Final Report FWF P26174 “The evolution of solar storms in the inner heliosphere”

1. Report on research work

1.1. Information on the development of the research project

The project’s overall scientific/scholarly concept and goals.

In this project our goal was to develop new methods which allow modeling and prediction of solar coronal mass ejections (CMEs) as observed in heliospheric imagers (HI). Such instruments are operational since 2006 on the two *STEREO* spacecraft, and since 2018 on *Parker Solar Probe*. They have led to groundbreaking discoveries on the 3D structure of the solar wind. Their usefulness has been proven with *STEREO,* so they are further planned to operate on the *Solar Orbiter* mission (launch early 2020) and a possible mission to the Sun-Earth Lagrange 5 point (launch planned in the mid-2020s).

Here, we have invented the state-of-the-art in modeling single-spacecraft HI imager observations with our *ELEvoHI* method (*Ellipse Evolution for Heliospheric Imagers*). The method can be used for both the interpretation of data and for forecasting CMEs, also in real-time settings (e.g. *STEREO-A* approaching the Earth until 2023, or with a mission to L5). *ELEvoHI* allows a calculation of CME directions, arrival times, kinematics and arrival speeds, and in this projected we developed the model and tested its predicted parameters with multipoint solar wind in-situ observations of the bulk plasma and magnetic field, which were used as a ground truth.

Fundamental changes in research orientation from project beginning to end.

In addition to modeling heliospheric imager data, we introduced a new semi-empirical model *3DCORE* (*3-dimensional coronal rope ejection,* Möstl et al. 2018) to describe the magnetic flux rope in a CME, which is so far only accessible by in situ solar wind observations. For predicting geomagnetic effects, the southward component of the magnetic field needs to be known. *3DCORE* makes it possible to model the in situ magnetic field rotations observed by spacecraft, thus it is complementary to *ELEvoHI*, which derives basic CME parameters like kinematics and direction. Both models taken together are suitable for a complete prediction of the geomagnetic effects of a CME.

1.2. Most important results and a brief description of their significance

Did the results of your project contribute to the advancement of the research field or increase the importance of the research field?

We have advanced the field of heliospheric imaging by developing the ability of using heliospheric imagers for the prediction of solar coronal mass ejections with a physically consistent model. Before the project, HI techniques such as self-similar-expansion-fitting (SSEF, see e.g. Möstl et al. 2014) lacked key physics: the resulting drag due to the interaction with the solar wind, and a flattening of the CME front during propagation. The strong assumptions of

circular front shape and constant speed caused large errors particularly in the propagation directions for fast CMEs (Möstl et al. 2014). With the ELEvoHI developed in this project (Rollett et al. 2016, Amerstorfer et al. 2018) now a model exists that captures CME physics to a much more realistic degree when modeling single-spacecraft HI data.
Thus, we have clearly increased the importance of the research field. HI instruments are now discussed to be flown on an L5 mission or a combined L5/L1 imaging system for real-time space weather forecasting.

Did your project result in new important scientific/scholarly advances? If so, to what extent and in what respect?

We shortly discuss several key advances we made during the project. Please see the list of 25 publications in total for all results.

(1) In Möstl et al. (2014), we derived definitive connections between solar, heliospheric and in situ data for CMEs for a list of 22 events, which is a mandatory prerequisite in order to reliably test any CME propagation/prediction model from the Sun to Earth.
(2) Möstl et al. (2015) demonstrated with observations from 7 different spacecraft that CME active regions can strongly channel the CME initial direction by over 40° away from the radial direction, showing this process is of high importance the prediction of space weather.
(3) Amerstorfer et al. (2018) established ensemble simulations for ELEvoHI, first presented in Rollett et al. (2016), which were driven by a new method for setting the CME initial conditions which employs ecliptic cuts of the Thernisien et al. GCS model shape. Amerstorfer et al. (2018) showed that a considerable part of the error in CME arrival times arises from small errors in the initial conditions; this has been largely overlooked in the field so far.
(4) A similar issue has been found by Möstl et al. (2018) by empirical modeling of CME flux ropes: small changes in the inclination of the rope lead to large differences in the resulting geomagnetic response. Nevertheless, we found that with our own 3DCORE flux rope model, it is possible to produce predictions of in situ data that might be able to match the observed geomagnetic response in the future, given a set of 3 free parameters (drag parameter, diameter and axial field strength) is constrained.
(5) Kubicka et al. (2016) have demonstrated the possibility to directly predict the CME geomagnetic effects from Venus orbit, showing the minimum of Dst to be modeled well with a 21 hour lead time, but the timing being a few hours too late, which was surprising given only a 6° difference in longitude from Venus to Earth for the event. This highlights the necessity to better understand the meso-scales (0.01 to 0.1 AU) of CME flux ropes and shocks.

