NKFIH / OTKA FK128548
2018/10/01-2019/03/31 & 2020/04/01-2023/09/30 (48 months)

Inner Heliosphere

Participants

- Dr. Andrea Opitz (PI: 2018-2023) - Senior Research Fellow (Wigner RCP)
- DSc. Géza Erdős (senior member: 2018-2023) - Scientific Advisor -> Retired Research Associate (Wigner RCP)
- Dr. Péter Kovács (junior member: 2022-2023) - Research Fellow -> Senior Research Fellow (Wigner RCP)
- Dr. Melinda Dósa (junior member: 2018-2021) - PhD student -> Research Fellow (Wigner RCP)
- Dr. Mohammed Talafha (junior member: 2023) - Research Fellow (Wigner RCP)
- Ákos Madár (junior member: 2020-2023) - PhD student (Eotvos University and Wigner RCP)
- Nikolett Biró (junior member: 2021-2023) - PhD student (Eotvos University and Wigner RCP)
- Gergely Kobán (junior member: 2021-2023) - PhD student (Eotvos University and Wigner RCP)
- Gábor Tróznai (junior member: 2018-2023) - Research Engineer (Wigner RCP -> Centre for Energy Research)

Introduction

The Sun is the primary energy source of the plasma physical processes in our Solar System, its permanent outflow of charged particles (solar wind) and fields interact with the plasma environment of planets, comets or any space infrastructure. The solar wind dominated region is called the heliosphere, it forms a bubble in the interstellar medium ([O1]). In this project we have concentrated on plasma processes in the inner heliosphere ([O2]) between Mercury and Earth orbits as a preparation for the space missions BepiColombo (to Mercury launched in 2018) and Solar Orbiter (launched in 2020; [O3]), and in order to improve space weather forecasts through better understanding of the plasma processes heading Earth.

The solar trigger

The Sun is our central star and it forms the heliosphere by ejecting the solar wind that carries out the solar magnetic field lines to beyond 100 AU. Trivially, the solar behaviour effects the plasma processes in the entire regime and the solar magnetic cycle plays an important role.

Our team contributes to improve an MHD solar dynamo model, the surface flux transport model (SFT), by considering the effect of the 'non-linear surface inflows into the activity belts' on the solar cycle modulation. We have found that these surface inflows can be considered as one of the non-linearities to the model by linking their dipole moment contribution to the solar dynamo effectivity range parameter for different representations of these inflows. Figure 1 shows the relative importance of latitude quenching versus the surface inflows with respect to dynamo effectivity range parameter (λ_R), which is related to the ratio of meridional flow velocity to diffusivity. This is shown for different values of the decay time (τ in years, for $\tau = \infty$ means no decay term), for each value of τ we have a quadratic fit line showing that the inflow with respect to latitude quenching is a truly nonlinear mechanism for the solar dynamo ([C1], [C2], [C3], [C4], [C5], [C6], and [P1]).

Recent observations by the Parker Solar Probe showed that the magnetic field fluctuations are quite large in the inner heliosphere, which includes cases when the radial component of the magnetic field vector changes sign in short time scales of observations. We attempt to reconstruct the geometry of these switchback events by Grad-Safranov technique in order to better understand their properties and origin. Our analysis has shown that they are planar structures. They are most probably the remnants of closed field lines, dragged to interplanetary space, and during the propagation later they become open ones with reconnection ([C7]).

Additionally, we started to study the solar corona from observations (space-borne coronagraph images in [P2]) and coronal model results [P3] in order to understand better the source of the solar wind. See more in the next section.

Temporal evolution and spatial variation of the solar wind

Our research group has an extended solar wind plasma and magnetic field database from observations by solar and planetary spacecraft, where we are either team members (Co-Investigator level, see for instance [P4]) or we have strong collaborations. We based part of this 'Inner heliosphere' project on our 'Propy' problem-tailored improved-ballistic propagation tool ([T1]) that was further developed during the project and extensively used. Additionally, we have created an ICME list with start and stop times of in-situ ICME signatures for several spacecraft, see in [D1]. We have studied the temporal evolution of the solar wind source, the effect of the latitudinal spacecraft separation on solar wind predictions [P2] and created a 3-dimensional model for the ambient solar wind prediction for the inner heliosphere [P3]. These were presented at several conferences ([C4], [C8], [C9], [C10], [C11], [C12], [C13], [C14], [C15], [C16]) and the manuscripts ([P2] and [P3]) were submitted.

The 'Propy' propagation tool

Based on our database and the simple ballistic solar wind propagation model, we have created a tool to extrapolate the background solar wind to any points in the inner heliosphere. The model uses real observational data and extrapolates the solar wind plasma from the observing spacecraft to the target point. We separate the problem to three components: radial propagation, longitudinal and latitudinal separation in HCI coordinate system.

Longitudinal extrapolation

Considering the longitudinal extrapolation, we shift the observed time series in time by the time lag calculated from the longitudinal spacecraft-target separation and the solar rotation rate. There is an assumption that the solar wind source is persistent between the two ejection times. One of our studies focuses on this persistency, the temporal evolution of the solar wind source by exploiting the excellent constellation of the twin STEREO solar probes that are at 1 AU distance from the Sun, but at different longitudes ([C8], [C10], [C16]). The results are mainly influenced by the latitudinal spacecraft separation, hence we have started a parallel study to quantify these effects ([C11], [C14], [C15], and [P2]). Trivially, at longitudinal extrapolation non-corotating events, such as ICMEs have to be removed from the input data in order to avoid potential false alarms. For this we needed the precise start and stop dates and times of the ICME signatures in the in-situ plasma and magnetic field data for all spacecraft that we use, so we have created ICME lists for several spacecraft and published this database at Mendeley Data ([C17] and [D1]).

Radial propagation

The radial propagation applies the observed solar wind bulk velocity and assumes that it does not change during the radial propagation. This is not true near the Sun where acceleration is still going on, so we avoid to apply this technique in the very near proximity of the Sun. Also fast-slow stream interaction regions (SIR/CIR) form and evolve during the radial propagation and cause acceleration and deceleration. Hence we studied these structures in detail ([P5]) and applied a pressure difference based correction ([P3]) to improve our model.

