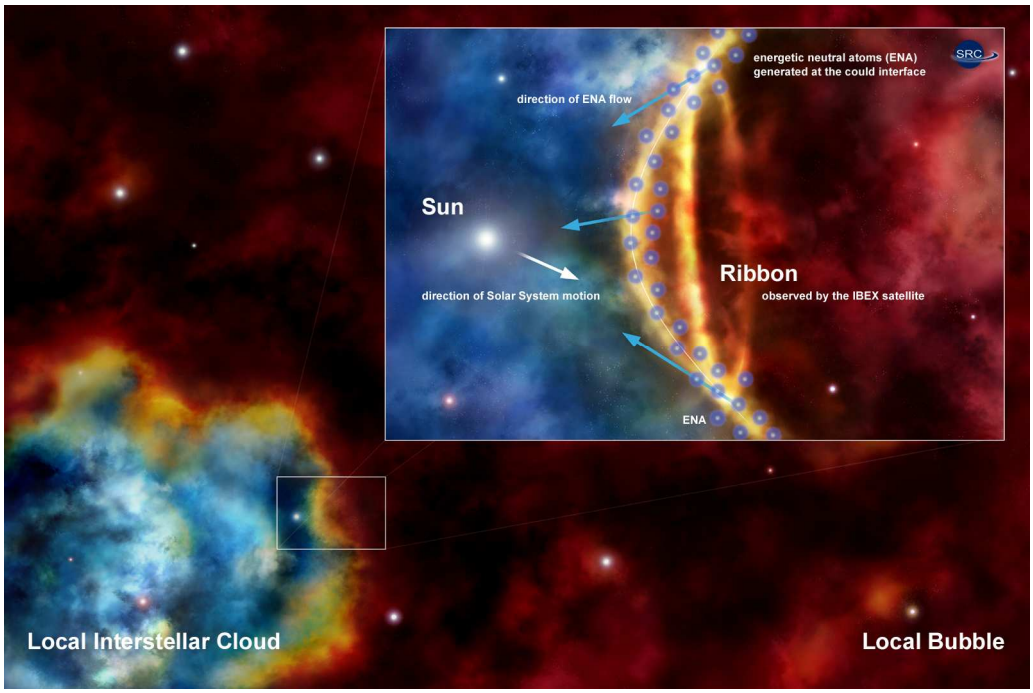
Research activities in 2010[1]

Laboratory for Solar System Physics & Astrophysics, SRC PAS

Analysis of IBEX observations of flux of Energetic Neutral Atoms: The brightest and most surprising feature in the first all-sky maps of Energetic Neutral Atoms (ENA) emissions (0.2—6 keV) produced by the Interstellar Boundary Explorer (IBEX) is an almost circular ribbon of a ~140° opening angle, centered at (*l*,*b*) = (33°, 55°), covering the part of the celestial sphere with the lowest column densities of the Local Interstellar Cloud (LIC). A novel interpretation of the IBEX results was proposed, based on the idea of ENA produced by charge-exchange between the neutral H atoms at the nearby edge of the LIC and the hot protons of the Local Bubble (LB). These ENAs can reach the Sun's vicinity because of very low column density of the intervening LIC material. It was shown that a plane-parallel or slightly curved interface layer of contact between the LIC H atoms (n_H = 0.2 cm^{-3}, T = 6000—7000 K) and the LB protons (n_p = 0.005 cm^{-3}, T ~ 10^6 K), together with indirect contribution coming from multiply-scattered ENAs from the LB, may be able to explain both the shape of the ribbon and the observed intensities provided that the edge is < (500—2000) AU away, the LIC proton density is (correspondingly) < (0.04—0.01) cm^{-3}, and the LB contains ~1% of non-thermal protons over the IBEX energy range. If this model is correct, then IBEX, for the first time, has imaged in ENAs a celestial object from beyond the confines of the heliosphere and can directly diagnose the plasma conditions in the LB. Published in the *Astrophysical Journal Letters*.



