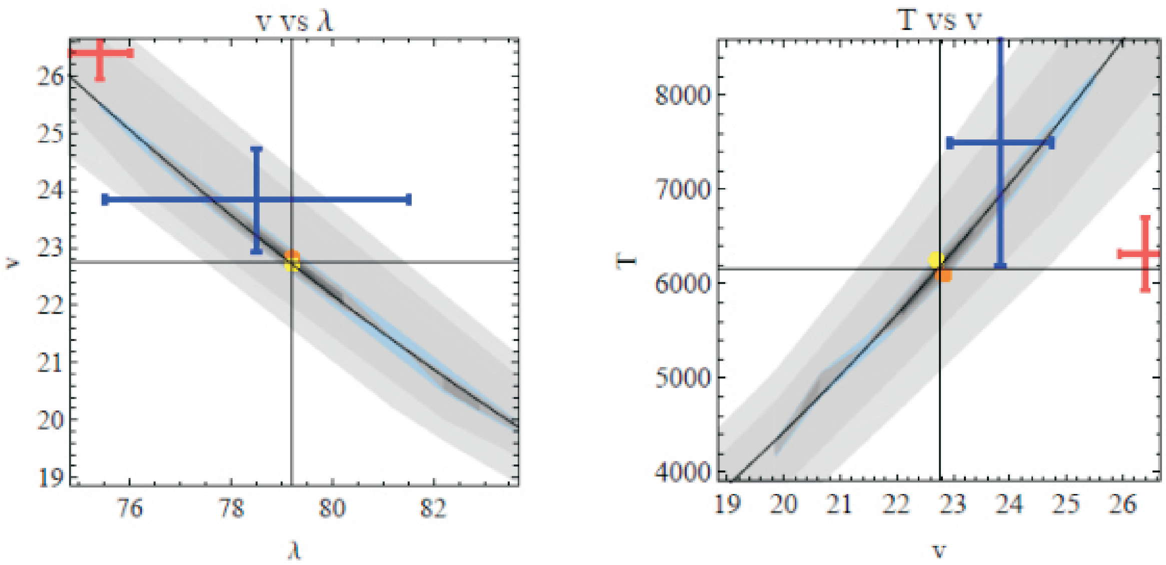


Figure 1. Relation between ecliptic longitude of the flow direction and flow speed (left-hand panel), and flow speed and temperature of neutral interstellar helium in front of the heliosphere (right-hand panel), determined from observations from IBEX-Lo using the Warsaw Neutral Gas Test Particle Model. The gray contours mark increasing confidence-level regions in these cuts of the four-dimensional parameter space. The blue contour marks the most plausible region in the parameter space, while the black cross hairs mark the best-fit parameter set. The fit was made to the data from 2009 and 2010 combined, while the orange and yellow dots mark the best fit results for 2009 and 2010. To be acceptable, a parameter set must be within the blue contours in all six two-dimensional cuts through the four-dimensional parameter space. The red cross marks the previous determination of the flow parameters obtained from GAS/Ulysses and the blue cross marks the parameter set obtained by Redfield and Linsky in 2008 for the flow parameters of the Local Interstellar Cloud from extensive observations of interstellar absorption lines in the spectra of nearby stars. It is clear that Redfield and Linsky's result agrees with the IBEX result within error bars, while the Ulysses/GAS result does not.

detection process by IBEX instruments. The other one was developed at the University of New Hampshire with participation of the SRC team and is based on an approximate, analytical model of the gas flow and its detection on IBEX.

The analysis was separately performed on the data from the 2009 and 2010 observing seasons and subsequently repeated on the data set merged. All these results agree that the inflow parameters of interstellar helium are markedly, statistically significantly different than previously thought. The best fit to the data was obtained for the flow velocity about 23 km/s, temperature 6000 K, ecliptic longitude 79 deg, and latitude -5.1 deg. The parameters of the flow resulting from the analysis are all related to each other, forming narrow alleys in the four-dimensional parameter space. The new results are statistically significantly different from the results obtained previously from analysis of Ulysses/GAS observations by Witte et al. in 2004, but do agree with the results of analysis of interstellar matter lines observed in the spectra of stars in the Local Interstellar Medium by Redfield and Linsky in 2008.

The consequences are far reaching: the Sun may be close to the boundary between the LIC and G Cloud as previously thought, but is still within the LIC. This conclusion is now confirmed by results obtained from two independent studies using different experimental methods. The flow speed and direction of the LIC are different than previously believed based on observations from GAS/Ulysses. The lower magnitude of speed results in a deficit in ram pressure from the interstellar side in the pressure balance that maintains the shape and size of the heliosphere. This deficit in the model pressure has to be compensated for by an increased magnetic pressure (and thus a stronger magnetic field) and/or an increased plasma density in the LIC. The local interstellar magnetic field vector is expected to be in the so-called hydrogen deflection plane, defined by the directions of inflow of neutral interstellar hydrogen and helium. The seemingly small difference in the flow direction of helium found by the IBEX Team suggests that the orientation of the hydrogen deflection plane is markedly different than previously thought, namely by about 25 deg, and thus the orientation of the interstellar magnetic field is different.

