Annual Report 2014: Heliospheric Physics[1]

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Studies of the heliospheric boundary region and Galactic neighborhood of the Sun

The supersonic, ionized solar wind, emitted by the Sun, carves out a cavity in the interstellar matter called the heliosphere. Its size is determined by a balance between the pressures of the magnetized solar wind and the interstellar gas, which is also magnetized. The heliosphere is bounded by a contact discontinuity layer called the heliopause, which separates the solar wind and interstellar plasmas. While the interstellar plasma is deflected and flows past the heliopause, the neutral component, mainly hydrogen and helium, with small admixtures of other species, like oxygen, neon, and deuterium, penetrates freely into the heliosphere, where it can be directly observed.

The distance to the heliopause had been unknown until recently, when the Voyager 1 spacecraft, which in the last quarter of the 20th century had visited all giant planets of the Solar System, crossed the heliopause. The identification of this event was not immediately obvious from the available data and in fact is still contested by some members of international community of heliospheric researchers. Scientists from the SRC actively participated in the debate.

One of the unexpected developments from the Voyager data was the direction of the ambient magnetic field. Intuitively, scientists expected that crossing the heliopause should be marked by an abrupt change in the intensity of the anomalous component of cosmic radiation (ACR) and galactic cosmic radiation (GCR), as well as and in the direction of the ambient magnetic field. While indeed the CR intensity showed an abrupt change (which, by the way, was the principal evidence for the heliopause crossing), the direction of magnetic field changed very little. A team of SRC scientists led by J. Grygorczuk proposed a very simple and natural explanation for these measurements. Interstellar magnetic field (ISMF) is "frozen" in the interstellar plasma and when the plasma flows past the heliopause, the field lines are draped around it, which means they should be locally tangent to the heliopause. The direction of the magnetic field inside the heliopause, i.e., in the inner heliosheath, follows the Parker spiral and thus at the Voyager location it should be contained in the local plane parallel to the solar equator. The direction of the unperturbed ISMF is very likely parallel to the direction to the center of the Ribbon of enhanced emission of energetic neutral atoms, discovered in 2009 by the science team of the Interstellar Boundary Explorer mission. If so, then by coincidence the heliolatitude of the point of Voyager crossing the heliopause and of the direction of ISMF are very similar, and the angular distance between these two directions is relatively small. Thus, as the SRC researchers argue, the direction of draped ISMF at this point just happens to be almost parallel to the direction of the field inside the heliopause. The intensity of the field changes as expected. Detailed MHD modeling showed that the small direction difference shown in the Voyager measurements is in agreement with the predicted difference for the assumed direction conforming with the Ribbon center and strength of ~3 μG. This finding lends support to the hypothesis that Voyager 1 has crossed the heliopause indeed, which happened at ~122 AU from the Sun, much closer than anticipated. The team of SRC scientists points out that since the geometry of the trajectory of Voyager 2 and ISMF is

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[1] Adapted from The Space Research Centre PAS Annual Report 2014, partly based on abstracts of papers authored or co-authored by members and PhD students of the Lab. The full list of papers published in 2014 by the members of the Lab is available http://pfusia.cbk.waw.pl/files/pfusiaPubl.2014.html.

different, so the jump in the direction of the measured magnetic field will also be different when the latter spacecraft crosses the heliopause at some time in the future. These findings were published by J. Grygorczuk, A. Czechowski, and S. Grzedzielski in *The Astrophysical Journal Letters*.

Another indirect evidence of crossing the heliopause by Voyager 1 was offered by a team of SRC scientists led by W.M. Macek. During past years, the team studied the multifractal character of the solar wind plasma, analyzing time series of solar wind speed and magnetic field based on observations carried out from the immediate solar neighborhood (~0.3 AU) up to 120 AU and using measurements from many spacecraft, spanning almost 40 years. The solar wind plasma has been known to be turbulent and the SRC scientists showed a few years ago that the turbulence is intermittent in the entire heliosphere, even in the outer heliosheath, which can be described by a phenomenological multifractal model based on a generalized Cantor set with two rescaling and one weight parameter. Last year, the team analyzed magnetic field measurements carried out by Voyager 1 during the time when the spacecraft was certainly in the inner heliosheath and also after the abrupt change in the CR intensity had been observed. They showed that the degree of multifractality decreases with the heliocentric distance and is correlated with variations of solar activity throughout the heliosphere, including the inner heliosheath. But after the rapid change in CR intensity, the variation in the measured magnetic field changed the character: the modulation stopped, and the scaling parameters in the multifractal model changed, drifting towards a non-intermittent (non-multifractal) behavior. This qualitative change suggests that Voyager 1 is now in a different plasma than the solar wind plasma, as expected after the crossing of the heliopause, which separates the solar and interstellar plasmas. The team predicts that a similar change in the multifractality of the ambient magnetic field is expected also when Voyager 2 will have crossed the heliopause in the future, which potentially may be used as evidence for the heliopause crossing. These findings were published by a team of SRC scientists W.M. Macek and A. Wawrzaszek, supported by L.F. Burlaga, in a paper in *The Astrophysical Journal Letters*, and reviewed by W.M. Macek in a paper in the *Proceedings of ITISE 2014*.