Briefly describe the relevance of the most important hypotheses/research questions developed in your research project.

In general, we developed heliospheric imaging into a field where the interpretation of data is now augmented by a model that includes many aspects of known physics of CME to a very high degree. This opens up the possibility to ask with which accuracy an HI instrument is capable of predicting CMEs from the L5 or L1 points. A new hypothesis which came up in our project in this respect is that the errors in the initial conditions of CMEs, derived in coronagraphs, may be preventing us from making more accurate CME arrival time predictions. Thus, new research question are: How well do we need to observe the CME initial conditions? What data time and spatial resolution would an HI instrument need in order to improve these predictions to which level of accuracy?

Further, in Möstl et al. (2015), we found that active regions on the Sun can strongly push the CME away from the radial direction, resulting in false alarms and false negatives. From here new the research questions arise: How often does this process happen? What are ways to predict this what process that we called “channeling” from solar images?

Several studies (Möstl et al. 2015, Amerstorfer et al. 2018, Janvier et al. 2019) hinted that ellipses are good proxies for the CME front shape (either the shock or density enhancement), which opens up the possibilities to reliably model shocks and magnetic flux ropes on a global scale with predefined shapes, such as 3DCORE. The question is whether these shapes hold for individual events, i.e. how much these shapes evolve from the Sun to Earth by interaction with other CMEs or high speed solar wind streams.

Have new research methods or instruments been developed?

We have developed *ELEvoHI*, which is now the the state-of-the-art in single-spacecraft HI CME interpretation and prediction, and a semi-empirical modeling framework for CME magnetic flux ropes, *3DCORE*. For the codes, please see:

https://github.com/tamerstorfer/ELEvoHI (actively under development)

https://github.com/IWF-helio/3DCORE (new version currently under development)

https://github.com/cmoestl/3DCOREprototype (first version described in Möstl et al. 2018)

Was your project of relevance for related or other areas of research?
Were there transdisciplinary issues and methods?

We have published with collaborators in Germany on the effects of space weather on Mars (Forstner et al. 2019), which is of relevance for the atmospheric evolution this planet as well as a possible human exploration. We have worked on the understanding of the effects of stellar storms on hot Jupiter exoplanets with a Russian group (Cherenkov et al. 2017, Bisikalo et al. 2018). An interdisciplinary issue between exoplanet and space weather research was how we extrapolated solar system observations to a stellar environment. Note that already in the project itself we seamlessly integrated many aspects of solar physics, space physics, and geophysics.

1.3. Information on the execution of the project, the use of available funds and (where appropriate) any changes to the original project plan.

Duration

The duration of the project has been extended from early 2017 to early 2019 due to an overlap with the EU HELCATS project, which partly funded the position of the PI C. Möstl, who was a local PI of this project and involved in the steering committee.

Use of personnel

Due to the implementation of HELCATS, project lead Christian Möstl was allocated 33% of his working time to the FWF project during the HELCATS lifetime (May 2014 - April 2017). From May 2017 to February 2019 he worked 100% on the FWF project. Tanja Amerstorfer (former Rollett) was employed as a PhD student for three months and as a PostDoc for three years. Two master students were employed, each for the duration of one year.

There were no major items of equipment purchased.

Significant deviations from the original plan

There were two master students employed in the project instead of one, as some personnel costs were available due to different allocations of the PI position with respect to the original plan. The work plan was carried out approximately as planned (< 25% deviation), with the addition of creating the new 3DCORE model which was not part of the original proposal.

2. Career development – Importance of the project for the research careers of those involved (including the principal investigator)

Briefly describe the project's effects on the research careers of all project members, including special qualifications and special possibilities or opportunities opened up by the project.

Christian Möstl: This was his first project as PI. He is now PI of two new research projects funded by the FWF, which run until early 2023. Among other achievements, he is currently a science Co-I on proposed NASA mission, he was awarded the EGU Arne Richter Award in 2016, held three invited talks, organized 3 sessions at EGU, and increased his portfolio of publications strongly to a total number of about 70 (h-index: 29, ADS, May 2019). The project opened the opportunity to be involved in the possible mission to the L5 point in the mid 2020s.