Apart from the new flow parameters of the primary component of neutral interstellar helium, IBEX discovered another component, which is most probably created in the outer heliosheath via charge exchange between interstellar He atoms and He^{+} ions. The implications of the latter discovery are important for future heliospheric research because a careful analysis of the flow of the secondary helium component may independently reveal a distortion of the heliosphere from axial symmetry and thus provide a handle to estimate the strength and direction of the local interstellar magnetic field.

These findings are now in press in three papers in a special section in *The Astrophysical Journal Supplement Series*, scheduled for publication in the beginning of 2012, and were presented in a talk at the Fall Symposium of the American Geophysical Union.

(M. Bzowski, M. A. Kubiak, M. Hłond, J. M. Sokół and a team of IBEX researchers)

IBEX performed the first direct measurement of the Ne/O abundance ratio in the interstellar neutral gas flowing into the inner heliosphere. From the IBEX data collected in spring 2009, the fluxes of interstellar neutral oxygen and neon at the location of IBEX at 1 AU from the Sun were derived and the flux ratio calculated. Based on the measured flux ratio and on the ionization rates of neon and oxygen prevailing in the heliosphere during the period of solar minimum, the neon/oxygen ratios at the heliospheric termination shock and in the gas phase of the inflowing local interstellar medium was estimated. The estimate is (Ne/O) = 0.27 ± 0.10 in the gas phase of the local interstellar medium, which is – within the large uncertainties – consistent with earlier estimates from pickup ions. This value is larger than the solar abundance ratio, possibly indicating that a significant fraction of oxygen in the local interstellar medium is locked in grains and/or ices. These results are now in press in a paper in a special section in *The Astrophysical Journal Supplement Series*, scheduled for publication in the beginning of 2012, and were presented in a poster at the Fall Symposium of the American Geophysical Union.

(M. Bzowski in a team of IBEX researchers)

Hydrogen is the dominant component of the local interstellar medium. However, due to ionization and interaction with the heliosphere, direct sampling of neutral hydrogen in the inner heliosphere is more difficult than sampling of the local interstellar neutral helium. The first analysis of direct sampling of neutral hydrogen from the local interstellar medium by IBEX was performed. The arrival direction of hydrogen was found to be offset from that of the local helium component. The observations are consistent with hydrogen experiencing an effective ratio of outward solar radiation pressure to inward gravitational force greater than unity (>1). The temporal change observed in the local interstellar hydrogen flux between 2009 and 2010 can be qualitatively explained by solar variability. These results are now in press in a paper in a special section in *The Astrophysical Journal Supplement Series*, scheduled for publication in the beginning of 2012, and were presented in a poster at the Fall Symposium of the American Geophysical Union.

(M. Bzowski in a team of IBEX researchers)

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

IBEX observes a remarkable feature, the IBEX ribbon, which is an ENA flux enhancement over a narrow region ~20 deg wide by a factor of ~2.3 higher than the globally distributed ENA flux. The ENA emissions in the ribbon were separated from the distributed flux by applying a transparency mask over the ribbon and regions of high emissions, and then solving for the distributed flux using an interpolation scheme. The analysis showed that the energy spectrum and spatial distribution of the ribbon are distinct from the surrounding globally distributed flux. The ribbon energy spectrum shows a knee between ~1 and 4 keV, and the angular distribution is approximately independent of energy. In contrast, the distributed flux does not show a clear knee and more closely conforms to a power law over much of the sky. Consistent with previous analyses, the slope of the power law steepens from the nose to tail, suggesting a weaker termination shock toward thetail as compared to the nose. The knee in the energy spectrum of the ribbon suggests that its source plasma population is generated via a distinct physical process. Both the slope in the energy distribution of the distributed flux and the knee in the energy distribution of the ribbon are ordered by latitude. The heliotail may be identified in maps of globally distributed flux as a broad region of low flux centered ~44 deg W of the interstellar downwind direction. The observed location of the flux minimum suggests that the heliotail is deflected, most probably by the interstellar magnetic field. These findings were published in a paper in *The Astrophysical Journal.*

(M. Bzowski in a team of IBEX researchers)