In attempt to better understand the behavior of the ambient plasma during the passage of the Voyager 1 spacecraft through the boundary region near the heliopause, and in particular of the ambient magnetic field, which featured a series of abrupt changes in strength and to some degree in direction, a team of SRC scientists led by M. Strumik carried out a detailed hydromagnetic modeling of the plasma dynamics near the heliopause. The model was validated by calculating the expected variation of the ambient magnetic field vector on a virtual spacecraft following the trajectory of Voyager 1 during the crossing of the heliopause. The model field showed a very good agreement with the observed time series. This enabled the researchers to propose an explanation for the characteristic features in the Voyager observations as due to dynamical processes driven by magnetic reconnection, occurring at two closely separated current sheets: the heliospheric current sheet and the heliopause. The model showed that density intrusions (enhancements) should appear in the plasma just inside the heliopause, which may be indicative of an advective transport of the relatively dense interstellar plasma across the heliopause region. This hypothetical transport may be responsible for the density enhancements in the inner heliosheath, indirectly observed by Voyager 1. At present, it is not clear how the advective transport effects predicted by the model are related to the abrupt CR intensity jumps, observed by Voyager. The density enhancements from the model may shed some light on the problem of the heliospheric current sheet (HCS) pile-up problem. The HCS folding are constantly produced by the changing magnetic polarity of the Sun and advected by the solar wind to the inner heliosheath, up to the heliopause. Voyager 1observations suggest that at least some of the HCS foldings and the magnetic sectors between them survive the advective transport in the turbulent solar wind and appear very close to the heliopause. This suggests that the solution to the HCS pileup problem near the heliopause may be the annihilation of magnetic sectors in the direct heliospheric neighborhood. Thus the density intrusions shown by the simulations in the inner heliosheath might be expected to repeat periodically in the nature. These findings were published by a team of SRC scientists including M. Strumik, S. Grzedzielski, A. Czechowski, W.M. Macek, and R. Ratkiewicz in a paper in *The Astrophysical Journal Letters*.

SRC scientists worked on a resolution of the so-called IBEX-Ulysses dilemma on the flow vector and temperature of interstellar neutral helium (ISN He) in the heliosphere. Before IBEX launch in 2008, these parameters had been considered as well known and used as baseline for the heliospheric studies. They were established by an international team of scientists, including D. Ruciński and M. Bzowski from SRC PAS, who analyzed data from different spacecraft and observation techniques. The solution they came up with was mostly based on results of analysis of observations obtained from the GAS experiment onboard the Ulysses spacecraft. The experiment development and data analysis had been carried out with a contribution from SRC PAS (M. Banaszkiewicz, M. Hłond, T. Żarnowiecki, S. Błeszyński) and its operation ceased in 2007 with the end of the Ulysses mission.

The Interstellar Boundary Explorer' (IBEX), launched in 2008, samples the ISN He gas from the Earth orbit. Preliminary analysis of measurements of interstellar neutral He flux by a team of IBEX researchers led by SRC scientists (M. Bzowski, M.A. Kubiak, J.M. Sokół, M. Hłond) showed that statistically the most likely flow vector of the gas relative to the Sun is different than the one measured beforehand, but the temperature is in agreement. A statistically less likely, but still acceptable solution was that the flow vector is in agreement with the earlier measurements, but then the temperature must be significantly higher. Based on the statistically more likely solution and on other recent evidence from heliospheric observations, P.C. Frisch with a team including M. Bzowski and J.M. Sokół from SRC PAS pointed out that measurements of the direction of the ISN He inflow vector carried out over the past 40 years are statistically consistent with a temporal change in the direction of the flow. The measurements of the ISN He flow vector and temperature from the last decade of the 20th century were statistically dominated by direct-sampling observations from GAS. Ulysses carried out observations within a long time interval from 1992 to 2007 and the measurements were collected during three seasons, when the spacecraft was in the perihelion part of its polar orbit around the Sun, but the last season was left not analyzed.