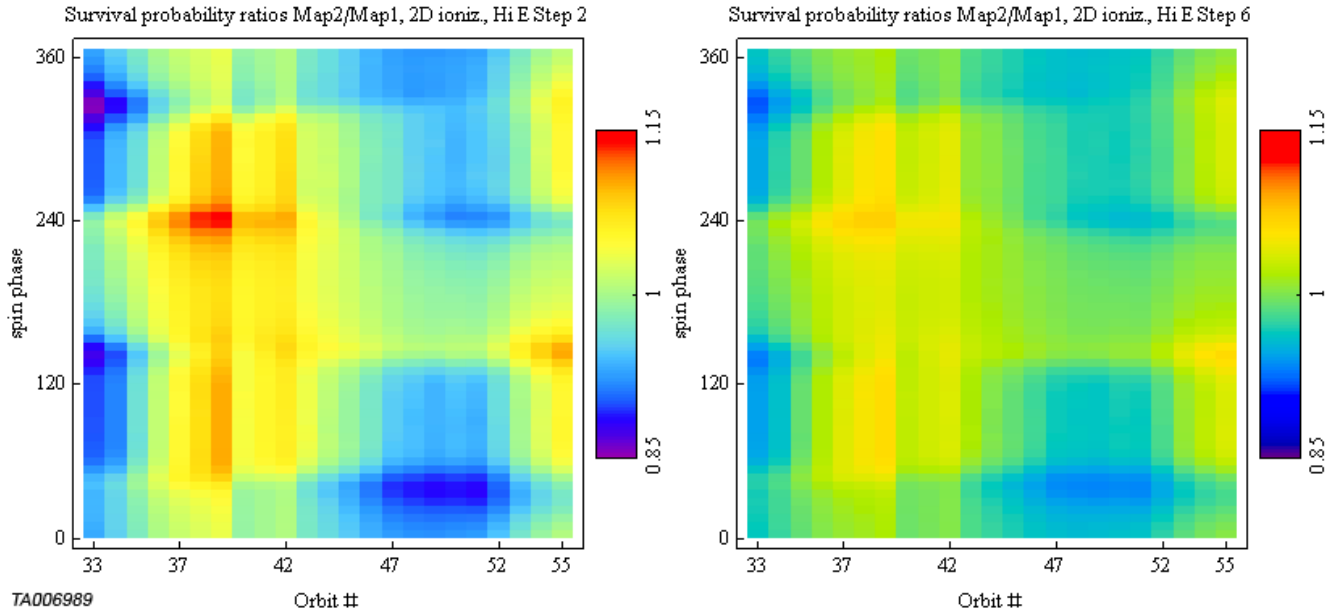
Cartoon illustration of the idea of formation of IBEX Ribbon at a nearby boundary between the Local Cloud, in which the Sun is embedded, and a very nearby hot, tenuous, fully ionized Local Bubble.

(S. Grzędzielski, A. Czechowski, M. Bzowski and a group from the IBEX Science Team)

Compared was the second set of IBEX sky maps to the first one in order to assess the possibility of temporal changes over the six months between views of each portion of the sky. While the large-

[1] Adapted from abstracts of articles authored and co-authored by members of the PFUSiA Lab

scale structure is generally stable between the two sets of maps, there are some remarkable changes that show that **the heliosphere is also evolving over this short timescale**. In particular, it was found that 1) the overall ENA emissions coming from the outer heliosphere are slightly lower in the second set of maps compared to the first, 2) both the north and south poles have significantly lower (~10-15%) ENA emissions in the second set of maps compared to the first across the energy range from 0.5-6 keV, and 3) the "knot" in the northern portion of the ribbon in the first maps is less bright and appears to have spread and/or dissipated by the time the second set was acquired. Finally, the spatial distribution of fluxes in the southern-most portion of the ribbon has evolved slightly, perhaps moving as much as 6º (one map pixel) equatorward on average. The observed large-scale stability and these systematic changes at smaller spatial scales provide important new information about the outer heliosphere and its global interaction with the galaxy and help inform possible mechanisms for producing the IBEX ribbon. Published in *Journal of Geophysical Research*.



Example maps of ratios of survival probabilities of heliospheric H ENA as observed by IBEX during the first and second half of the first year of observations.

(M. Bzowski, M.A. Kubiak in a group from the IBEX Science Team)

The effort to check the IBEX_Lo Z axis orientation at various orbits during the mission based on the data from the IBEX-Lo Star Sensor continued. The goal was to verify that the optical axis of the IBEX-Lo instrument maintained its pre-launch alignment and thus that the field of view of the instrument is indeed as intended. A very accurate knowledge of this parameter is necessary to correctly interpret the measurements of neutral interstellar gas made by this instrument and intensely worked on in SRC. Algorithms to automatically process the telemetry data and to determine positions of stars seen by the Star Sensor were refined and applied to the data from the full duration of the mission (orbits 20-98). Positions of observed stars (at least two per orbit) were used to calculate time series of current positions of the IBEX spin axis (Fig. 1). The spin axis positions found for the all orbits, transferred to the S/C polar coordinate system (Fig. 2a) were statistically compared with the positions of the axis obtained totally independently from the navigation system of the spacecraft. It was concluded that the deviation of the IBEX-Lo axis from the perfect alignment stays within pre-launch tolerance and the adopted interpretation of observations of neutral interstellar gas remains valid. (Fig. 3 and 4). Published in a poster presented at the American Geophysical Union Fall Meeting.

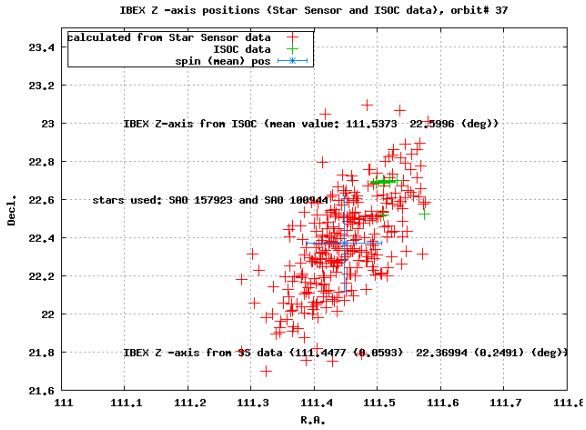


Figure 1. IBEX Z-axis positions for orbit #37 from the ISOC and Star Sensor data

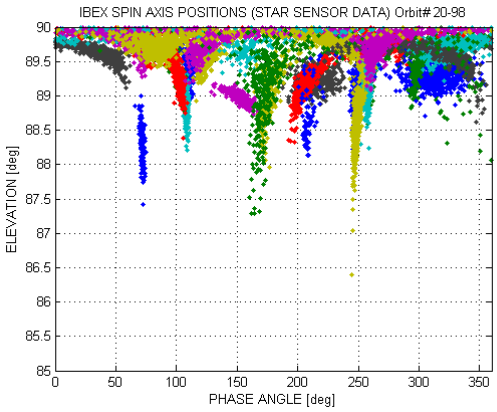


Figure 2. IBEX_Lo Z-axis positions found from the Star Sensor data (orbits # 20-98)