Effect of the latitudinal separation

For the latitudes the problem is very hard because the solar surface and corona, so the solar wind source can be very structured hence ejecting solar wind parcels with different characteristics at different latitudes. Our empirical and statistical study shows that with increasing latitudinal separation between the observing spacecraft and the target, the prediction accuracy falls steeply. We suggest that above ~4 degrees spacecraft-target separation one should avoid extrapolation ([C11], [C14], [C15], and [P2]). These findings can be useful for the improvement of data-assimilation based models, and provide estimates for the accuracy of solar wind predictions by the future ESA Vigil (L5) space weather mission.

Background solar wind prediction

Our 'Propy' model provides problem-tailored improved ballistic background solar wind extrapolations from spacecraft observations to any target points in the inner heliosphere. Our model is problem-tailored in the sense that we create the predictions to the needs of the project that would use it, for instance an ICME propagation drag model needs different prediction output than a planetary space weather study. This is also the reason why the tool can only be run by our team, and it cannot be an automatized web tool such as the one in the Europlanet SPIDER services, where the PI of this project is also involved through a parallel project (see in acknowledgements).

This background solar wind prediction is originally based on the simple ballistic model applied on multi-spacecraft observations. In order to improve the results, we clean the input data from ICME signatures to avoid potential false alarms at longitudinal extrapolation ([C17] and [D1]), we apply a pressure-correction at SIR/CIRs during radial propagation ([P3]) and consider even the differential rotation of the Sun ([P2]).

3-dimensional pressure-corrected ballistic extrapolation of the solar wind speed

Instead of extrapolating from the position of a single spacecraft, here we apply the pressure-corrected ballistic method to two-dimensional velocity maps of the solar source surface available from solar coronal models in order to determine the solar wind velocity in the inner heliosphere in 3 dimensions, between latitudes of ±50°. Our method is simple, fast and it can be applied to different source surface datasets. The results of our model are validated with in situ data from the ACE spacecraft. Figure 2 shows that the pressure-corrected extrapolation gives better agreement. Hence, we find that the pressure-corrected ballistic method can give accurate predictions of the solar wind in 3 dimensions ([C9], [C12], [C13], and [P3]).

Discontinuities in the solar wind

The large number of solar spacecraft throughout the inner heliosphere in the recent years has provided us a rich dataset to analyze discontinuities in the solar wind.

Orientation of the stream interface in SIR/CIRs

As mentioned earlier, SIR/CIRs are important features that form during the radial propagation of the solar wind. Exploiting the advantage of multi-spacecraft observations we managed to reconstruct the orientation of their stream interface, the plane that separates the interacting fast and slow solar wind streams. We have applied a sliding window correlation method on ACE, WIND and STEREO-A plasma and magnetic field data in order to obtain the time delay between the spacecraft. Using these time lags and in-situ solar wind velocity measurements, we could shift their positions, and together with the position of the reference spacecraft, we can reconstruct the spatial orientation of the stream interface. The determined planes generally follow the Parker spiral in the ecliptic, as expected; their off-ecliptic tilt is determined by the position of the source of the high-speed stream. In Figure 3 there are four events from two solar sources. Events A and B are related to the same coronal hole but one Carrington rotation separated in time. Similarly, events C and D are from the same solar source. At event D the results are inconclusive, the method has reached its limit because the STEREO-A spacecraft was already too far away (>2.5 million km) from the other spacecraft ([C18] and [P5]).

Directional discontinuities

The Solar Orbiter and Parker Solar Probe spacecraft provide a whole new insight at the inner heliosphere on both spatial and temporal scales. We exploit this unique opportunity to study the spatial distribution of directional discontinuities (rotational and tangential discontinuities) in order to investigate heating mechanisms and turbulence. We find that their spatial density decreases with increasing radial distance from the Sun that refers to some kind of decay process ([C19], [C20], [C21], [C22]).

Study of the terrestrial space weather in relation to the dynamics of the Sun and solar wind

One of the goals of our project concerns the study of the geoeffectivity of the various solar wind structures, such as the slow and fast solar wind streams or their corotating interaction regions. In line with this goal, we investigate the behaviour of the dynamics of the terrestrial magnetosphere and ionosphere with respect to the solar wind impact and to its solar cycle variation. Particular attention is devoted to phenomena that might affect our human infrastructure (navigation or communication facilities, electric power grid, etc.), that is, the space weather contexts of the solar and solar wind dynamics ([O4]).

Magnetic field irregularities in the ionosphere

Making use of the high-frequency three-component magnetic records of ESA's low-Earth orbit (LEO) Swarm mission the typical occurrences of irregular magnetic field fluctuations are explored in the high-latitude and equatorial geomagnetic regions. Relying on the turbulent nature of the irregularities, we have previously developed an intermittency index (IMI) for the quantitative monitoring of the irregular magnetic fluctuations along the orbits of the Swarm spacecraft, in the framework of ESA's EPHEMERIS project (Heilig and Kovács, 2021). It turned out, that in the equatorial region, the most intermittent fluctuations appeared symmetrically about the dip equator, at +/-10° magnetic latitudes, in post-sunset magnetic local times. Clearly, this finding was explained by the appearances of equatorial spread F (ESF) and plasma bubble phenomena. The occurrence rate of equatorial irregularities exhibited a clear solar cycle dependence, being greater in solar maximum than in minimum. The space weather context of the equatorial irregularities was shown by the subtle correlation of these events with GNSS loss of lock (LOL) occurrences onboard Swarm spacecraft as well as with scintillation effects recorded in ground GNSS stations.

In the framework of the OTKA project, IMIs in the polar region are modelled by Adjusted Spherical Cap Harmonic analysis, for three levels of geomagnetic activity. The models exhibit intermittent fluctuations in two oval regions about the geomagnetic poles. It is suggested that the poleward region is coincident with the auroral oval, while the equatorward region is indicative to the ionosphere footprint of the plasmapause ([C23] and [C24]). Both regions expand toward the Equator with increasing geomagnetic activity (see Figure 4).