In attempt to resolve the IBEX—Ulysses dilemma, a team of SRC scientists led by M. Bzowski reanalyzed the GAS data, including the previously not analyzed last observation season. The team included the key personnel who previously had analyzed the IBEX and GAS data. The analysis method and simulation program were analogous as in the analysis of the IBEX data. The results showed that the velocity vector obtained in the original analysis is supported, which means it is different from the statistically most likely solution obtained from the analysis of IBEX data. The results from all three observation seasons agree with each other, which implies that there is no statistically significant evidence of a change with time. But the temperature originally obtained from the Ulysses analysis needs revision: the value obtained from the present study is higher by ~1000 K. This study was published by a team of SRC scientists M. Bzowski, M.A. Kubiak, M. Hłond, J.M. Sokół, and M. Banaszkiewicz, supported by the former PI of the GAS experiment M. Witte, in *Astronomy & Astrophysics*.

Continuing studies of ISN He, SRC scientists leading an international scientist team discovered a new population of neutral helium in the heliosphere, which they dubbed "The Warm Breeze". This tenuous population of neutral gas flows into the heliosphere from a direction different by ~20° from the direction of ISN He at a speed lower by half than ISN He, but is substantially – more than two-fold –

warmer. Its density in front of the heliosphere is ~7% of the density of the ISN He population. The nature of the Warm Breeze is not clear. The discovery team checked that the source gas is more likely in thermal equilibrium than featuring departures from the equilibrium described by a kappa function. Two working hypotheses formulated by the discovery team are (1) the Warm Breeze is the secondary population of ISN He, which is expected to come up in the outer heliosheath, or (2) it is a "gust" of neutral He in the ambient interstellar medium, which was created within ~10 000 AU from the Sun by an unknown process. A hypothetical cause of this process might be a mechanism similar to the mechanism suggested by Grzedzielski et al. 2012 to be responsible for the IBEX H Ribbon, i.e., effect of charge exchange between neutral atoms and helium ions in a boundary layer between the nearby edge of the Local Interstellar Cloud and a highly ionized, warm or hot medium, like the Local Bubble. The SRC researchers found that because the charge exchange and elastic collisions of neutral He atoms H and He neutral atoms and ions have the differential cross section strongly preferring forward scattering, the spatial range of such a hypothetical gust may be on the order of 10^4 AU, which is in agreement with current estimates of the distance from the Sun to LIC boundary. The alternative hypothesis, i.e., that the Warm Breeze is the secondary population of neutral He which comes up due to the increased charge exchange rate between the IS He and He^+ in the outer heliosheath, was qualitatively verified by dedicated Monte Carlo modeling, carried out by international members of the discovery team using a sophisticated model of the heliosphere. The deflection of the inflow direction of this hypothetic secondary component from the direction of the original ISN He is due to the distortion of the outer heliosheath, caused by the interaction of the heliosphere with the interstellar magnetic field. The expected magnitude of the deflection, the reduction in speed and increase in temperature are in qualitative agreement with the values found from the fitting of the model to the data collected by IBEX-Lo during the 2009/2010 IS neutrals observation season. This discovery was published in *The Astrophysical Journal Supplement Series* by an international team of scientists led by M.A. Kubiak and including M. Bzowski, J.M. Sokół, P. Swaczyna, and S. Grzedzielski from SRC.

Studies of the chemical composition of interstellar gas in the immediate solar neighborhood

SRC scientists participated in studies of the chemical composition of the interstellar gas in the solar environment. To that end, they updated the earlier developed models of the ionization factors of neutral gas in the heliosphere, in particular of the photoionization by the solar EUV radiation. This aspect is still challenging due to the lack of long-term stability of the EUV photometers on one hand, and to the secular changes in the solar activity on the other hand, which results in possibly changing correlations between various parts of the solar spectrum. In effect, maintaining a homogeneous, well-calibrated, long-term time series of the solar EUV flux in the wavebands responsible for photoionization of H, He, O, and Ne requires cross-correlating the so-called solar proxies and direct measurements. A team of SRC scientists including J.M. Sokół and M. Bzowski participated in this effort, developing a time series of Carrington-rotation averaged photoionization rates for these species based both on direct and indirect evidence, which reflects the current knowledge of the instrument degradation effects. This time series is the basis for further studies of interstellar neutral gas in the heliosphere. It was published by an international team of scientists led by P. Bochsler and including J.M. Sokół and M. Bzowski from SRC PAS in a paper in *The Astrophysical Journal Supplement Series*, and as an update by J.M. Sokół and M. Bzowski in a report posted on the ArXiv.