Tanja Amerstorfer (former Rollett): She finished her PhD within the first three months of the project and continued her work as a PostDoc for the next 2.5 years. Based on the results gained in this project, she proposed a first project as PI (funded by FWF), which is currently ongoing. She increased her list of publications to a total number of 24 refereed articles (850 citations, h-index: 14, ADS, May 2019). She was invited to give her first solicited talk at EGU 2017. She is currently involved in two pending H2020 proposals and a tender proposed to ESA SSA related to a possible L5 mission.

Manuel Kubicka: He finished his master thesis in 2016, and published his first paper. The project also allowed him to make his first conferences presentations, and after finishing his master degree he moved on to a PhD position on spacecraft operations software at the Technical University in Graz, Austria.

Julia Donnerer: She finished her master thesis in 2019 an co-authored her first publication, as well as presenting for the first time posters at international conferences. She is now applying for PhD positions.

3. Effects of the project beyond the scientific/scholarly field

Did your project have any effects beyond the scientific/scholarly field? If so, describe those effects, including activities outside the sphere of academia.

We have started a real time space weather prediction website, driven by STEREO-A data, with the prototype here:
https://www.iwf.oeaw.ac.at/fileadmin/staff/SP/cmoestl/readtime/predstorm_real.png
Since end of 2018, we made these predictions available via social media to aurora enthusiasts all over the world, with great response. The twitter account @chrisoutofspace by PI C. Möstl has now > 900 followers. We have also written blogs and were quoted many times in the media in articles on project results, see the full list here:
https://www.iwf.oeaw.ac.at/de/fwf/p-26174-n27/outreach/
This includes for example visualizations from our group that were used in a TED talk by M. Janvier with > 1 million views.

Did your project have an impact on the economy, society or policy-making? If so, what kind of impact and to what extent?

The project improved the Austrian expertise on space weather prediction in general, and our group is now taking part in activities of the Austrian space weather community, which is currently underway of forming as an interdisciplinary think-tank including academia and industry. In our three new projects we are now making the step towards an Austrian space weather prediction system, including aurora forecasts and predictions of geomagnetically induced currents for the Austrian power grid.

4. Other important aspects

Project-related participation in national and international scientific/scholarly conferences and a list of the most important lectures held

Project-related work was shown at these conferences:

- EGU General Assembly, Vienna, Austria (2014, 2015, 2016, 2017, 2018).
- SHINE 2018, Cocoa Beach, USA, July 2018.
- 15th European Solar Physics Meeting, Budapest, September 2017.
- First VarSITI General Symposium, Albena, Bulgaria, June 2016.
- AGU Fall Meeting, San Francisco, December 2015.
- European Space Weather Week 12, Ostende, November 2015.
- CORAMOD workshop, Hvar Observatory, Croatia, May 2015.
- 7th Solar Image Processing workshop, La-Roche-en-Ardenne, Belgium, August 2014.

Most important talks:

Amerstorfer, T., Möstl, C., et al., Predicting a CME arrival as observed from L1 by Heliospheric Imagers using ELEvoHI, COSPAR 42nd assembly, Pasadena, USA, July 2018.

Möstl, C., Amerstorfer, T., et al., Forward modeling of coronal mass ejection flux ropes in the inner heliosphere with 3DCORE, EGU General Assembly 2018, Vienna, Austria, April 2018.

Möstl, C.: Predicting CME arrivals and their planetary impacts: A review of methods and results (invited), 15th European Solar Physics Meeting, Budapest, September 2017.

Amerstorfer, T.: CME prediction: present and future perspectives (invited), EGU general assembly 2017, Vienna, Austria, April 2017.

Rollett, T., C. Möstl, et al., ElEvoHI-a novel CME prediction utility using heliospheric imagery, First VarSITI General Symposium, Albena, Bulgaria, June 2016

Möstl, C., A new view of solar coronal mass ejections with the Heliophysics System Observatory (Arne Richter Award for Outstanding Young Scientists Lecture), EGU General Assembly, April 2016.

Rollett, T., Möstl, C., et al., ElEvoHI - Improving CME arrival predictions using heliospheric imaging, EGU General Assembly, April 2016.

Rollett, T., C. Möstl, et al., Combined multipoint remote and in situ observations of the asymmetric evolution of a fast coronal mass ejection, EGU General Assembly 2015, Vienna, April 2015.

