Annual Report 2012: Heliospheric physics[1]

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

As the Sun moves through the local interstellar medium, its supersonic, ionized solar wind carves out a cavity called the heliosphere. Recent observations from the Interstellar Boundary Explorer (IBEX) spacecraft showed that the relative motion of the Sun with respect to the interstellar medium is slower and in a somewhat different direction than previously thought. Based on two very similar assessments of the neutral interstellar helium flow in the heliosphere, found in the previous year, now a combined consensus values for this velocity vector was worked out. The new flow parameters of interstellar matter in the immediate neighborhood of the heliosphere have important implications for the global interstellar interaction. In particular, the velocity is almost certainly slower than the fast magnetosonic speed, with no bow shock forming ahead of the heliosphere as was formerly widely expected. These results were published in a paper in *Science* (M. Bzowski in an international team of scientists)

Having a reference model for how the heliosphere and interstellar winds interact is critical for understanding our current Galactic environment, and it requires untangling the roles of two major actors: the time-variable solar wind and the local interstellar magnetic field. Numerical simulations predict a distortion of the heliosphere caused by both solar wind anisotropy and interstellar magnetic field orientation. Previous model comparisons to deep space probes' measurements led to contradictory reports by *Voyager* 1 and *Voyager* 2 of both several crossings of the solar wind's termination shock and of the strength of the local interstellar field, with values ranging from 1.8 to 5.7 μG. Now it was shown, however, that *Voyager* 1 and 2 plasma, fields, and Lyman-α sky background measurements, as well as space observations of high-energy particles of heliospheric origin, may all be explained by a rather weak interstellar field 2.2 ± 0.1 μG pointing from Galactic coordinates (*l*, *b*) ~ (28, 52) ± 3°. For the 2000 epoch Ulysses-based helium parameters assumed thus far, the interstellar bow shock must exist. By contrast, using the 2010 epoch IBEX-based He parameters and a stronger magnetic field leads to a plasma configuration that is not consistent with the Voyagers TS crossings. For the newly proposed interstellar He parameters, more simulations are required before one may determine whether the interstellar bow shock truly does disappear under those assumptions. These results were published in a research note in *Astronomy & Astrophysics* (L. Ben Jaffel and R. Ratkiewicz)

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

The Interstellar Boundary Explorer (IBEX) has observed Energetic Neutral Atom (ENA) hydrogen emissions from the edge of the solar system for more than three years. The observations span energies from 0.01 to 6 keV FWHM. The unexpected, yet defining feature discovered by IBEX is a ribbon that extends over the energy range from about 0.2 to 6 keV. This ribbon is superposed on a more uniform, globally distributed heliospheric neutral population. As a result of an extensive study carried out in 2012, a complete and validated data set from the first three years (2009-2011) of the IBEX mission was provided. Energetic Neutral Atom (ENA) fluxes were corrected for both the time-variable cosmic ray background and for orbit-by-orbit variations in their probability of surviving *en route* from the outer heliosphere in to 1 AU where IBEX observes them. In addition to showing all six six-month maps, new annual ram and anti-ram maps were introduced, which can be charted without the need for algorithm-

[1] Excerpt from the Annual Report 2012 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 2012 by the members of the Lab is available at http://pfusia.cbk.waw.pl/files/pfusiaPubl.2012.html.

dependant Compton-Getting corrections. Together the ENA maps, data, and supporting documentation support the full release of these data to the broader scientific community and provide the citable reference for them. In addition, it was shown that heliospheric ENA emissions have been decreasing over the epoch from 2009-2011 with the IBEX Ribbon decreasing by the largest fraction and only the heliotail (which is offset from the down wind direction by the interstellar magnetic field) showed essentially no reduction and actually some increase. The much more complete observations resulting from this study strongly indicate a quite direct and latitude-dependant solar wind source of the Ribbon. These results were published in a paper in *The Astrophysical Journal Supplement Series* (M. Bzowski, J.M. Sokół and M.A. Kubiak in an international team of scientists)

With some important exceptions, the focus of early IBEX studies had been on neutral atoms with energies greater than ~0.5 keV. With nearly 3 years of science observations, enough low energy neutral atom measurements have been accumulated to extend IBEX observations to energies below ~0.5 keV. Using the energy overlap of the sensors to identify and remove backgrounds, energy spectra over the entire IBEX energy range were produced. Compared to spectra at higher energies, neutral atom spectra at lower energies do not vary greatly from location to location in the sky, including in the direction of the IBEX ribbon. Neutral fluxes were used to show that low energy ions contribute approximately the same stationary pressure as higher energy ions in the heliosheath. However, contributions to the dynamic pressure are very high unless there is turbulence in the heliosheath with fluctuations of the order of 120 km/s. These results were published in a paper in *The Astrophysical Journal* (M. Bzowski, M.A. Kubiak in an international team of scientists)

At energies greater than 0.5 to 6 keV, and for a travel distance of ~100 AU, the travel time difference between the slowest and the fastest ENA is more than a year. Therefore, the effect that slower ENAs left the source at an earlier time than faster ones was taken into account in constructing the ENA spectra in their source region in the heliosheath. If the source produces a steady rate of ENAs and the extinction does not vary, then it is expected that the spectral shape would be time independent. However, while the extinction of ENAs has been fairly constant during the first two and a half years, the source appears to have changed, and thus the spectra at a single time may not represent the conditions at the source. IBEX's viewing allows continuous sampling of the ecliptic poles where fluxes can be continuously monitored. For a given source distance, spectra assuming that the measured ENAs left the source at roughly the same time were calculated. To accomplish this construction, time lag corrections to the signal at different ENA energies were applied. These corrections take into account the travel time difference. Based on these corrected spectra it was shown that the spectral shape at the poles exhibits a statistically significant change with time within a time interval corresponding to the IBEX observations time of ~3 years. These results were published in a paper in *The Astrophysical Journal Letters* (M. Bzowski, M.A. Kubiak in an international team of scientists)