With the updated ionization model, SRC scientists participated in finalization of studies of the abundance of deuterium in the interstellar gas, begun earlier by an international team of scientists from the Science Team of the Interstellar Boundary Explorer (IBEX) mission, led by D. Rodriguez. The last year's effort focused on refining the signal processing aspect of the measurement, which is challenging because the very small number of expected D atoms must be first identified in the complex signal registered by the IBEX-Lo instrument, and then the atoms from the interstellar space must be discerned from the D atoms sputtered from the thin layer of terrestrial water covering the active surface of the detector. The results of this study were published by a team lead by D. Rodriguez, with M. Bzowski, M.A. Kubiak, and J.M. Sokół from SRC PAS in *Entropy*.

Another international team of IBEX researchers studied the abundance of Ne/O in the immediate interstellar medium based on observations from the IBEX-Lo instrument. A preliminary study published in 2012 by Bochsler, et al. suggested that this abundance is much higher than solar. In 2013, a team lead by M. Bzowski from SRC PAS analyzed the attenuation of interstellar neutral atom flux inside the heliosphere by ionization by solar factors based on a detailed model of the ionization losses and concluded that the measurements of the Ne/O abundance at IBEX were consistent with the Ne/O abundance in the local interstellar gas very close to solar. During the report year, a team lead by J.W. Park meticulously analyzed the observations from a longer time interval and came up with a modified assessment of the Ne/O abundance at IBEX. Using the updated model of the ionization losses developed in SRC PAS, the team concluded that the abundance of Ne/O in the Local Interstellar Cloud is higher from the solar abundance and equal to 0.33 ± 0.07, which is in agreement with indirect assessments based on measurements of pickup ions. These findings were published by the team led by J.W. Park and including M. Bzowski, J.M. Sokół, and M.A. Kubiak from SRC PAS in a paper in *The Astrophysical Journal*.

Studies of the distant heliosphere by remote-sensing observations of Energetic Neutral Atoms

Researching the outer heliosphere and the heliospheric boundary region on a global scale is currently possible solely by remote sensing with the use of energetic neutral atoms (ENA), which are the products of the charge exchange reaction between the solar wind ions from the local plasma and the neutral H atoms from the Local Interstellar Cloud, freely drifting into the heliosphere. Since the resonant charge exchange reaction between H atoms and protons for energies on the order of 1 keV occurs practically with no momentum exchange, the ENA resulting from this reaction bring information on the distribution function of the parent plasma. This information can be carried at distances on the order of ~100 AU because the ionization losses underway are limited, and the ENA are immune to electromagnetic forces and travel solely under the influence of solar gravity and resonant radiation pressure, which are well understood.

The IBEX Science Team, including researchers from SRC, published a review study, collecting conclusions from the first 5 years of IBEX operations. The full-sky maps from 5 years, corrected for attenuation due to ionization and for the Compton-Getting effect, show the IBEX Ribbon, which dominates the sky on energies up to ~1.7 keV, but at higher energies it starts to decompose and almost vanishes at ~4.3 keV. The global signal varies with time and generally seems to be correlated with the weakening of the solar wind. This global study, in which the SRC team composed of M. Bzowski, J.M. Sokół, and M. Kubiak were particularly responsible for the corrections of the signal for ionization losses, was led by the IBEX PI D.J. McComas and published in *The Astrophysical Journal Supplement Series*.