Organisation of symposia and conferences

C. Möstl, co-convener, EGU (2015): Session ST1.2/PS5.3 “Multipoint observations and modeling of the heliospheric plasma processes and their effects on the planets”
http://meetingorganizer.copernicus.org/EGU2015/session/18051

C. Möstl, co-convener, EGU (2016): ST1.2
“Observations, theory and modelling of the heliospheric plasma processes and solar eruptions, and their effects on the planets (including Arne Richter Award for Outstanding Young Scientists Lecture)”
http://meetingorganizer.copernicus.org/EGU2016/session/20495

C. Möstl, co-convener, EGU (2017): ST1.2
“Multipoint observations/modeling of heliospheric plasma processes and next steps through NASA’s Interstellar Mapping and Acceleration Probe (IMAP)”
http://meetingorganizer.copernicus.org/EGU2017/session/24849

There are none ongoing applications for patents or licences.

List of the most important pending applications for grants:

T. Amerstorfer as part of consortium in proposal for H2020-SPACE-2019: STORMCAST, coordinator: P. Gallagher, Dublin Institute of Advanced Studies, Ireland.

T. Amerstorfer as deputy coordinator at IWF in proposal for H2020-INFRAIA-2019-: Europlanet 2024-RI, coordinator: N. Mason, University of Kent, UK.

T. Amerstorfer as part of consortium in response to ESA Invitation to Tender AO/1-9703/19/D/CT: Use of L5 Data in CME Propagation, coordinator: C. Perry, RAL Space, UK.

Peer-reviewed publications

25 Freiherr von Forstner, J.L., J. Guo, Robert F. Wimmer-Schweingruber, M. Temmer, M. Dumbović, A. Veronig, C. Möstl, Tracking and validating ICMEs propagating towards Mars using STEREO Heliospheric Imagers combined with Forbush decreases detected by MSL/RAD, Space Weather, in press, (2019). http://arxiv.org/abs/1904.10859

24 Vrsnak, B., T. Amerstorfer, M. Dumbovic, M. Leitner, A.M. Veronig, M. Temmer, C. Möstl, U.V. Amerstorfer, C.J. Farrugia, A.B. Galvin, Heliospheric Evolution of Magnetic Clouds, The Astrophysical Journal, in press, (2019). http://arxiv.org/abs/1904.08266

23 Yu, W., C. J. Farrugia, N. Lugaz, A. B. Galvin, C. Möstl, K. Paulson, P. Vemareddy, The Magnetic Field Geometry of Small Solar Wind Flux Ropes Inferred from their Twist Distribution, Solar Physics, 293, 12, 165, 26 pp. (2018). https://arxiv.org/abs/1811.10283
doi: 10.1007/s11207-018-1385-3

22 M. Janvier, R. Winslow, S. Good, E. Bonhomme, T. Amerstorfer, P. Demoulin, S. Dasso, C. Möstl, N. Lugaz, E. Soubri, P. Boakes, Generic profiles of Interplanetary Coronal Mass Ejections at Mercury, Venus and Earth from superposed epoch analyses, Journal of Geophysical Research - Space Physics, 124, 2, pp. 812-836 (2019).
http://arxiv.org/abs/1901.09921 doi: 10.1029/2018JA025949

21 Reiss, M., P. J. MacNeice, L. M. Mays, C. N. Arge, C. Möstl, L. Nikolic, T. Amerstorfer, Forecasting the Ambient Solar Wind with Numerical Models: I. On the Implementation of an Operational Framework, ApJS, 240, 2, 35, (2019). doi: 10.3847/1538-4365/aaf8b3
https://arxiv.org/abs/1905.04353

20 Bisikalo, D. V., Shematovich, V. I., Cherenkov, A. A., Fossati, L., Möstl, C., Atmospheric mass loss from hot Jupiters irradiated by stellar superflares, ApJ, 869, 108 (2018). https://arxiv.org/abs/1811.02303 doi: 10.3847/1538-4357/aaed21

19 Riley, P., Mays., M.L., J. Andries, T. Amerstorfer, V. Delouille, M. Dumbovic, X. Feng, J. A. Linker, C. Möstl, M. Nunez, M. Temmer, W.K. Tobiska, C. Verbeke, X. Zhao, Forecasting the Arrival Time of Coronal Mass Ejections: Current Capabilities and Uncertainties, Space Weather, 16, 9, pp. 1245-1260, (2018).
doi: 10.1029/2018SW001962 https://arxiv.org/abs/1810.07289