In 2010, a team of SRC researchers showed that the shape of the IBEX ribbon can be reproduced by MHD modeling of the heliosphere assuming that energetic neutral atoms originate in regions beyond the heliopause where the interstellar magnetic field is the strongest and perpendicular to radial directions from the Sun (published in 2011 by Grygorczuk et al.). In 2011, the team continued the studies and compared the modeling results with the Voyager and IBEX observations together. Two comparison criteria were adopted: the distances of the termination shock crossing by Voyagers and the location of IBEX ribbon in the sky. These observables were compared with the MHD model solutions for the shape and size of the heliosphere, obtained for different strengths and orientations of the local interstellar magnetic field (LIMF) assuming asymmetric magnetized solar wind flow. It was shown that the ribbon criterion itself is weakly sensitive to the LIMF strength. Thus, this condition provides primarily a constraint on the orientation of the LIMF vector. However, additionally including the termination shock criterion one can obtain relatively narrow limits for the estimated strength and orientation of the LIMF. The model approximately reproduces the position of the IBEX ribbon and the distance of termination shock crossing by Voyager 2 for the local interstellar magnetic field strength of 2.4 ± 0.3 μG and direction close to the hydrogen deflection plane. The inclination of the magnetic field to the local interstellar flow direction was found to be 39 ± 9 deg. In the ecliptic coordinates, this solution corresponds tothe LIMF vector pointing from (longitude, latitude)= (227 ± 7, 35 ± 7) deg. These findings show that simultaneously meeting the

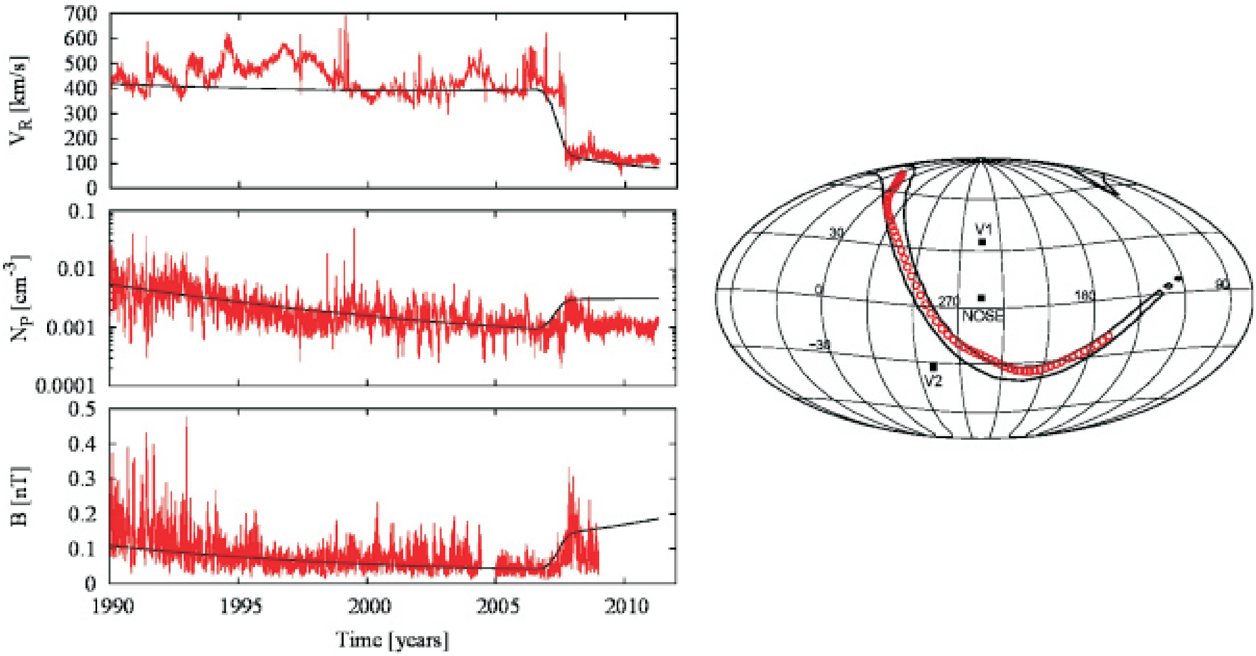


Figure 2. Comparison of Voyager 2 and IBEX observations with models developed recently in SRC. On the left, measured solar wind parameters (in red) are juxtaposed with model predictions (in black) for the radial component of plasma velocity V_R, density N_P, and strength of the magnetic field *B*. On the right a sky map in ecliptic coordinates is presented, where the ridge of the observed IBEX ribbon (red points) is compared with the angular locations where the perpendicularity condition **B** ·**r**≈*0* is satisfied in a layer just beyond the heliopause (the area inside the black contour). The direction of interstellar matter inflow assumed in the simulations is marked as NOSE and the current positions of the Voyager spacecraft as V1, V2, respectively.

constraints from the Voyager 2 termination shock crossing and IBEX ribbon observations leads to a lower estimate of the strength of LIMF in comparison with earlier studies, based solely on Voyager observations. These results are consistent with an independent study by Heerikhuisen and Pogorelov (2011) and were published in a paper in *The Astrophysical Journal Letters*.