Complementary to this study was decomposing of the observed ENA emission into the portions due to the IBEX Ribbon and the distributed heliospheric flux. This program was initiated by a team of IBEX researchers led by N.A. Schwadron in 2011, and now extended to encompass the observations taken during the first five years of IBEX operation. Using a specially developed algorithm, the team extracted the signal due to the Ribbon and interpolated the global heliospheric flux into the geometric locations covered by the Ribbon on the sky, to analyze the properties of the Ribbon and the distributed flux separately. This analysis brought a number of important results. (1) The global distributed ENA flux was found to feature an asymmetry both in the thickness of the heliosheath near the helioltail and an offset of the tail. The heliosheath appears to be thinner at the port side (i.e., opposite to the side from which the Warm Breeze is coming), and the tail is shifted to the starboard direction. These asymmetries are likely a result of compressing and draping of the interstellar magnetic field on the heliosphere. The heliotail signature fades out at the highest energies observed by IBEX. (2) The cooling-length limit for the ENA lines of sight decreases with increasing energy, which is consistent with fading out the heliotail signature at energies above ~1.7 keV, where the cooling length is reduced below ~100 AU. (3) The width of the Ribbon broadens towards the nose of the heliosphere, and narrows towards the tail, which seems to be consistent with the draping of the interstellar magnetic field on the heliopause. (4) It seems that during the 5 years of IBEX observations, the pressure in the nose region of the heliosheath significantly dropped, consistently with the drop in the flux of solar wind that was observed from 2006 to 2010. (5) Details of the creation of the Ribbon remain enigmatic. It seems that it is not produced in any well defined region in three dimensions in space. This finding is important because it invalidates a class of presently considered models of the ribbon creation. The study was published in *The Astrophysical Journal Supplement Series* by an international team of researchers led by N.A. Schwadron and including M. Bzowski, M.A. Kubiak, and J.M. Sokół from SRC.

In addition to these resume studies, a number of particular aspects of IBEX observations were analyzed. IBEX researchers, including the IBEX team from SRC, studied the distribution of ENAs from the lower energy range accessible by IBEX, i.e., from the IBEX-Lo instrument. The spectral range of the sensitivity of this instrument spans from 10 eV to ~2 keV, but the heliospheric signal is only registered at energies above 100 eV, as shown in separate studies led by S. Fuselier and A. Galli, with participation of SRC scientists. The study focused on the lowest-energy heliospheric signal, not analyzed up to now because of the poorly investigated background. This background was investigated and the study showed that in addition to the heliospheric and magnetospheric signal there is another component of unknown origin, most probably instrumental. This component is approximately uniformly distributed on the sky and is the dominant portion of the signal in the so-called anti-ram hemisphere of the Sun, i.e., in the hemisphere facing in the opposite direction to the Earth's motion. With this local background and magnetospheric foreground identified, it was possible to study the heliospheric portion of the signal down to ~15 eV in energy. It was shown that the IBEX ribbon, which is the strongest at energies to the slow solar wind energy, gradually fades away and decomposes towards lowest energies and cannot be identified below ~0.1 keV. The energy spectra of heliospheric ENAs follow an uniform power law down to 0.1 keV in the low-energy portion of the spectrum. These findings were published in two papers in *The Astrophysical Journal*, authored by international teams of IBEX researchers, led by S. Fuselier and P. Galli, with M. Bzowski, J.M. Sokół, and M.A. Kubiak from SRC.

Continuing the investigation of the spectrum of heliospheric ENA, another team of IBEX researchers analyzed in detail the spectra collected during three years of IBEX observations gathered from small regions on the sky where the two Voyager spacecraft are visible. This approach enables synergizing the in situ measurements of the inner heliosheath plasma obtained from the Voyagers with the line-of-sight global view from IBEX. The researchers found that the IBEX spectra for energies above ~0.7 keV are composed mostly of ENAs originating from the pickup ions created in the inner heliosheath, and that a significant fraction of the lower-energy ENAs between ~0.1 and 0.5 keV may originate from interstellar neutral gas charge exchanging with a non-thermalized, hot population of pickup ions in the outer heliosheath, i.e., from beyond the heliopause. This implies that careful studies of various portions of the ENA spectra seen by IBEX may bring insight into the physical processes operating in different regions of the distant heliosphere. These findings were published in *The Astrophysical Journal* by an international team led by M.I. Desai, including M. Bzowski, M.A. Kubiak, and J.M. Sokół from SRC.