18 Plaschke, F., T. Karlsson, C. Götz, C. Möstl, I. Richter, M. Volwerk, A. Eriksson, E. Behar, and R. Goldstein, First observations of magnetic holes deep within the coma of a comet, Astronomy & Astrophysics 618, A114 (2018). doi: 10.1051/0004-6361/201833300
https://www.aanda.org/articles/aa/pdf/2018/10/aa33300-18.pdf

17 Amerstorfer, T., C. Möstl, Hess, P., Temmer, M., Mays, M. L., Reiss, M., Lowrance, P., Bourdin, P.-A., Ensemble Prediction of a Halo Coronal Mass Ejection Using Heliospheric

Imagers, Space Weather, 16, 784–801 (2018). doi: 10.1029/2017SW001786
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2017SW001786

16 E. Palmerio, E. K. J. Kilpua, C. Möstl, V. Bothmer, A. W. James, L. M. Green, A. Isavnin, J. A. Davies, and R. A. Harrison, Coronal Magnetic Structure of Earthbound CMEs and In situ Comparison, Space Weather 16, 5, pp. 442-460 (2018). doi: 10.1002/2017SW001767 https://arxiv.org/abs/1803.04769

15 Möstl, C., Amerstorfer, T., Palmerio, E., Isavnin, A., Farrugia, C. J., Lowder, C., Winslow, R. M., Donnerer, J., Kilpua, E. K. J., Boakes, P. D., Forward modeling of coronal mass ejection flux ropes in the inner heliosphere with 3DCORE, Space Weather 16, 3, pp. 216-229 (2018). doi: 10.1002/2017SW001735
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017SW001735

14 Good, S. W., R.J. Forsyth, J.P. Eastwood and C. Möstl, Correlation of ICME Magnetic Fields Observed at Radially Aligned Spacecraft, Solar Physics, 293, 3, id. 52, 21 pp. (2018). doi: 10.1007/s11207-018-1264-y
https://link.springer.com/content/pdf/10.1007%2Fs11207-018-1264-y.pdf

13 Cherenkov, A., Bisikalo, D., Fossati, L., Möstl, C. (2017), The Influence of Coronal Mass Ejections on the Mass-loss Rates of Hot-Jupiters, The Astrophysical Journal 846, 31 (2017). doi: 10.3847/1538-4357/aa82b2 https://arxiv.org/abs/1709.01027

12 Möstl, C., A. Isavnin, A., P.D. Boakes, E.K.J. Kilpua, J. A. Davies, R. A. Harrison, D. Barnes, V. Krupar, J.P. Eastwood, S.W. Good, R. J. Forsyth, V. Bothmer, M.A. Reiss, T. Amerstorfer, R. M. Winslow, B. J. Anderson, L.C. Philpott, L. Rodriguez, A. P. Rouillard, P. T. Gallagher, T.L. Zhang, Modeling observations of solar coronal mass ejections with heliospheric imagers verified with the Heliophysics System Observatory, Space Weather 15, 955, (2017). doi:10.1002/2017SW001614
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017SW001614

11 Kubicka, M., C. Möstl, T. Rollett, P. D. Boakes, L. Feng, J. P. Eastwood, O. Törmänen, Prediction of Geomagnetic Storm Strength from Inner Heliospheric In Situ Observations, The Astrophysical Journal 833, 255 (2016). https://arxiv.org/abs/1610.06713
doi: 10.3847/1538-4357/833/2/255

10 Vemareddy, P., C. Möstl, T. Rollett, W. Mishra, C. Farrugia, and M. Leitner, Consistency of twist in a magnetic cloud and its solar source on 2013 April 14, The Astrophysical Journal 828, 1, 12, 10 pp., (2016). http://arxiv.org/abs/1607.03811
doi: 10.3847/0004-637X/828/1/12

9 Edberg, N. J. T., Alho, M., Andre;, M., Andrews, D. J., Behar, E., Burch, J. L., Carr, C. M., Cupido, E., Engelhardt, I. A. D., Eriksson, A. I., Glassmeier, K.-H., Goetz, C., Goldstein, R., Henri, P., Johansson, F. L., Koenders, C., Mandt, K., Möstl, C., Nilsson, H., Odelstad, E.,