(M. Strumik, L. Ben-Jaffel, R. Ratkiewicz, and J. Grygorczuk)

Some of the earlier attempts to explain the IBEX ribbon were based on the assumption that the local interstellar magnetic field **B** within the ribbon is perpendicular to the heliocentric line of sight **r**. This is referred to as the **B** ·**r** = 0 condition. Both the MHD model developed in SRC reported above and the model by Heerikuisen et al. (2010, 2011) were able to more or less correctly reproduce the geometry of the ribbon. However, the distribution of the ENA flux along the ribbon circumference reported by Heerikhuisen et al. was not in agreement with observations. Further studies of possible ribbon origin carried out in SRC in 2011 were motivated by the hypothesis proposed in 2010 by Chalov et al. that the magnetic mirror effect in the local interstellar magnetic field, which is draped on the heliopause (cf Ratkiewicz et al. 2000), contributes to the creation of the enhanced flux of the ribbon. Assuming that this hypothesis is correct it was expected that the regions of strong magnetic compression in the outer heliosheath would be highly populated by protons that originate from ENAs that the heliosphere emits to the outer heliosheath. Some of these ENAs are subsequently ionized and the newborn ions are picked up by the draped magnetic field. These pickup ions gyrate about the field lines and some of them exchange charge with hydrogen atoms from the ambient interstellar gas and become ENA again. In the regions where the magnetic field lines are perpendicular to the heliocentric radial direction the gyration is hypothesized to be mostly in the plane perpendicular to the magnetic field lines. Some of the new ENAs formed in these regions could form the enhanced ENA emissions in the ENA sky maps observed by IBEX as the ribbon.

Hence a group of SRC researchers investigated the correlation between the geometric locations of the **B** · **r** = 0 condition and maxima of the LIMF strength taken along the magnetic field lines draped on the heliopause. They showed that in general such a correlation is reproduced by results of an MHD model of the heliosphere obtained for various strengths and orientations of the external magnetic field and that the region of magnetic mirror effect forms an arc (and not a full circle) in the sky maps. In particular, the SRC team was able to fit a set of magnetic field parameters that reproduce the observed geometry of the ribbon. This result, which was submitted to *The Astrophysical Journal Letters*, lends support to the hypothesis that IBEX ribbon is related to the interaction of the heliosphere with LIMF.

(R. Ratkiewicz, M. Strumik, J. Grygorczuk)

Launched in 1996, HSTOF onboard SOHO was the first instrument to detect ENA from the heliosheath. Since mid-2003, the field of

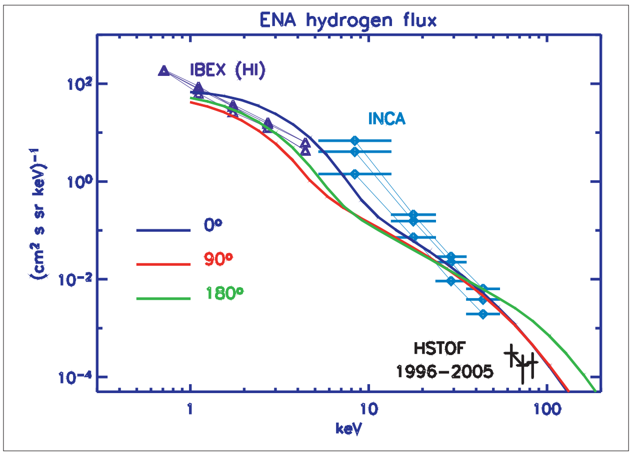


Figure 3. Composite ENA spectrum showing the observations (HSTOF, IBEX, INCA) and the results from the model of the energetic ion transport in the heliosphere (A. Czechowski, M. Hilchenbach, K.C. Hsieh). Results from the model are shown for three cases: nose (0 deg); flank (90 deg) and heliotail (180 deg).

view of HSTOF has been restricted to the flank sectors ofthe heliosheath, where the energetic iondistributions are still unknown. Interpretation of these data requires understanding of the energetic ion transport in the inner heliosheath.

The work in 2011 aimed at updating the HSTOF H and He ENA spectra by adding the results from

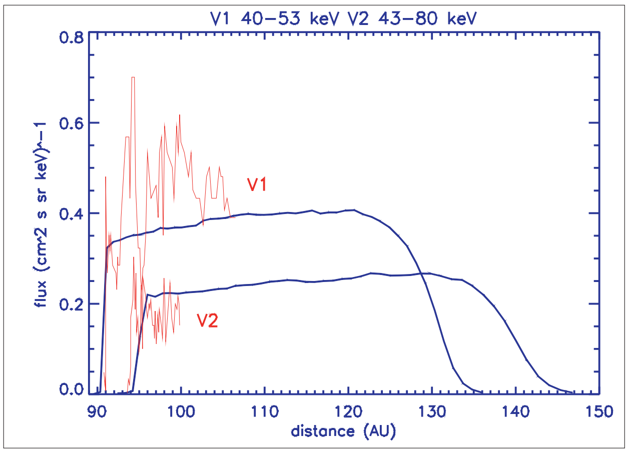


Figure 4. The proton flux profiles between the termination shock and the heliopause along the Voyager 1 and Voyager 2 directions (blue) as predicted by the model of energetic ion transport in the heliosphere (A. Czechowski, M.. Hilchenbach, K.C. Hsieh), compared to Voyager measurements. The Voyager measurements (marked V1 and V2 in the plot) are shifted in distance to agree with the termination shock positions resulting from the model.