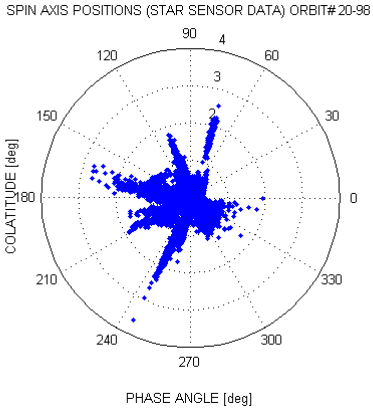


Figure 3. IBEX_Lo Z-axis positions in the polar S/C coordinates system (orbits # 20-98)

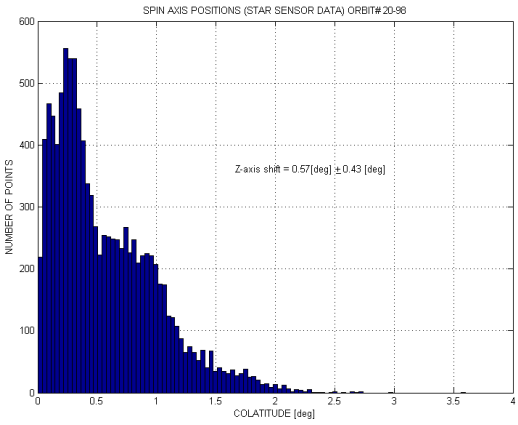


Figure 4. Histogram of the IBEX_Lo Z-axis positions against IBEX axis spin position

(M. Hłond, M. Bzowski)

Studies of the global shape of the heliosphere in relation to the local interstellar magnetic field: In relation to in-situ observations of the distant heliosphere by the Voyagers and remote-sensing by IBEX mission, the following verification criteria of heliospheric models were formulated: 1) the model should place the termination shock at the distances where detected by the Voyagers, 2) the solar wind in the inner heliosheath that comes out from the model should follow the physical parameters of plasma measured by Voyager 2 (because the plasma instrument on Voyager 1 is unserviceable), 3) the model should be able to reproduce the IBEX ribbon shape in case the observed energetic neutral atoms come from the outer heliosheath regions. Studies aimed at verification of the Warsaw MHD model of the heliosphere continued in this context. Published in the *Solar Wind 12 Proceedings.*

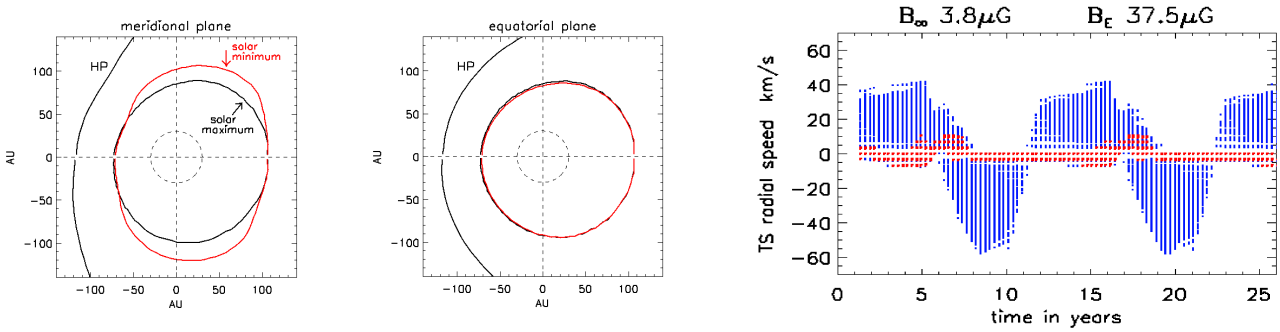
(R. Ratkiewicz, J. Grygorczuk)

and *Proceedings of the 9-th Annual International Astrophysics Conference*

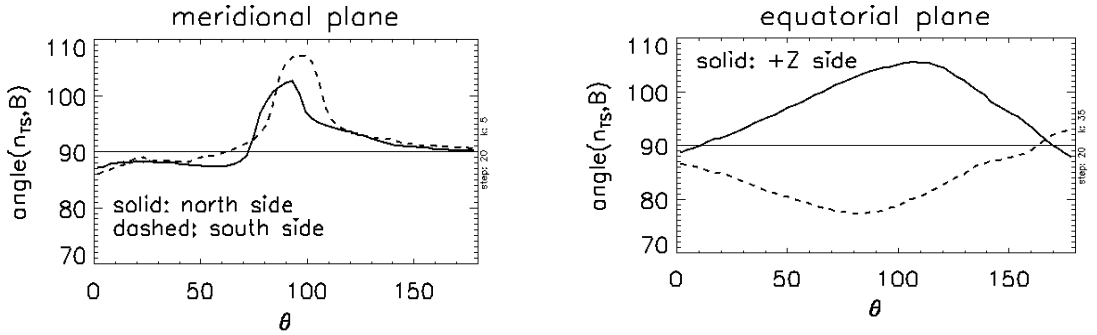
(R. Ratkiewicz, J. Grygorczuk, M. Strumik).