The ecliptic poles are observed continuously by the *Interstellar Boundary Explorer* (*IBEX*); thus, it is possible to discern temporal variations in the ENAs from the outer heliosphere on time scales much shorter than the time it takes for *IBEX* to generate a full sky map (6 months). Observations indicate that the ENA flux from the polar directions incident at Earth has been steadily decreasing for the two-year period from December 2008 through February 2011. Over the IBEX-Hi energy range, the decrease in flux is energy dependent, varying at the south ecliptic pole from no drop at 0.71 keV, to 70% at 1.1 keV. At higher energies the drop ranges between 10% and 50%. The decline observed at the north ecliptic pole is as high as 48%, also at 1.1 keV. The trend correlates with the steady decline in solar wind dynamic pressure observed at 1 AU between 2005 and 2009, the likely period when solar wind protons that provide the source for ENAs observed by *IBEX* would have been outbound from the Sun. We propose a method by which the correlation between the 1 AU solar wind dynamic pressure and the ENA-derived pressure within the inner heliosheath (IHS) can be used to estimate the distance to the termination shock and the thickness of the IHS in the direction of the ecliptic poles. The new analysis based on *IBEX* data showed the TS distances to be 110 AU and 134 AU at the south and north poles, respectively, and the corresponding IHS thicknesses to be 55 AU and 82 AU. This analysis is consistent with the notion that the observed ENA fluxes originate in the inner heliosheath and their variations are driven by the solar wind as it evolves through the solar cycle. These papers were published in a paper in *The Astrophysical Journal* (M. Bzowski, M.A. Kubiak in an international team of scientists)

A model of heliosheath density and energy spectra of alpha-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, gives rise to ~0.2 – ~100 keV fluxes of energetic neutral He atoms. Such fluxes, if observed, would give information about plasmas in the heliosheath and heliospheric tail. Helium ions crossing the termination shock constitute suprathermal (test) particles convected by hydrodynamically calculated background plasma flows. Locally, the He ions also diffuse through the ambient plasma. Three alternative versions of the flows are employed in the study. The He ions proceed from the termination shock towards the heliopause and finally to the heliospheric tail. Calculations of the evolution of alpha- and He^+ particle densities and energy spectra include binary interactions with background plasma and interstellar atoms, adiabatic heating (cooling) resulting from flow compression (rarefaction), and Coulomb scattering on background plasma. Based on the developed models it was shown 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 (kappa-distributions were assumed), 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 by the instruments of the IBEX spacecraft. Data could offer insight into the heliosheath structure and improve understanding of the post-termination shock wind plasmas. The heliotail direction and extent could be assessed. These results were published in *Astronomy & Astrophysics* (S. Grzędzielski, P. Swaczyna, M. Bzowski)

Detection and modeling of nanodust in the solar wind

After the discovery of nanodust particles in the solar wind, dust impacts recorded by the S/WAVES radio instrument onboard the two STEREO spacecraft near 1 AU during the period 2007–2010 were analyzed. The impact of a dust particle on a spacecraft produces a plasma cloud whose associated electric field can be detected by on-board electric antennas. For this study the electric potential time series recorded by the waveform sampler of the instrument was used. The high time resolution and long sampling times of this measurement enabled extracting considerably more information than in previous studies based on the dynamic power spectra provided by the same instrument or by radio instruments onboard other spacecraft. The large detection area compared to conventional dust detectors provides flux data with a better statistics. It was shown that the dust-generated signals are of two kinds, corresponding to impacts of dust from distinctly different mass ranges and that it is possible to use S/WAVES as a dust detector with convincing results both in the nanometer and micrometer size ranges. Appropriate calibration formulas were proposed. The orbital motion of the spacecraft enables distinguishing between interstellar and interplanetary dust components. The measurements reported cover the mass intervals ~10^{-22} – 10^{-20} kg and ~10^{-17} – 5×10^{-16} kg. The flux of the larger dust agrees with measurements of other instruments on various spacecraft. These results were published in a paper in *Journal of Geophysical Research* (A. Czechowski in an international team of scientists)

Studies of multifractal scaling properties of interplanetary magnetic field

First results of the multifractal scaling of the fluctuations of the interplanetary magnetic field strength as measured onboard Voyager 2 in the very distant heliosphere and in the heliosheath were obtained. The spectra observed by Voyager 2 in a wide range of heliospheric distances from 6 to 90 AU were compared with previously analyzed spectra from Voyager 1 observed between 7 and 107 AU. The focus was on the singularity multifractal spectrum before and after crossing the termination heliospheric shock by Voyager 1 at 94 AU and Voyager 2 at 84 AU from the Sun. It was shown that the spectrum is prevalently right-skewed inside the whole heliosphere. It was discovered that there a change of the asymmetry of the spectrum at the termination shock occurs. The spectrum changes from (left-) right-skewed in the very distant heliosphere to the (right-) left-skewed or possibly symmetric spectrum in the heliosheath. It was confirmed that the degree of multifractality falls steadily with the distance from the Sun. In addition, the multifractal structure is apparently modulated by the solar activity, with a time shift of several years, corresponding to a distance of about 10 AU, resulting from the evolution of the whole heliosphere. Hence this basic result also brings significant additional support to some earlier claims suggesting that the solar wind termination shock is asymmetric. These results were published in a paper in *Journal of Geophysical Reserarch* (W.M. Macek, A. Wawrzaszek, V. Carbone)