In 2023, a proxy of the GNSS amplitude scintillation index is computed along the orbits of the Swarm triplet, by adapting the methodology of Juan et al. (2017) developed for the assessment of amplitude scintillations from the records of commercial GPS receivers. Ionosphere related scintillations of radio signals have a particular impact on the accuracy of the navigation systems. By processing three years (2015-2017) of RINEX GPS records of Swarm-A and Swarm-B spacecraft we show that the scintillation events at low latitudes are distributed about the geographic equator, in contrast to the magnetic latitude dependence of the equatorial plasma irregularities. The resolution of this contradiction is in progress. It is also concluded that the scintillations occur more often during post-sunset period than during the day, in accordance with the occurrences of equatorial spread F and plasma bubble phenomena. As for the relation with the solar dynamics, we also show that the scintillations exhibit a clear dependency on the geomagnetic conditions, being stronger during disturbed than quiescent magnetic periods.

By the support of the OTKA fund, our results have been presented in 2023 at conferences ([C25], [C26], and [C27]) and the paper is in preparation.

Electric currents in the magnetosphere-ionosphere system

One of the fundamental consequences of the coupling between the solar wind and the magnetosphere-ionosphere (MI) system is the amplification of coherent electric currents (magnetopause currents, ring currents, auroral currents, field-aligned currents, etc.) flowing in and among different MI regions. The investigation and modelling of this process is essential for the prediction of various terrestrial space weather events, and for the assessment of their risks. Several space missions have been in service to study the dynamics of the MI system, for decades. Currently, the most relevant are the Cluster, Themis and MMS missions, which fly in the inner and outer magnetosphere (and partly also in the solar wind), and the Swarm mission, which orbits in polar orbit in the ionosphere. Each of these missions is composed of a constellation of 3 or 4 satellites orbiting in parallel, allowing the 3D studies of the electromagnetic field variation along the orbits, as well as the study of multiscale turbulent processes at different spatial/temporal scales.

Making use of the magnetic field gradients measured among satellites of multi-spacecraft missions, the strength and spatial occurrences of electric currents can be inferred along the mission orbits by applying the Ampere's law. This is the Curlometer method introduced by Vallat et al. (2005). In our recent study, we investigate the strength of the terrestrial ring current by adapting the curlometer technique to the Cluster mission data. We conclude that in order to achieve the best current estimations, supplementary data processing must be carried out prior or after the application of the curlometer technique. For instance, it turned out that in many cases the constellation of the mission was not suitable for the accurate current determination. When the spacecraft fly in a big distance (more than some hundreds of km) from each other, the gradients are dominated by the main terrestrial field, therefore a relevant improvement in the current determination can be achieved by the subtraction of IGRF model values from each spacecraft observation. In another case, if at least three from the four mission elements fly close to each other, the electric current can be estimated in the direction normal to the plane determined by the positions of the nearby spacecraft. From this single measurement the real strength of the ring current can be assessed by assuming its azimuthal direction in the equatorial plane. Additionally, if we assume the stationarity of the ring current, and the constellation and flying direction of the mission is favorable, the three nearby magnetic field observations can be complemented by a virtual observation obtained in the distant spacecraft before or after the other observations.

Making use of the above methods as supplements of the curlometer technique we were able to determine the ring current strength in each equatorial crossing of the Cluster mission orbit at perigee, between 2002 and 2005. Our results were validated by the Dst indices deduced from the magnetic observations of equatorial ground-based observatories. After the methodological studies, we intend to continue the current estimations in different regions of the MI system by applying Themis, MMS and Swarm mission data, as well.

By the support of the OTKA fund, our results have been and will be presented in the following conference appearances (2023 only): [C28] and [C29].

<u>Development of a nonlinear analysis tool</u>

Within the framework of the European FP7 STORM project (Echim et al., 2016) the development of a Matlab tool has been initiated for the comprehensive nonlinear analyses of spaceborne and ground based magnetic field and plasma data. The tool is called Integrated Nonlinear Analysis software, in short INA. INA is prepared to carry out spectral, multifractal and wavelet analyses on various data sets, in a user-friendly graphical user interface (GUI) environment. Though our European cooperation has officially finished, the development of INA is still ongoing. By 2022, we arrived at a stage when the facilities and advantages provided by INA became far worthy for their publication and for making them available for the broader scientific community via a scientific paper. The paper was published in the journal of Earth and Space Science in 2023 with the support of the OTKA fund: [P6].

<u>Impact of the ICME- and SIR/CIR-driven geomagnetic storms on the ionosphere</u>

Thanks to our expertise with ICMEs and CIRs, we were invited to participate in a study about the differences between the effect of ICME-related and of SIR/CIR-related geomagnetic storms in the ionospheric F2-layer during the maximum of Solar Cycle 24. A unique list of the ICME- and SIR/CIR-driven geomagnetic storm events was created for the time interval November 2012 - October 2014. The individual geomagnetic storm periods were sorted and analyzed by seasons, time of day and local time of minimum Dst. The main phase days of the ICME- and SIR/CIR-induced geomagnetic storms were investigated. The geomagnetic Kp, Dst and AE indices characterize the global geomagnetic activity, the intensity of the ring current and the auroral electrojets, respectively. For each study group, the foF2 parameter was correlated with different geomagnetic indices in order to determine which index represents best the variation of the electron density in the F2-layer. One of our aims was to find the best parameter(s), which could be used as input in empirical space weather prediction models [P7].

Space weather at other planets and comets

The Solar System is very rich on different plasma regimes with its strongly and weakly, or even un-magnetized planets with and without ionosphere. Comets are also highly interesting due to their changing activity and hence plasma environment depending on their solar distance. Their interaction with solar wind provides a great research topic. Our role is to provide these studies mainly the provisional solar wind input either through extrapolating plasma observations from solar probes located at other heliospheric positions or through ingenious techniques.