measurements in 2006 to 2010. A numerical model was developed to calculate the distribution of energetic ions in the heliosheath and estimate the production of HSTOF ENA. From a comparison of the model results with observations it was found that the energetic ion density in the flank sectors of the heliosphere is lower than in the forward sector. In result, the contribution of the flanks of the heliosheath to the production of ENA is not directly proportional to the thickness of the heliosheath. Instead, it is comparable to the contribution of the forward sector, in agreement with the HSTOF data. The HSTOF ENA flux intensity is, nevertheless, significantly lower than the model predictions. Near the heliopause, a region of low energetic ion density appears due to the charge-exchange and escape losses. These results were presented in a presentation at the IGPP conference and in the conference proceedings, as well as in a poster at the AGU Fall Symposium.

(A. Czechowski and an international team of researchers)

Studies of solar factors relevant for heliospheric research

The three-dimensional structure of solar wind and its evolution in time is needed for heliospheric modeling and interpretation of energetic neutral atoms observations. The solar wind structure in heliolatitude and time was established using complementary in situ and remote-sensing data. The heliolatitude structure of solar wind speed was determined on a yearly time grid over the past 1.5 solar cycles based on remote-sensing observations of interplanetary scintillations (IPS), in-situ out-of-ecliptic measurements from Ulysses, and in-situ in-ecliptic measurements from the OMNI-2 database. Since the available in-situ information on the solar wind density structure out of ecliptic is limited to the Ulysses data, correlation formulae between solar wind density and speed were derived and used to retrieve the 3D structure of solar wind density for the whole span of available IPS measurements of solar wind speed. With the variations of solar wind density and speed in time and heliolatitude established, variations in solar wind flux, dynamic pressure, and charge exchange rate in the approximation of stationary H atoms were calculated. Also rates of photoionization of heliospheric neutral species were critically reviewed and new time series of these quantities, consistently based on the most up to date observations and calibrations of the solar EUV measurements and proxies, were derived. A review of the solar factors relevant for the global modeling of the heliosphere and for analysis of heliospheric observations was compiled and submitted for publication as a part of the report from the Fully ON-Line Datacenter for Ultraviolet Emissions Working Team, fostered by the International Space Science Institute (ISSI) in Bern, Switzerland, and in a research paper submitted to *Solar Physics*.

The solar factors were incorporated in a model of survival probabilities of ENA in the heliosphere between the termination shock and a detector in the inner heliosphere. The model is used in the ongoing heliospheric neutral atoms research carried out by the IBEX Team to calculate survival probabilities of the ENA observed by IBEX as well as in the studies of neutral inter-stellar gas reported above.