Richter, I., Wedlund, C. S., Stenberg Wieser, G., Szego, K., Vigren, E., & Volwerk, M., CME impact on comet 67P/Churyumov-Gerasimenko, Monthly Notices of the Royal Astronomical Society 462, S45 (2016). doi:10.1093/mnras/stw2112
https://academic.oup.com/mnras/article-lookup/doi/10.1093/mnras/stw2112

8 Hu, H., Liu, Y. D., Wang, R., Möstl, C., Yang, Z., Sun-to-Earth Characteristics of the 2012 July 12 Coronal Mass Ejection and Associated Geo-effectiveness, The Astrophysical Journal 829, 97., (2016). http://arxiv.org/abs/1607.06287 doi:10.3847/0004-637X/829/2/97

7 Rollett, T., C. Möstl, A. Isavnin, J.A. Davies, M. Kubicka, U.V. Amerstorfer, R.A. Harrison, ElEvoHI: a novel CME prediction tool for heliospheric imaging combining an elliptical front with drag-based model fitting, The Astrophysical Journal, 824:131, 10 pp., 2016. doi:10.3847/0004-637X/824/2/131 http://arxiv.org/abs/1605.00510

6 Erratum: Amerstorfer, T., Möstl, C., Isavnin, A., Davies, J. A., Kubicka, M., Amerstorfer, U. V., & Harrison, R. A., Erratum: ElEvoHI: A Novel CME Prediction Tool for Heliospheric Imaging Combining an Elliptical Front with Drag-based Model Fitting, The Astrophysical Journal 831, 210 (2016). doi:10.3847/0004-637X/831/2/210

5 Mays, M.L., B. J. Thompson, L. K. Jian, R. C. Colaninno, D. Odstrcil, C. Möstl, M. Temmer, N. P. Savani, G. Collinson, A. Taktakishvili, P. J. MacNeice, and Y. Zheng, Propagation of the 7 January 2014 CME and resulting geomagnetic non-event, The Astrophysical Journal, 812, 145, 15 pp., 2015. http://arxiv.org/abs/1509.06477
doi: 10.1088/0004-637X/812/2/145

4 Möstl, C., T. Rollett, R. A. Frahm, Y. D. Liu, D. M. Long, R. C. Colaninno, M. A. Reiss, M. Temmer, C. J. Farrugia, A. Posner, M. Dumbovic, M. Janvier, P. Demoulin, P. Boakes, A. Devos, E. Kraaikamp, M. L. Mays, B. Vrsnak, Strong coronal channeling and interplanetary evolution of a solar storm up to Earth and Mars, Nature Communications, 6:7135, 10 pp., 2015. open access. doi: 10.1038/ncomms8135
https://www.nature.com/articles/ncomms8135.pdf

3 Rollett, T., C. Möstl, M. Temmer, R. A. Frahm, J. A. Davies, A. M. Veronig, B. Vrsnak, U.V. Amerstorfer, C.J. Farrugia, T. L. Zhang, Combined Multipoint Remote and In Situ Observations of the Asymmetric Evolution of a Fast CME, The Astrophysical Journal Letters, 790, 1, L6, 7 pp., 2014. http://arxiv.org/abs/1407.4687
doi: 10.1088/2041-8205/790/1/L6

2 Vršnak, B., M. Temmer, T. Zic, A. Taktakishvili, M. Dumbovic, C. Möstl, A. M. Veronig, M. L. Mays, Heliospheric propagation of coronal mass ejections: Comparison of numerical WSA-ENLIL+Cone model and analytical Drag-Based Model, The Astrophysical Journal Supplement Series, 213, 2, 21, 9 pp., 2014. doi: 10.1088/0067-0049/213/2/21
https://iopscience.iop.org/article/10.1088/0067-0049/213/2/21/pdf

1 Möstl, C., K. Amla, J.R. Hall, P.C. Liewer, E.M. DeJong, R. C. Colannino, A. M. Veronig, T. Rollett, M. Temmer, V. Peinhart, J.A. Davies, N. Lugaz, Y. D. Liu, C. J. Farrugia, J.G. Luhmann, B. Vrsnak, R. A. Harrison, A. B. Galvin, Connecting speeds, directions and arrival times of 22 coronal mass ejections from the Sun to 1 AU, The Astrophysical Journal, 787, 2, 119, 17 pp., 2014. http://arxiv.org/abs/1404.3579
doi: 10.1088/0004-637X/787/2/119