Global structure of the heliosphere predicted by the Warsaw 3D MHD time dependent code was

studied. Time variations of the solar wind (SW) caused by the 11-year solar cycle were simulated. It was found that the shape of the heliopause is approximately time independent, while the termination shock (TS) is affected by the SW dynamic pressure changes and more extended during solar minimum conditions. Maps of radial velocity of the TS motion were calculated. These velocities can be as large as tens of km/s in the simulated case. The angles between the magnetic field vectors and the TS normals (about 90 degrees) do not change much over an 11 year solar cycle. The magnetic field spiral is tightly wound in the outer heliosphere and produces a quasi-perpendicular shock, at which it is difficult to accelerate low energy particles. Published in the *Solar Wind 12 Proceedings*.



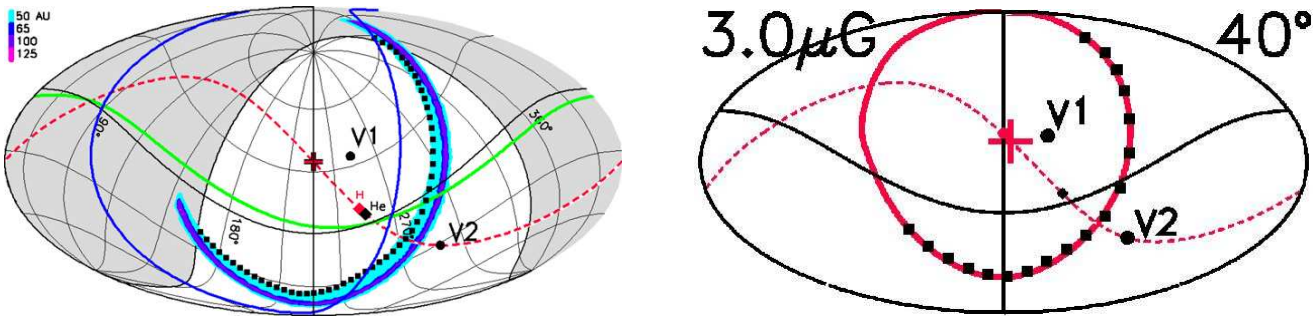
HP and TS shape in the Sun's meridional and equatorial plane (left and middle panel, respectively) for the epochs of minimum and maximum of solar activity. HP for minimum and maximum is almost in the same position. Right panel: radial velocity of the TS motion during solar cycle, calculated for each direction of the spherical grid of the model; directions up to 30° from the interstellar inflow direction are marked in red.



Angles between the magnetic field vector and the TS normal as a function of position in meridional and equatorial planes. Angle θ is counted from the interstellar helium inflow direction. Solid/dashed lines correspond to +Z /-Z side of the plane.

(J. Grygorczuk, A. Czechowski, R. Ratkiewicz i M. Strumik)

It was also shown that the shape of the IBEX ribbon can be reproduced assuming that energetic neutral atoms originate in the regions beyond the heliopause where the interstellar magnetic field is strongest and perpendicular to radial directions from the Sun. The best fit to the observed ribbon was obtained for the local interstellar magnetic field $B_\infty = 3.0 \pm 1.0$ μG pointing from ecliptic/ galactic coordinates (λ, β)/(l, b) = (225°±5°, 5°±5°)/(27°±5°, 51°±5°) close to the apparent ribbon center at (λ, β)/(l, b) = (221°, 39°)/(33°, 55°). These geometrical considerations should prove useful in identifying the mechanism of ribbon formation. Accepted for publication in the *Astrophysical Journal Letters* in 2011.



Left-hand panel: All-sky map showing spatial distribution of directions $\boldsymbol{r}$ at which $\theta = 89^{\circ}$–91° within 200 AU beyond the HP (blue–violet band; color scale indicates the distance intervals at which the perpendicularity criterion is fulfilled). Right-hand panel: loci where $\theta = 90°$ at a surface of $\max(\boldsymbol{B}_{IS}(\boldsymbol{r}))$. Both maps were obtained for $B_{\infty} = 3.0$ μG, $\alpha = 40^{\circ}$

(J. Grygorczuk, R. Ratkiewicz i M. Strumik, S. Grzędzielski)

Detection and modeling of nanodust in the solar wind: Dust grains in the nanometer 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, and they are accelerated to a speed of the order of magnitude of the solar wind speed. When such fast nanoparticles impact a spacecraft, they produce craters whose matter vaporizes and ionizes, yielding transient voltages as high as those resulting from impacts of much larger grains of smaller speed. These properties are at the origin of their recent detection at 1 AU in the solar wind. Aspects of detection of fast nanoparticles by wave instruments of different configurations, with applications to the recent detections on STEREO/WAVES and CASSINI/RPWS, as well as the opportunities for nanoparticle detection by wave instruments on future missions in the inner heliosphere such as Bepi-Colombo and Solar Orbiter were discussed. Published in 2 papers in the *Solar Wind 12 Proceedings* and in a paper in *Plasma Physics and Controlled Fusion*.