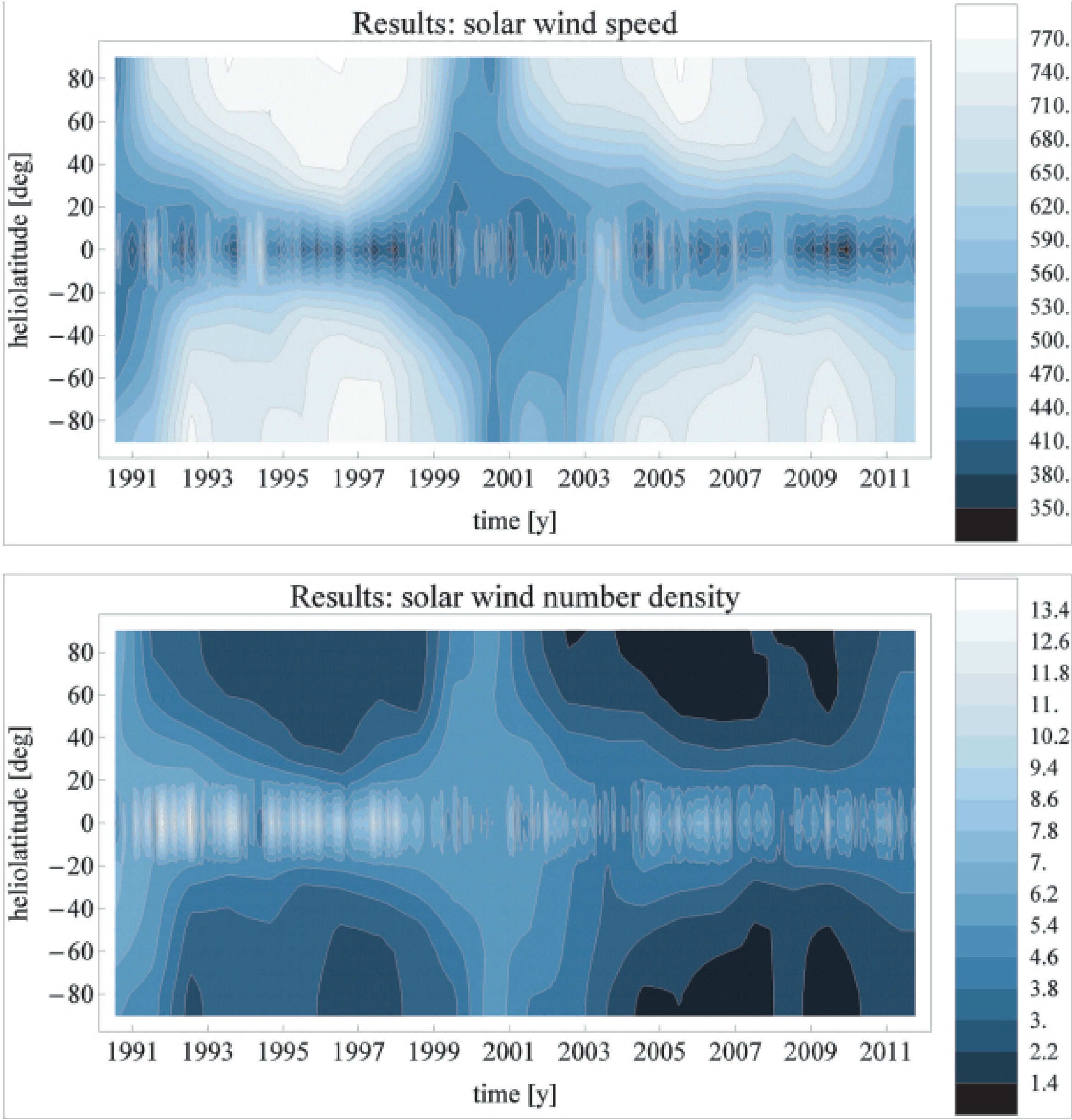


Figure 5. Heliolatitude vs time map of the solar wind speed evolution between 1990 and the end of 2011, inferred by an international team of scientists led by M. Bzowski and J.M. Sokół (upper panel). The map is based on yearly-averaged latitudinal profiles of solar wind speed obtained from Computer Assisted Tomography analysis of the interplanetary scintillation observations carried out by a collaborating team from the Solar Terrestrial Environment Laboratory in Nagoya, Japan. Those profiles were calibrated against Ulysses in situ measurements. Using a density-speed correlation inferred from Ulysses measurements, the team calculated the map of solar wind density as a function of time and heliolatitude, shown in the lower panel. The central band in the two maps is from in-situ measurements of solar wind collected in the OMNI-2 time series, averaged over Carrington rotation periods. These results are now basis for the software pipeline used to calculate survival probabilities of ENA for interpreting IBEX measurements of heliospheric ENA and neutral interstellar gas (M.A. Kubiak)

(J. M. Sokół, M. Bzowski, M. A. Kubiak and an international team of researchers)

Detection and modeling of nanodust in the solar wind

Dust grains in the nanometer size range bridge the gap between atoms and larger grains made of bulk material. Their small size embodies them with special properties. Due to their high relative surface area, they have a high charge-to-mass ratio, so that the Lorentz force in the solar wind magnetic field strongly exceeds the gravitational force and other forces. In 2011, studies on the production and dynamics of nanodust particles in the Solar System continued. A qualitative understanding of the nanodust dynamics is