Multi-spacecraft observations are very favorable for planetary space weather studies since they can provide simultaneous in-situ measurements of the ambient solar wind and the planetary plasma environment. In order to facilitate the planning of such coordinated multi-spacecraft observations in the inner heliosphere, we have developed the 'Soltra' visual tool with a freely adjustable solar wind velocity parameter [T2]. As part of the ESA BepiColombo (2018-) science working team, we have suggested time periods for coordinated multi-spacecraft observational campaigns at Mercury and we have described Mercury’s space environment concerning solar wind properties ([C30], [C31], [C32], [P8], [P9], [P10], and [O5]).

Considering ingenious techniques, we have created a 'solar wind dynamic pressure proxy' from magnetic field observations of ESA's Rosetta cometary mission, when it was deep inside the induced cometary magnetosphere of Comet 67P. We validated the Rosetta pressure proxy by comparing it to extrapolated solar wind measurements from near-Earth and STEREO-A spacecraft to the position of the comet. The Rosetta pressure proxy was proven to be valuable not just for studies related to Rosetta or comets, but also as a novel and independent input database for space weather propagation to different locations in the Solar System [P11].

Our team is involved in ESA's JUICE mission to the icy moons of Jupiter, our PI is Co-Investigator of the PEP plasma experiment on-board. The JUICE spacecraft was launched in 2023 and it is currently in its cruise phase to Jupiter (until 2030's), where sporadically (when instruments are switched on) solar wind observations are available. These observations are often at very interesting locations in the heliosphere, hence our solar wind extrapolations can be further tested. Additionally, based on our expertise we can provide reliable solar wind predictions for the JUICE trajectory through the 'Propy' tool and running the BATS-R-US 3-dimensional MHD model that was brought to our team during this project. Note that another complex model is now in house, namely the EU-funded Euhforia that is rather optimized on solar-terrestrial relations. They will both support the continuation of the work started during this "Inner heliosphere" project.

Summary

The Sun is the primary energy source of the plasma physical processes in our Solar System, its permanent outflow of charged particles (solar wind) and fields interact with the plasma environment of planets, comets or any space infrastructure. Our project focused on the plasma processes in the inner heliosphere, especially on the solar wind origin, characteristics, propagation, and its interactions. We have created methods and tools to characterize and predict the solar wind and its disturbances through modelling and analyzing observations. Our results show the importance of the non-linear surface inflows in solar magnetic dynamo modelling, the latitudinal effects in solar wind predictions, and the proper multi-spacecraft constellation when calculating the electric current in the terrestrial magnetosphere. A special part of our activities was dedicated to solar wind dynamics by deriving the orientation of stream interfaces in the CIRs and by implementing a pressure-based correction into our solar wind predictions, so we managed to improve the ballistic propagation model. These results and tools can be applied for space weather predictions, where information on provisional solar wind conditions at the terrestrial magnetosphere is of vital importance. For instance, we have found that the ionosphere plasma irregularities exhibit close correlations with the solar dynamics, and these have an impact on the distortions of GNSS radio signals measured onboard the Swarm mission.

Acknowledgements

Our 'Inner heliosphere' research groups is highly grateful to NKFIH for the OTKA grant FK128548 that made possible to expand our team and extend our expertise, as well as to produce scientific results and services. Special thanks to the OTKA reviewers for their supporting comments.

This multi-spacecraft project would not have been possible without the precious work of the spacecraft teams of Parker Solar Probe, Solar Orbiter, STEREO, WIND, ACE, BepiColombo, JUICE, Swarms, etc.

We want to acknowledge all our colleagues at the Wigner Space Physics and Space Technology Department, especially Zoltan Nemeth (Department Head), Zsuzsanna Dalya (for ICME list help), Aniko Timar (3D propagation model), Lajos Foldy (for technical support) and the technical team (for building space instrumentation). We also thank for the collaboration opportunities with Tamas I. Gombosi (BATS-R-US), Stefaan Poedts and Manuela Temmer (EUHFORIA).

We would like to note that part of our group for complementary work was additionally supported by ESA Solar Orbiter test data project (2018) and H2020 Europlanet-RI-2024 project (2020-2024).

References

Echim M. and the STORM Consortium (www.storm-fp7.eu), *Solar system plasma Turbulence: Observations, Intermittency and Multifractals (STORM)*, Final report, EC FP7-SPACE-2012 / Grant Agreement Number 313038 (2016).

Heilig B. and Lühr H.: *Quantifying the relationship between the plasmapause and the inner boundary of small-scale field-aligned currents, as deduced from Swarm observations*, Ann. Geophys. 36, 595-607 (2018). https://doi.org/10.5194/angeo-36-595-2018.

Heilig B. and Kovacs P.: *New Space Weather Information Exploited from the Swarm Observations (EPHEMERIS)*, Final report, ESA/Contract No. 4000128162/19/I-DT (2021).

Juan J.M., Aragon-Angel A., Sanz J. et al.: *A method for scintillation characterization using geodetic receivers operating at 1 Hz*, J. Geod. 91, 1383–1397 (2017). https://doi.org/10.1007/s00190-017-1031-0.

Vallat C., Dandouras I., Dunlop M., Balogh A., Lucek E., Parks G.K., Wilber M., Roelof E.C., Chanteur G., and Rème H.: *First current density measurements in the ring current region using simultaneous multi-spacecraft CLUSTER-FGM data*, Ann. Geophys., 23, 1849–1865 (2005). https:// doi.org/10.5194/angeo-23-1849-2005.

Xiong C. and Lühr H.: *An empirical model of the auroral oval derived from CHAMP field-aligned current signatures – Part 2*, Ann. Geophys. 32, pp. 623-631 (2014). DOI: 10.5194/angeo-32-623-2014.

Publications of the group

Refereed international scientific papers

[P1] Talafha M., Petrovay K., Opitz A.: *Effect of the nonlinear surface inflows into activity belts on the solar cycle modulation*, submitted to Astronomy & Astrophysics.

[P2] Biro N., Opitz A. Koban G., Nemeth Z.: *Latitudinal variation of the background solar wind in the Inner Heliosphere from multi-spacecraft observations*, submitted to AGU Space Weather.