Pioneering researching He ENA from the heliosphere and the Local Interstellar Cloud

SRC scientists pioneer the research of energetic neutral atoms of helium (He ENA). Helium is the second abundant species in the universe and thus it is plentiful in space. While it is a substrate of charge exchange reactions just as hydrogen, its properties make it a potential unique source of information on the neighboring interstellar medium at the distance range of 0.01 – 0.0.05 pc from the Sun, too close for the traditional telescopic observations. Analysis by PhD student in SRC P. Swaczyna showed that neutral He atoms can travel large distances of ~0.1 pc in the LIC before they are thermalized in the ambient gas, which offers a potential opportunity to study processes resulting in intense charge exchange reactions within a few thousand of AU around the Sun, i.e., at distances consistent with the hypothetical distance to the boundary of the Local Interstellar Cloud. This finding was published as a preliminary insight in the discovery paper on the Warm Breeze, as presented earlier in this report. Another study by SRC researchers showed that He ENA can be used as a discriminating observable for some hypotheses of the IBEX Ribbon origin. They developed models of the expected He ENA emission from the heliosphere, including the IBEX Ribbon, if it is created near the heliosphere due to a multitier process of charge exchanges between various populations of heliospheric particles. This mechanism was proposed in 2010 by Heerikhuisen et al. for H ENA and is currently the preferred model of the Ribbon creation. The SRC researchers showed that creating He ENA in the Heerikhuisen mechanism results in a very weak He ENA Ribbon, mostly because the supply of the parent He ENA from the heliosphere will be low. The strongest He ENA signal is expected from the heliospheric tail and generally, regardless of details, which are still not known well enough, the He ENA intensity from the heliosphere should be very low, making it just a foreground for a possible He ENA signal from outside the heliosphere. The researchers modeled also the He ENA signal in the alternative hypothesis for the origin of the Ribbon, proposed by SRC scientists, led by S. Grzedzielski, a few years ago. In this hypothesis, Ribbon is a geometric effect, and the ENA are produced by charge exchange of the neutral atoms from the LIC penetrating a nearby hot interstellar plasma. In the report year, an equivalent model for the He ENA emission was developed. It was shown that a LIC boundary within a few AU from the Sun could produce a Ribbon of intensity exceeding by far the intensity expected from the heliospheric mechanism. Thus, if Ribbon is observed in He ENA at some time in the future, it will be a strong evidence for the extra-heliospheric hypothesis of the Ribbon origin. These findings were published by SRC researchers P. Swaczyna, S. Grzedzielski and M. Bzowski in *Astronomy & Astrophysics*.

He ENA have been already observed in the heliosphere. Since 1996, during periods of low solar activity the instrument HSTOF onboard the SOHO spacecraft has been measuring weak fluxes of He ENA at energies 28 – 58 keV/n. The source region for these atoms was unknown, but hypothesized to be the inner heliosheath. A team of SRC researchers led by S. Grzedzielski carried out a study to better understand the emission mechanism for He ENA based on the knowledge of the spatial extent of the heliosheath and its plasma content that emerge from Voyager 1 and 2 measurements after these spacecraft crossed the termination shock of solar wind. In the mechanism studied by the SRC researchers, the relatively high-energy He ENA are generated by the neutralization of energetic He ions by charge exchange with neutral interstellar H and He atoms flowing into the heliosphere from the Local Interstellar Cloud. The expected energy spectra of the parent He ions were calculated by following the evolution of their velocity distribution function while these ions are carried by the inner heliosheath plasma and undergo binary collisions with the ions from the ambient plasma. The ambient plasma flow is modeled approximately, so that it agrees with the measurements from Voyagers. Based on this study, the researchers concluded that the high-energy He ENA observed by HSTOF are indeed the high-energy portion of the population of heliospheric He ENA and within $\pm 2\ \sigma$ uncertainty can be explained by the proposed generation mechanism. The main factor determining the level of the ENA emission and its uncertainty is the energy spectrum of the parent He^+ pickup ions in the plasma downstream of the termination shock. These findings were published in *Astronomy & Astrophysics* by SRC researchers S. Grzedzielski, P. Swaczyna, and A Czechowski, supported by M. Hilchenbach from the HSTOF instrument team.