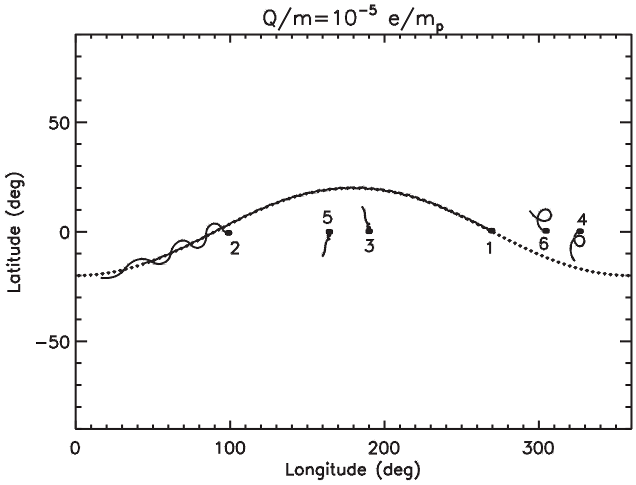


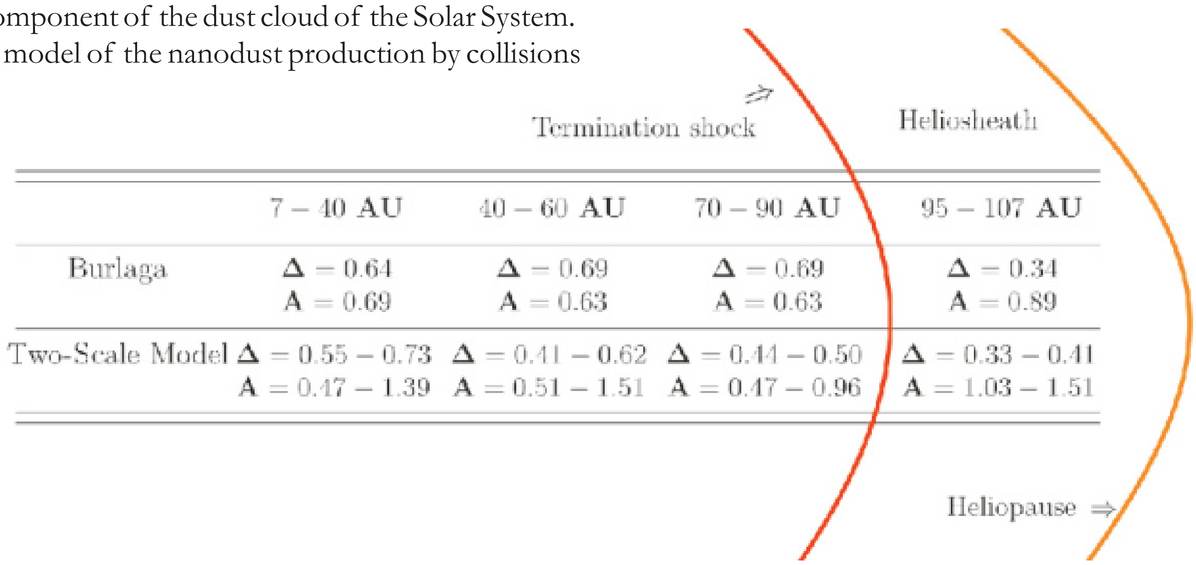
Figure 6. Example trajectories of charged nanodust particles drifting near to or along the heliospheric current sheet (A. Czechowski and I. Mann). The trajectories are shown in projection along the magnetic field lines onto the source surface of the solar magnetic field. This projection is particularly convenient for imaging the drift along the heliospheric current sheet.

possible with the use of ideas derived from the guiding centre approximation. It was found that nanodust particles close to the Sun can be trapped in bound nonkeplerian orbits, while the grains created outside the trapped region are accelerated to the velocities on the order of solar wind speed and escape to large distances from the Sun. This finding, together with the fact that nanodust has been continuously observed by the STEREO spacecraft at ~1 AU from the Sun, lends support to the idea that nanodust is a permanent component of the dust cloud of the Solar System. A model of the nanodust production by collisions between the dust grains from the circumsolar cloud was developed and used to study the creation of nanodust particles. It was concluded that the total mass flux of the observed nanodust particles is a small fraction of the mass that is destroyed by mutual collisions of interplanetary dusty particles inside 1 AU. The collision model, however, has large uncertainties and further studies are needed to understand the processes of nanodust formation. These findings were collected in two chapters submitted for a monograph to be published by Springer. The study was performed in cooperation with the WAVES on STEREO experiment group (observation of dust nanoparticles effects).

(A. Czechowski and I. Mann)

Studies of multifractal scaling properties of interplanetary magnetic field

The multifractal scaling of fluctuations of the interplanetary magnetic field strength was studied. The multifractal spectrum in a wide range of heliospheric distances from 7 to 107 AU was analyzed, including spectra observed by Voyager 1 before and after crossing the heliospheric termination shock. The obtained results show a change of the asymmetry of the spectrum at the termination shock: the spectrum is right-skewed in the outer heliosphere, in contrast to the left-skewed or possibly symmetric spectrum in



	7 – 40 AU	40 – 60 AU	70 – 90 AU	95 – 107 AU
Burlaga	Δ = 0.64 A = 0.69	Δ = 0.69 A = 0.63	Δ = 0.69 A = 0.63	Δ = 0.34 A = 0.89
Two-Scale Model	Δ = 0.55 – 0.73 A = 0.47 – 1.39	Δ = 0.41 – 0.62 A = 0.51 – 1.51	Δ = 0.44 – 0.50 A = 0.47 – 0.96	Δ = 0.33 – 0.41 A = 1.03 – 1.51

Figure 7. Degree of multifractality Δ and asymmetry A of the multifractal spectrum for the magnetic field strength observed by Voyager 1 at various heliospheric distances, before and after crossing the termination shock, as calculated by W. M. Macek, A. Wawrzaszek and V. Carbone in 2011. The orange arcs symbolize the positions of the termination shock and heliopause.

the heliosheath. Moreover, the degree of multifrac-tality falls steadily with the distance from the Sun and is apparently modulated by the solar activity. This analysis brings significant additional support to earlier results suggesting that the degree of multifractality of solar wind magnetic turbulence before the shock crossing is greater than that in the heliosheath, where the plasma is in equilibrium, and hence turbulence may become roughly monofractal. The results were published in *Geophysical Research Letters*. Similar results in the outer heliosphere (from Voyager 2 data) were published in *Nonlinear Processes in Geophysics,* and for the Earth's orbit (from ACE data) in 2010 in *Planetary and Space Science*.