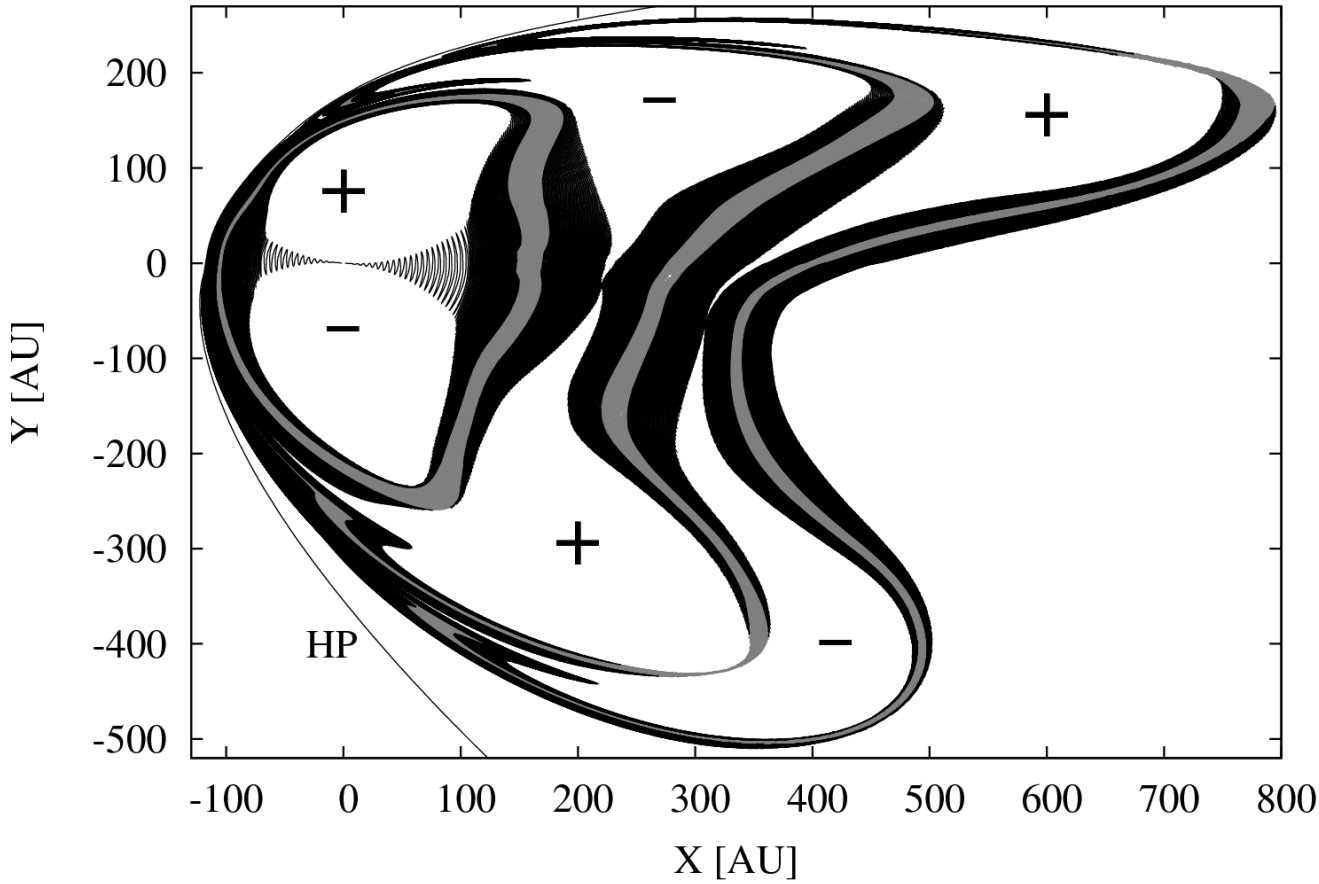
(A. Czechowski in an international research team)

A model of nanodust interaction with the solar wind was developed and applied to nanoparticles dynamics. Results: Assuming that the nanodust grains are created with velocities close to Keplerian, there exists a population of trapped grains within about 0.2 AU from the Sun despite the strong coupling to the magnetic field in the solar wind. Grains created outside this region are accelerated to the velocity of the order 400 km/s provided that the charge-to-mass ratio is not much less than 10^{-5} e/m_p. These values correspond to grain sizes equal to or smaller than about 10 nm. The results were used as basis for interpretation of the observations of dust impacts by STEREO (together with N. Meyer-Vernet): this was the discovery of nanodust. Published in the *Astrophysical Journal*.

(A. Czechowski, I. Mann)

Global structure of the heliospheric current sheet: The heliospheric current sheet (HCS) is a plasma layer dividing the heliosphere into the regions of different magnetic field polarity. Since it is very thin compared to the size of the system, it is difficult to incorporate into numerical models of the heliosphere. Because solar magnetic field keeps reversing and the plasma flow in the outer heliosphere diverges and slows down, the heliospheric current sheet is expected to have a complex structure, with important consequences for transport processes in the heliosheath. The shape and time evolution of the current sheet in selected time-dependent 3-D models of the heliosphere were determined assuming that the heliospheric current sheet is a tangential discontinuity convected by

the plasma flow. The shape of the heliospheric current sheet at a given time was derived by following the plasma flow lines originating at the neutral line on the source surface surrounding the Sun. The plasma flow used was as obtained from numerical MHD or gas-dynamical solutions. It was concluded that the large-scale structure of the magnetic field polarity regions and heliospheric current sheet in time-dependent asymmetric models of the heliosphere differs from the results obtained in simpler models. In particular, in the forward heliosheath it is characterized by secondary folds in the heliospheric current sheet that are caused by the solar wind latitudinal variation over the solar cycle. We present examples illustrating some cases of interest: a "bent" current sheet, and the HCS structure during the magnetic field reversal at the solar maximum. We also discuss the evolution of the magnetic polarity structure in the region close to the heliopause. Published in *Astronomy & Astrophysics*.