Studies of various space plasma processes

Dynamics of irregular flows in viscous fluids is still not sufficiently well understood. SRC scientists W.M. Macek and M. Strumik carried out theoretical research that shed light on the problem of hydromagnetic convection. The behavior of a hydromagnetic convective system can be quite complex: from equilibrium or regular (periodic) motion, through intermittency, where irregular and regular motions of the fluid are intertwined, to a non-periodic behavior. Two types of such non-periodic flows are possible, namely chaotic and hyperchaotic motions. As discovered by Lorenz in 1963, deterministic chaos exhibits sensitivity to initial conditions so that the long-term behavior of the system becomes unpredictable (the “butterfly effect”, i.e., a change in the initial conditions as tiny as the effect of flapping butterfly wings results in a totally different solution). Obviously, *hyperchaos* is a more complex non-periodic flow, which has now been discovered in the generalized Lorenz model, previously proposed by the authors in 2010. The results of the present study illustrate how all these complex motions can be studied by analyzing this simple model. In particular, it is shown that various kinds of complex behavior are closely neighbored depending on two control parameters of the model (see figure). Naturally, the convection appears in plasmas, where electrically charged particles interact with the magnetic field. Therefore, the obtained results could be important for explaining dynamical processes in solar sunspots, planetary and stellar liquid interiors, and possibly for plasmas in nuclear fusion devices. It is worth noting that in order to get similar information from direct numerical simulations one would require many years of instantaneous computations using tremendous computational resources. Results of this study were published in a paper in *Physical Review Letters*.

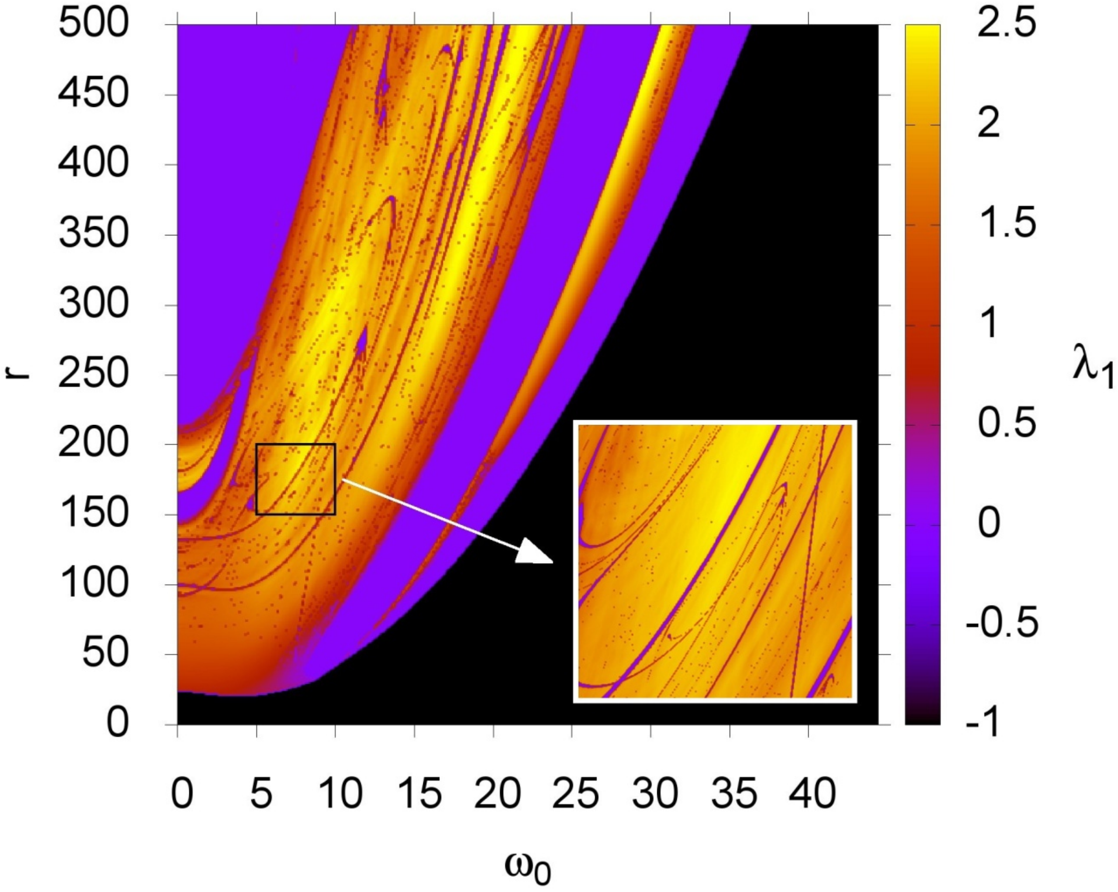

Figure. Different kinds of motions, shown in colors, are closely neighbored in the parameter space depending on two control parameters of the model related to an initial temperature gradient r and magnetic field applied to a thin fluid layer ω_0.