[P3] Timar A., Opitz A., Nemeth Z., Bebesi Z., Biro N., Facsko G., Koban G., Madar A.: *3D pressure-corrected ballistic extrapolation of solar wind speed in the inner heliosphere*, submitted to Journal of Space Weather and Space Climate.

[P4] Horbury T. et al. (including Erdos G.): *The Solar Orbiter magnetometer*, Astronomy & Astrophysics 642, paper A9 (2020).

[P5] Koban G., Opitz A., Biro N., Nemeth Z.: *Orientation of the stream interface in CIRs*, JSWC 13, 14 (2023): https://doi.org/10.1051/swsc/2023011.

[P6] Munteanu C., Kovacs P., Echim M.: *An integrated nonlinear analysis (INA) software for space plasma turbulence*, Earth and Space Science, 10, e2022EA002692 (2023). https://doi.org/10.1029/2022EA002692.

[P7] Berenyi K.A., Opitz A., Dalya Z., Kis A. and Barta V.: *Impact of ICME- and SIR/CIR-Driven Geomagnetic Storms on the Ionosphere over Hungary*, Atmosphere 14(9), 1377 (2023). DOI: 10.3390/atmos14091377.

[P8] Milillo A. et al. (including Dosa M.): *Investigating Mercury's Environment with the Two-Spacecraft BepiColombo Mission*, Space Science Reviews 216:5, paper 93 (2020).

[P9] Hadid L.Z. et al. (including Dosa M. and Madar A.): *BepiColombo's Cruise Phase: Unique Opportunity for Synergistic Observations*, Frontiers in Astronomy and Space Sciences, Vol. 8 (2021). DOI: 10.3389/fspas.2021.718024.

[P10] Mangano V. et al. (including Dosa M., Madar A., and Erdos G.): *BepiColombo Science Investigations During Cruise and Flybys at the Earth, Venus and Mercury*, Space Science Reviews 217:1, paper 23 (2021).

[P11] Timar A., Nemeth Z., Szego K., Dosa M., Opitz A., Madanian H.: *Estimating the solar wind pressure at comet 67P from Rosetta magnetic field measurements*, Journal of Space Weather and Space Climate 9, A3 (2019).

Conference presentations

[C1] Talafha M.: *The effects of the surface inflows on quenching of solar cycles*, talk at the SOLARNET Conference 'The Many Scales of the Magnetic Sun', Telegrafenberg in Potsdam (Germany), 8-12 May 2023. https://www.solarnet-project.eu/the-many-scales-of-the-magnetic-sun

[C2] Talafha M. and Opitz A.: *The solar activity cycle and its effects on planets*, talk at the Europlanet Research Infrastructure Meeting (ERIM), Bratislava (Slovakia), 19-23 June 2023.

[C3] Talafha M.: *What Determines The Dynamo Effectivity Of Solar Active Regions?*, invited talk at ISSI team meeting 'Effect of active region inflows on polar field buildup', Bern (Switzerland). 10-14 July 2023. issibern.ch

[C4] Bebesi Z., Biro N., Erdos G., Facsko G., Foldy L., Juhasz A., Koban G., Kovacs P., Madar A., Talafha M., Opitz A., Szalai S., Tatrallyay M., Timar A., Tomasik M., and Nemeth: *Wigner Research Centre for Physics, Institute for Particle and Nuclear Physics, Dept. of Space Physics and Space Technology*, talk and poster at Wigner 121 Scientific Symposium 'Heritage and Future', Budapest (Hungary), 18-20 September 2023.

[C5] Talafha M. and Opitz A.: *The effects of the surface inflows on quenching of solar cycles*, talk at 'The 14th Arabic conference of the Arab Union for Astronomy and Space Sciences', Astronomy Conference Home in Sharjah (UAE), 13-16 November 2023. sharjah.ac.ae

[C6] Talafha M., Opitz A., Petrovay K.: *The effects of the surface inflows on quenching the solar cycles*, poster at European Space Weather Week, Toulouse (France), 20-24 November 2023. https://esww2023.org/

[C7] Erdos G. and Madar A.: *Reconstruction of the geometry of magnetic field switchback events*, poster at the COSPAR conference, Athen (Greece), 16-24 July 2022.

[C8] Opitz A., Timar A., Nemeth Z.: *The background solar wind in the inner heliosphere (A háttér-napszél a belső helioszférában)*, talk in Hungarian at the Hungarian Space Assembly (Magyar Űrkutatási Fórum), Budapest (Hungary), 29 September - 1 October 2021.

[C9] Timar A., Opitz A., Facsko G., Nemeth Z.: *Propagation of solar wind data (Napszél adatok 3D propagációja)*, talk in Hungarian at the Hungarian Space Assembly (Magyar Űrkutatási Fórum), Budapest (Hungary), 29 September - 1 October 2021.

[C10] Opitz A., Timar A., Nemeth Z., Dalya Z., Koban G., Biro N., Madar A.: *Temporal evolution of the background solar wind throughout the inner heliosphere*, talk (EGU22-5466) at EGU, Vienna (Austria), 23-27 May 2022.

[C11] Biro N., Opitz A., Nemeth Z., Timar A., Madar A., Koban G., Dalya Z.: Spatial variation of the background solar wind in the Inner Heliosphere, talk (EGU22-4155) at EGU, Vienna (Austria), 23-27 May 2022.

[C12] Timar A., Opitz A., Facsko G., Dalya Z., Koban G., Biro N., Madar A., Nemeth Z.: *3D propagation of solar wind data*, talk at EGU, Vienna (Austria), 23-27 May 2022.

[C13] Timar A., Opitz A., Biro N., Dalya Z., Koban G., Madar A., Nemeth Z.: *Temporal evolution and spatial variation of the solar wind structures throughout the heliosphere*, poster at EPSC, Granada (Spain), 18-23 September 2022.

[C14] Biro N., Opitz A., Timar A., Nemeth Z., Koban G., Madar A., Dalya Z., Kovacs P.: *Temporal evolution and spatial variation of the solar wind structures throughout the heliosphere*, poster (P2.p09) at the European Space Weather Week, Zagreb (Croatia), 24-28 October 2022.