The global structure of the heliospheric current sheet and unipolar magnetic field regions in a model heliosphere near solar minimum (cut by the meridional plane).

(A. Czechowski , M. Strumik, J. Grygorczuk, S. Grzędzielski, R. Ratkiewicz)

Reconnection near the heliopause: Recent observations (up to 32 AU) of solar wind reconnection exhausts suggest fairly frequent occurrence of such events on current sheets associated with the ICME fronts and on the heliospheric current sheet (HCS). Comparison of relevant plasma β values and magnetic field strengths with conditions in the heliosheath indicates that reconnection may also take place in the heliosheath, especially towards the heliopause, where the folds of HCS are expected to be pressed together by the slowing of the solar plasma flow. We propose a Fermi I type acceleration mechanism, in which particles gain energy by random collisions with reconnection exhausts expanding typically with local Alfven speed. The most probable place for this process is a (several AU wide) region of tightly folded HCS near the nose of heliopause. The process may in particular provide the mechanism of accelerating the electrons needed for generation of the 2-3 kHz

heliospheric emissions. Published in the *Solar Wind 12 Proceedings*.

(A. Czechowski, S. Grzędzielski, M. Strumik)

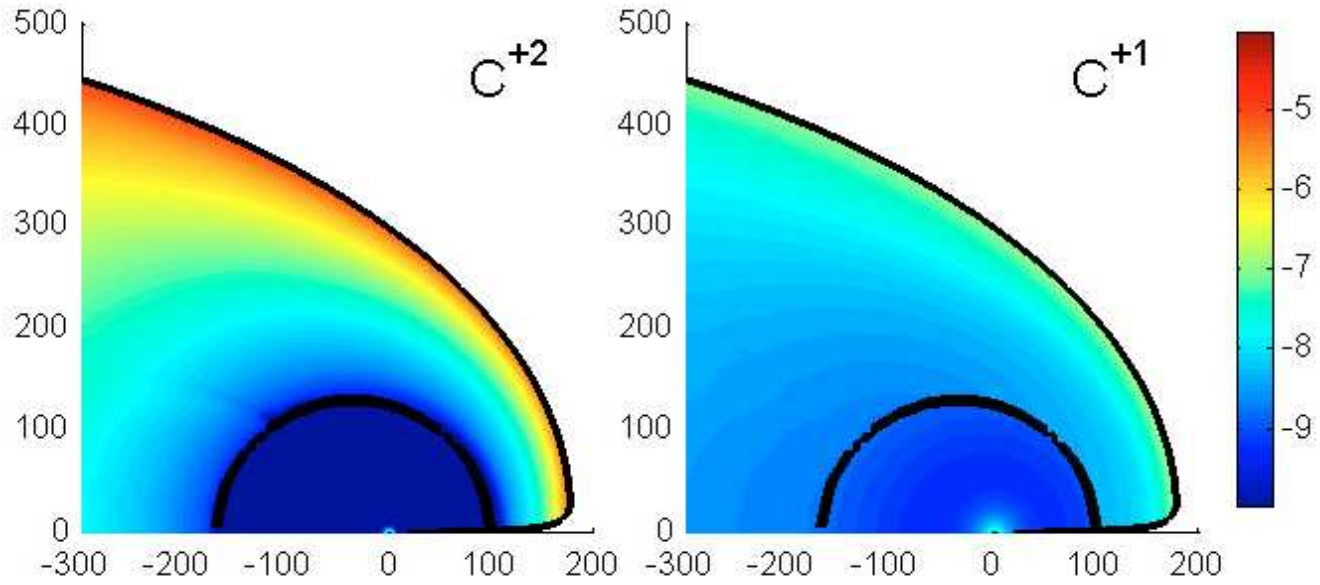
Observations of the heliosphere by means of energetic neutral atoms: Analysis of the observations by HSTOF on SOHO and their theoretical interpretation continued. Using results of remote sensing by energetic neutral atoms from *IBEX*, *SOHO*/HSTOF, and *Cassini*/INCA in situ measurements of 40–4000 keV protons in the heliosheath (HS) from the Low Energy Charged Particle (LECP) experiment on *Voyager 1* and *Voyager 2*, and outputs from numerical modeling of the termination shock, the characteristic thickness L of the HS in the "upwind" direction ($\pm 45^{\circ}$ in ecliptic longitude of the Nose at $\lambda = 255^{\circ}$) was estimated. A simple steady-state, internally consistent model gives $L = 21 \pm 6$ AU for *Voyager 1*, $L = 28 \pm 8$ AU for *Voyager 2*, and $L = 25 \pm 8$ AU assuming that the same L value is valid for both spacecraft. It was recognized that this is a very coarse cut at a very dynamic region of the heliosphere; but if the lower value $L = 21$ AU applies, one could expect *Voyager 1* to cross the heliopause as early as late 2010. Published in the *Astrophysical Journal Letters*.