(W. M. Macek and A. Wawrzaszek)

Modeling of solitary structures in space plasmas

Activities in 2011 focused on time-dependent simulations of filamentation of large-scale magnetosonic structures leading to the appea-rance of solitons. Large-amplitude magnetic pulsations on ion-inertial length scales are often observed in space plasmas, but their theoretical explanation is still controversial. Possible mecha-nisms for the generation of these pulsations, different from ideas based on the classical plasma instabilities, were reviewed in a study published in *Journal of Geophysical Research*. It was demonstrated that a competition between dispersion and wave steepening processes can lead to the transforma-tion of a large-scale magnetosonic structure into trains of solitons. This kind of longitudinal filamentation is possible for both slow and fast magnetosonic perturbations. Based on a compa-rison of the results of numerical simulations with Cluster spacecraft measurements it was shown that the steepening filamentation mechanism can explain the emergence of a certain class of solitary waves observed in space plasmas.

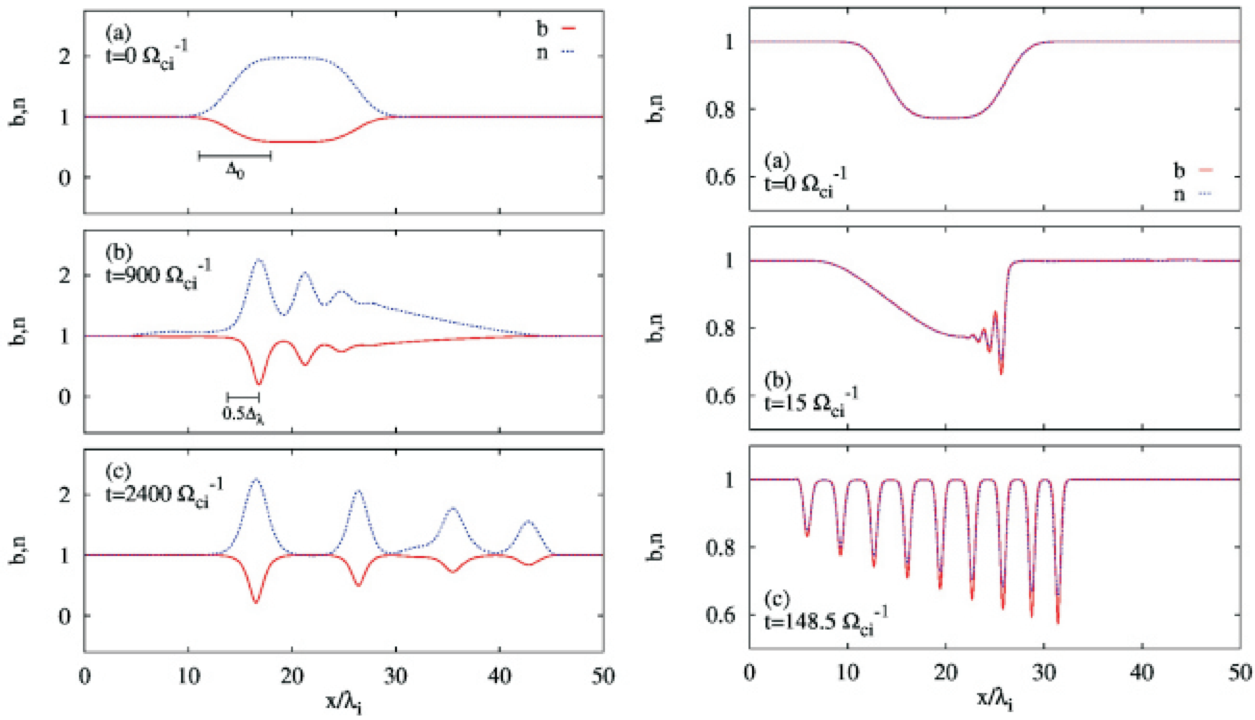


Figure 8. Results of Hall-MHD simulations for a quasi-perpendicular slow (panels on the left) and fast (on the right) magnetosonic structures: (a) the initial perturbation evolves through (b) an intermediate phase resembling a dispersive shock to (c) a final state where a train of solitary structures appears. Parameters of the background plasma in the simula-tions were set up to reproduce conditions typical for observations of slow solitary structures by the Cluster spacecraft. For the slow structure the simulations reproduce many properties of observed fluctuations, e. g. typical size, propagation speed, magnetic polarization, anticorrelation between the normalized density *n* and magnitude of the magnetic field *b*. The fast structures appearing in the simulations have not been identified in spacecraft measurements yet.

(M. Strumik, K. Stasiewicz and an international research team)