[C15] Biro N., Opitz A., Nemeth Z., Timar A., Koban G., Lkhagvadorj M., Facsko G., Madar A.: *Spatial and temporal evolution of solar wind structures in the inner heliosphere (Napszél struktúrák térbeli és időbeli fejlődése a belső helioszférában)*, talk at the Hungarian Space Assembly (Magyar Űrkutatási Fórum), Sopron (Hungary), 3-5 May 2023.

[C16] Opitz A., Timar A., Biro N., Koban G., Dalya Z., Nemeth Z.: *Solar wind propagation throughout the 3D inner heliosphere*, poster at European Space Weather Week, Toulouse (France), 20-24 November 2023. https://esww2023.org/

[C17] Dalya Z. and Opitz A.: *Removal of false alarms from solar wind predictions,* talk (EGU22-4987) at EGU, Vienna (Austria), 23-27 May 2022.

[C18] Koban G., Opitz A., Nemeth Z., Facsko G., Madar A., Timar A., Dalya Z., Biro N.: Spatial Structure of CIRs, talk (EGU22-4121) at EGU, Vienna (Austria), 23-27 May 2022.

[C19] Madar A., Erdos G., Opitz A., Nemeth, Z., Facsko G.: *Directional discontinuities in the inner heliosphere (Direkciós diszkontinuitások a belső helioszférában),* talk in Hungarian at the Hungarian Space Assembly (Magyar Űrkutatási Fórum), Budapest (Hungary), 29 September - 1 October 2021.

[C20] Madar A., Erdos G., Opitz A., Nemeth Z., Facsko G., Timar A., Biro N., Koban G., Dalya Z.: *Directional Discontinuities in the Inner Heliosphere*, talk (EGU22-6620) at EGU, Vienna (Austria), 23-27 May 2022.

[C21] Madar A., Erdos G., Nemeth Z., Opitz A., Facsko G., Koban G., Biro N., Timar A.: *Directional Discontinities in the Inner Heliosphere*, talk at the COSPAR conference, Athen (Greece), 16-24 July 2022.

[C22] Madar A., Erdos G., Nemeth Z., Opitz A., Facsko G., Koban G., Biro N., Timar A.: *Coherent structures in the Inner Heliosphere: Interplanetary discontinuities*, invited talk at the 'Turbulence at the Edge of the Solar Corona' team meeting, International Space Science Institute, Bern (Switzerland), 4-8 September 2023.

[C23] Kovacs, P. and Heilig, B.: *Irregular magnetic field fluctuations in the ionosphere; Analysis of the long-term high-frequency magnetic field records of the Swarm mission*, Living Planet Symposium, Bonn (Germany), 23-27 May 2022.

[C24] Kovacs P., Heilig, B., Opitz A., Biro N., Koban G., Nemeth Z.: *Spatial and temporal distribution of intermittent magnetic field irregularities in the upper ionosphere and their space weather consequences; Study of the Swarm mission magnetic field records*, European Space Weather Week, Zagreb (Croatia), 24-28 October 2022.

[C25] Kovacs P., Heilig, B., Bebesi, Z., Opitz A.: *Modelling the distribution of intermittent magnetic field fluctuations recorded by the Swarm mission in the polar area*, EGU, Vienna (Austria), 23-28 April 2023. EGU23-15810, https://doi.org/ 10.5194/egusphere-egu23-15810

[C26] Koban G., Kovacs P., Nemeth Z.: *Az ionoszféra vizsgálata a Swarm műholdak GPS jeleinek szcintillációi alapján*, talk at the Hungarian Space Assembly (Magyar Űrkutatási Fórum), Sopron (Hungary), 3-5 May 2023.

[C27] Kovacs P., Heilig B., Koban G.: *Swarm műholdak GPS és mágneses regisztrátumainak elemzése a felső ionoszféra dinamikai folyamatainak megismerésére*, poster at the Hungarian Space Assembly (Magyar Űrkutatási Fórum), Sopron (Hungary), 3-5 May 2023.

[C28] Tomasik M. and Kovacs P.: *Elektromos áramok vizsgálata a földi magnetoszférában, poszter előadás,* poster at the Hungarian Space Assembly (Magyar Űrkutatási Fórum), Sopron (Hungary), 3-5 May 2023.

[C29] Tomasik M. and Kovacs P.: *Study of the terrestrial ring current by the magnetic field observations of multi-spacecraft missions*, European Space Weather Week, Toulouse (France), 20-24 November 2023.

[C30] Dosa M. et al.: *THEMIS telescope images analysed for space weather traces*, poster at EPSC (online), 21 September – 9 October 2020.

[C31] Dosa M. et al.: *In Search for Background Solar Wind Effects on Mercrury's Na Exosphere*, presentation (P078-0003) at AGU Fall Meeting (online), 1-17 December 2020.

[C32] Hadid L., Dosa M., Madar A., et al.: *BepiColombo and Solar Orbiter coordinated observations: scientific cases and measurements opportunities*, presentation (EGU2020-17957) at EGU, Vienna (Austria), 4-8 May 2022.

Database

[D1] Dalya Z., Opitz A., Biro N.: Duration of ICME signatures in in-situ data from several space probes for the time interval of 2004-2021, Mendeley Data published on 9 June 2023. DOI: 10.17632/4zwbp8k7cr.1

Public outreach

[O1] Madar A., Opitz A., Szalai S., Kecskemety K., Dosa M., Erdos G., Troznai G.: Hungarian article about *The Solar Obiter mission (A Solar Orbiter napszonda)*, Space Year Book 2020 (Űrtan Évkönyv 2020 - Az Asztronautikai Tájékoztató 72. száma) by the Hungarian Astronautical Association (Magyar Asztronautikai Társaság), edited by Frey S. in Budapest (Hungary), 156, p87-104 (2021).