(A. Czechowski, S. Grzędzielski in an international research team)

Effects of energetic ion transport in the heliosheath were studied under a simple model. Near the heliopause there are two competing processes that affect the ion distribution: adiabatic acceleration and escape loss. One of the consequences is that the ENA flux from the tail is lower at low energy, but becomes dominant above about 60 keV. Therefore the estimates of thickness of the heliosheath that assume uniform ion distribution may be incorrect. Published in *Proceedings of 9-th Annual Astrophysics Conference*.

(A. Czechowski, S. Grzędzielski and an international research team)

Studies of heavy coronal ions in the outer heliosphere: De-charging of elements C, N, O, Mg, Si, and S-ions in the solar wind was studied and fluxes of the resulting ENA in the heliosphere were assessed. Developed was a model that treats the heavy ions as test particles convected by (and in a particular case also diffusing through) a hydrodynamically calculated background plasma flow from 1 AU to the termination shock (TS), heliosheath (HS) and finally heliospheric tail (HT). The ions undergo radiative and dielectronic recombinations, charge exchanges, photo- and electron-impact ionizations with plasma particles, interstellar neutral atoms (calculated in a Monte-Carlo model) and solar photons. Highly-charged heavy coronal ions flowing with the solar wind undergo successive de-ionizations, mainly in the heliosheath, which leads to charge-states much lower than in the supersonic solar wind. If Coulomb scattering is the main ion energy-loss mechanism, the end product of these deionizations are fluxes of ENA of ~1 keV/nucleon originating in the upwind heliosheath, which for C, Mg, Si and S may constitute sources of pickup ions (PUI) significantly exceeding the interstellar supply. Discussed processes result in (i) distinct difference of the ion charge q in the supersonic solar wind (approximately $q \geq +Z/2$, Z = atomic number) compared to that in the HS (approximately $0 \leq q \leq +Z/2$)); (ii) probable concentration of singly ionized atoms ($q = +1$) in the heliosheath towards the heliopause (HP) and in the HT; (iii) possible significant production of ENA in the HS offering natural explanation for production of PUI, and – after acceleration at the TS – anomalous cosmic rays (ACR) of species (like C, Mg, Si, S) unable to enter the heliospheric cavity from outside because of their total ionization in the local interstellar medium. Published in *Astronomy & Astrophysics*.

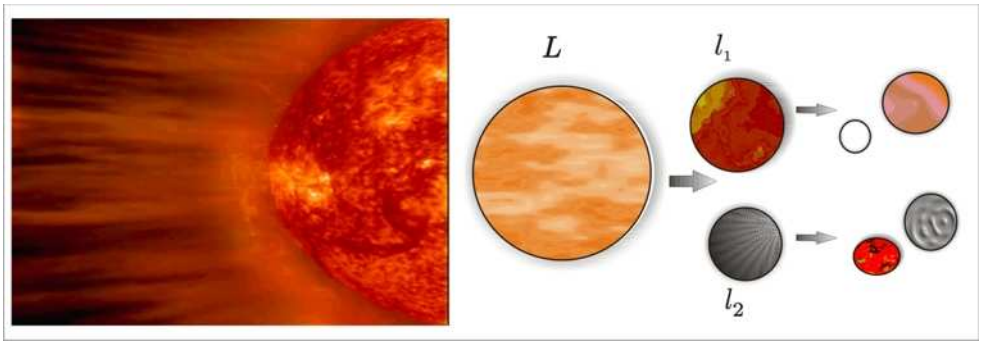


Example distribution of singly- and doubly-charged carbon ions in the heliosphere under assumption of heavy ion isotropization in the heliosheath. These ions may be the principal source of heliospheric carbon pickup ions and ACR populations because it is unlikely that interstellar carbon is able to penetrate inside the heliosphere since it is almost fully ionized.

(S. Grzędzielski, M. Wachowicz, M. Bzowski, V. Izmodenov)

Studies of Alfven waves in magnetohydrodynamics: Multidimensional Alfven simple waves in MHD were investigated using Boillat's formalism. For simple-wave solutions, all physical variables depend on a single phase function ϕ of space and time variables (gas density and pressure, fluid velocity, entropy, and magnetic field induction $\boldsymbol{B}$). The simple-wave ansatz requires that the wave normal $\boldsymbol{n}$ and the normal speed of the wavefront depend only on the phase function. Methods to construct simple-wave solutions based on specifying a solution ansatz either for $\boldsymbol{n}(\phi)$ or $\boldsymbol{B}(\phi)$ were developed. Published in *Journal of Plasma Physics*.

(R. Ratkiewicz in an international research team)



Generalized two-scale weighted Cantor set model for solar wind turbulence.