[O2] Nemeth Z. and Opitz A.: Hungarian article about the *Solar System research by solar probes - introduction (A Naprendszer űrszondás kutatása – szakmai bevezető)*, Fizikai Szemle 73: 7-8, p218-219, (2023). Corresponding talk at the Hungarian Academy of Sciences:

[O3] Opitz A. and Madar A.: Hungarian article about the *Inner heliosphere research (A belső helioszféra kutatása)*, Fizikai Szemle73: 7-8, p220-224 (2023). Corresponding talk at the Hungarian Academy of Sciences: https://www.youtube.com/watch?v=0bOMUVAraY4

[O4] Opitz A., Timar A., Nemeth Z., Kecskemety K., and Facsko G.: *When the Sun attacks: Space Weather report (Ha támad a Nap: űridőjárási helyzetjelentés)*, public talk at an event named 'Mars a tópartra', Szekesfehervar (Hungary), 13 November 2021.

[O5] Bebesi Z., Dosa M., Juhasz A., Kecskemty K., Nemeth Z.: Hungarian article about the *Milestones and scientific objectives of the BepiColombo mission at Mercury* (*A BepiColombo űrmisszió mérföldkövei és tudományos célkitűzései a Merkúr bolygónál)*, Fizikai Szemle 70: 7-8, p236-244 (2020).

Scientific tools

[T1] Propy problem-tailored improved-ballistic propagation tool: contact the team.

[T2] Soltra tool: https://space.wigner.hu/soltra.html

Our activities and results can be followed on our website dedicated to this project:
https://wigner.hu/~opitz/innerheliosphere.html

Figures

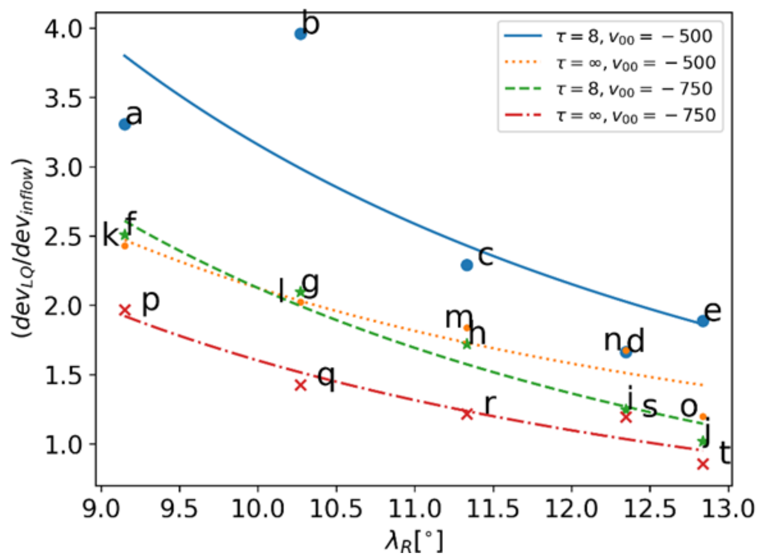

Figure 1: The relative importance of latitudinal quenching (LQ) versus inflows plotted against the dynamo effectivity range parameter (λ_R), for different parameter combinations: τ is the decay time in years (where $\tau = \infty$ means no decay term) and v_{00} is the initial inflow amplitude. Adapted from [P1].

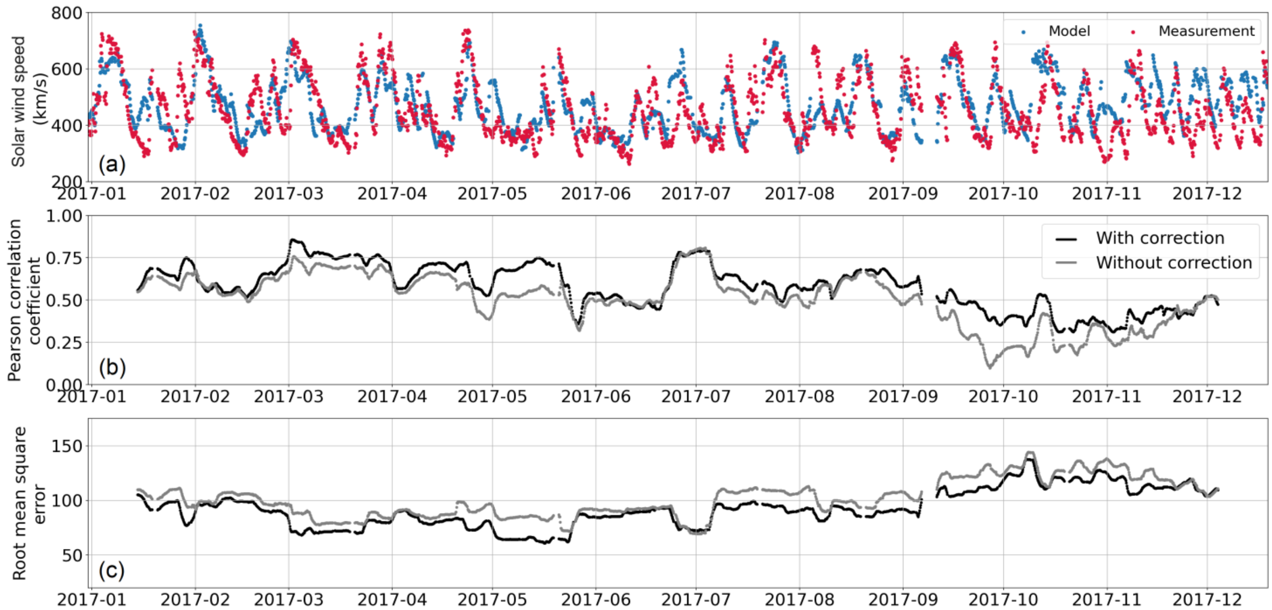

Figure 2: ACE SWEPAM solar wind ion speed measurements (red dots) and pressure-corrected 3D ballistic solar wind speed (blue dots) in 2017 with a temporal resolution of 3.6 hours (a). Non-corotating effects, such as ICMEs were removed from the datasets. The correlation coefficient (b) and the root mean square error (c) is shown with a sliding window of one Carrington rotation between the ACE solar wind speed and the pressure-corrected (black dots) and the non-pressure-corrected (grey dots) ballistic solution. Adapted from [P3].