A review on **studies of multifractal scaling properties of turbulence in the solar wind** was published in *Solar Wind 12 Proceedings***.** Since the work of Burlaga in 1991, various multifractal analyses have been performed to better characterize the intermittency of the fluctuations in the turbulent solar wind. These analyses were based either on the classical structure functions or on the partition function. Recently, two new multifractal analyses have been proposed to better characterize intermittent fluctuations: on one hand, Chang & Wu (2008) proposed a rank-ordered multifractal analysis based on range-limited structure functions instead of the classical ones. On the

other hand, Macek & Szczepaniak (2008) have developed a generalized two-scale weighted Cantor set using the partition function technique. Both methods were presented, with emphasize on their advantages over the previous multifractal analyses. As an illustration, these new multifractal analyses were applied to a set of magnetic field data measured by Ulysses.

A. Wawrzaszek, W.M. Macek in an international research team)

Time series of solar wind velocities during solar minimum conditions (1994 - 1997, 2006 - 2007) at various heliographic latitudes measured in situ by Ulysses was analyzed. Ulysses is the only mission that has investigated parameters of the solar wind out of the ecliptic plane, including the polar regions of the Sun. Non-homogeneous energy transfer rate in the turbulent cascade, which leads to the phenomenon of intermittency, was considered. To quantify the degree of multifractality and the degree of asymmetric scaling of solar wind turbulence, a generalized two-scale weighted Cantor set with two different scales describing nonuniform distribution of the kinetic energy flux between cascading eddies of various sizes was considered. Both characteristics exhibit latitudinal dependence with some symmetry with respect to the ecliptic plane. Generally, at high latitudes during solar minimum in the fast solar wind streams a somewhat smaller degree of multifractality and intermittency was observed in comparison with those at the ecliptic, while multifractal singularity spectrum was roughly symmetric. The minimum of intermittency was observed at mid-latitudes possibly related to the transition from the region where the interaction of the fast and slow streams takes place to a more homogeneous region of the pure fast solar wind. Published in *Journal of Geophysical Research*.

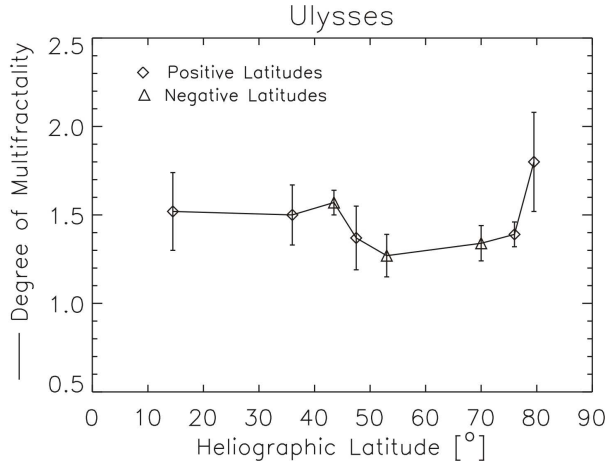


Figure: Degree of multifractality Δ (continuous line) for the slow (at 15°) and fast (above 15°) solar wind during solar minimum (1994 - 1996, 2006 - 2007) in dependence on heliographic latitude below (triangles) and above (diamonds) the ecliptic.

A. Wawrzaszek, W.M. Macek

Multifractal spectrum of fluctuations of the interplanetary magnetic field strengths observed by Advanced Composition Explorer at the Earth's orbit was considered. It was found that the multifractal scaling of magnetic fields is observed both on small and large scales from minutes to days. The multifractal spectrum obtained is asymmetric for small scales, in contrast to a rather symmetric spectrum observed at scales larger than a day. Moreover, it was shown that the degree of multifractality of magnetic fields at large scales is correlated with the solar activity and greater than that at the small scales, where the magnetic turbulence may become roughly monofractal. Published in *Planetary and Space Science*.

W.M. Macek, A. Wawrzaszek

The multifractal spectra of fluctuations of the interplanetary magnetic field strength before and after shock crossing by Voyager 1 near 85 and 95 AU from the Sun, were considered. It was shown that the multifractal scaling of magnetic field is asymmetric in the outer heliosphere, in contrast to the symmetric spectrum observed in the heliosheath. Moreover, the degree of multifractality of the solar wind before shock crossing is greater than that in the heliosheath, where the turbulence may become roughly monofractal. Published in *Solar Wind 12 Proceedings*.

W.M. Macek, A. Wawrzaszek

Studies of hydromagnetic convection: Convection in a horizontally magnetized viscous fluid layer in the gravitational field heated from below with a vertical temperature gradient was considered. Following Rayleigh-Bénard scenario and using a general magnetohydrodynamic approach, a simple set of four ordinary differential equations was obtained. In addition to the usual three-dimensional Lorenz model a new variable describes the profile of the induced magnetic field. It was shown that nonperiodic oscillations are influenced by anisotropic magnetic forces resulting not only in an additional viscosity but also substantially modifying nonlinear forcing of the system. On the other hand, this can stabilize convective motion of the flow. However, for certain values of the model parameters a deterministic intermittent behavior of the system, resulting from bifurcation, was identified. In this way, a basic mechanism of intermittent release of energy bursts, frequently observed in space and laboratory plasmas was identified. Hence, this model can be regarded as a useful tool for analysis of intermittent behavior of various environments, including convection in planets and stars. It is hoped that this simple but still a more general nonlinear model could shed light on the nature of hydromagnetic convection. Published in *Physics Review E*.

W.M. Macek, M. Strumik

Full list of papers and conference contributions authored by members of the Laboratory for Solar System Physics and Astrophysics is available at http://pfusia.cbk.waw.pl/pfusiaPubl.2010.html .