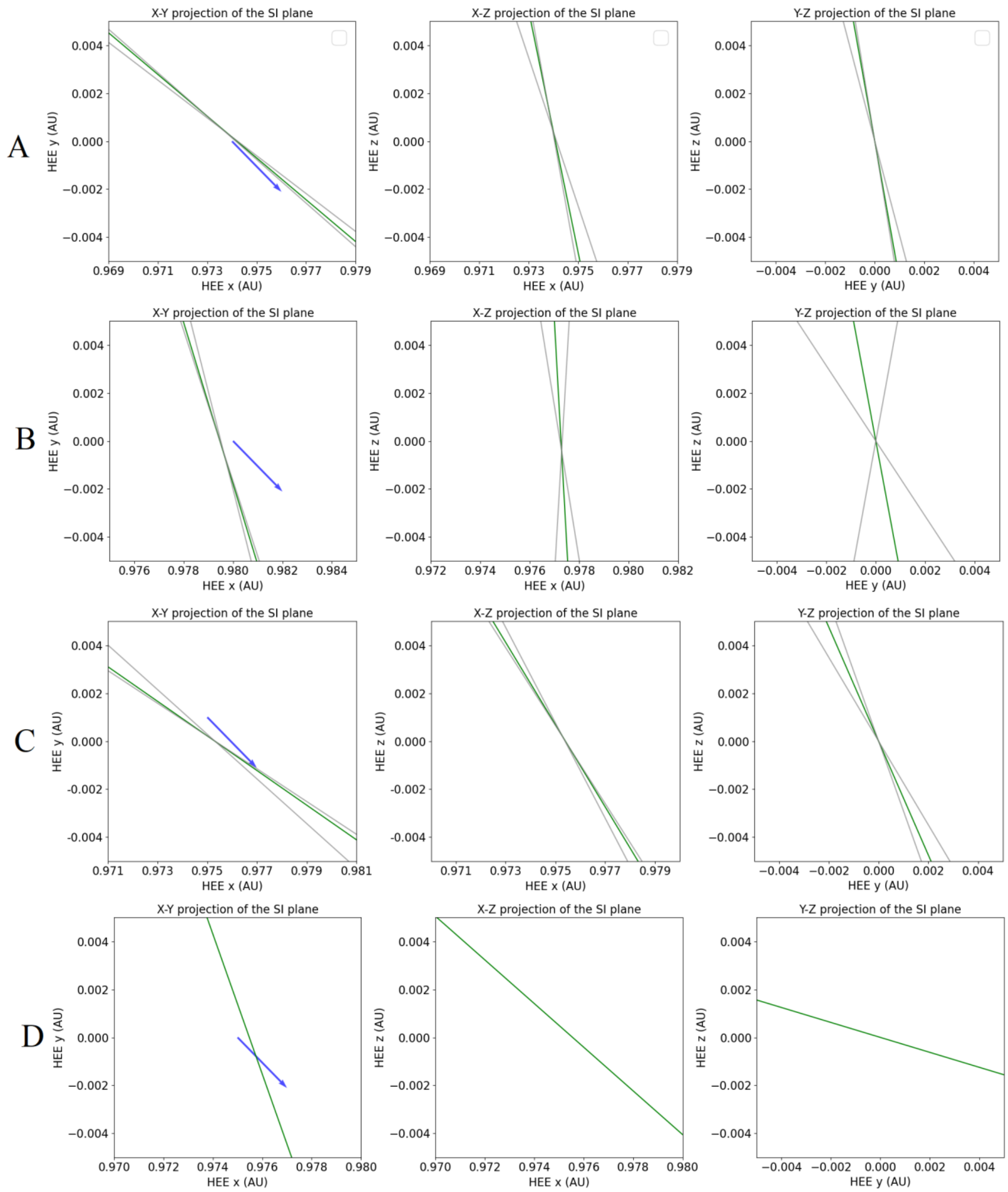

Figure 3: 2D projections of the obtained planes for four CIR events in 2007. The gray lines represent the uncertainty in the obtained plane, and the blue arrow depicts the ideal Parker spiral direction. Adapted from [P4].

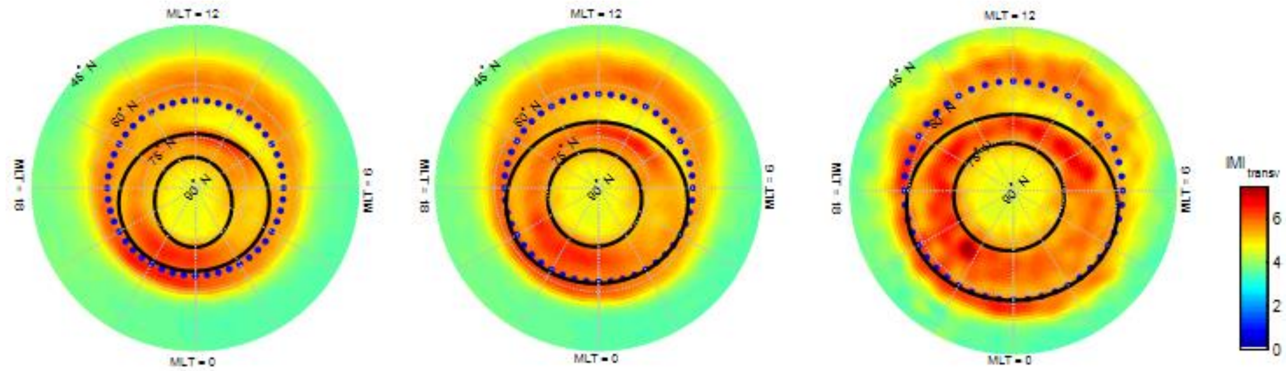

Figure 4: Adjusted spherical cap harmonic model of the transverse intermittency indices (IMI) in the northern polar region, for low (left), moderate (middle) and high (right) geomagnetic activities. IMIs were collected for Swarm A, C, and B spacecraft during the time period of 2014-2022 [Heilig and Kovács, 2021]. Black solid lines show the models of the poleward and equatorward boundaries of the auroral oval [Xiong et al., 2014]. Blue dots represent the plasmapause model by Heilig and Lühr, 2018.