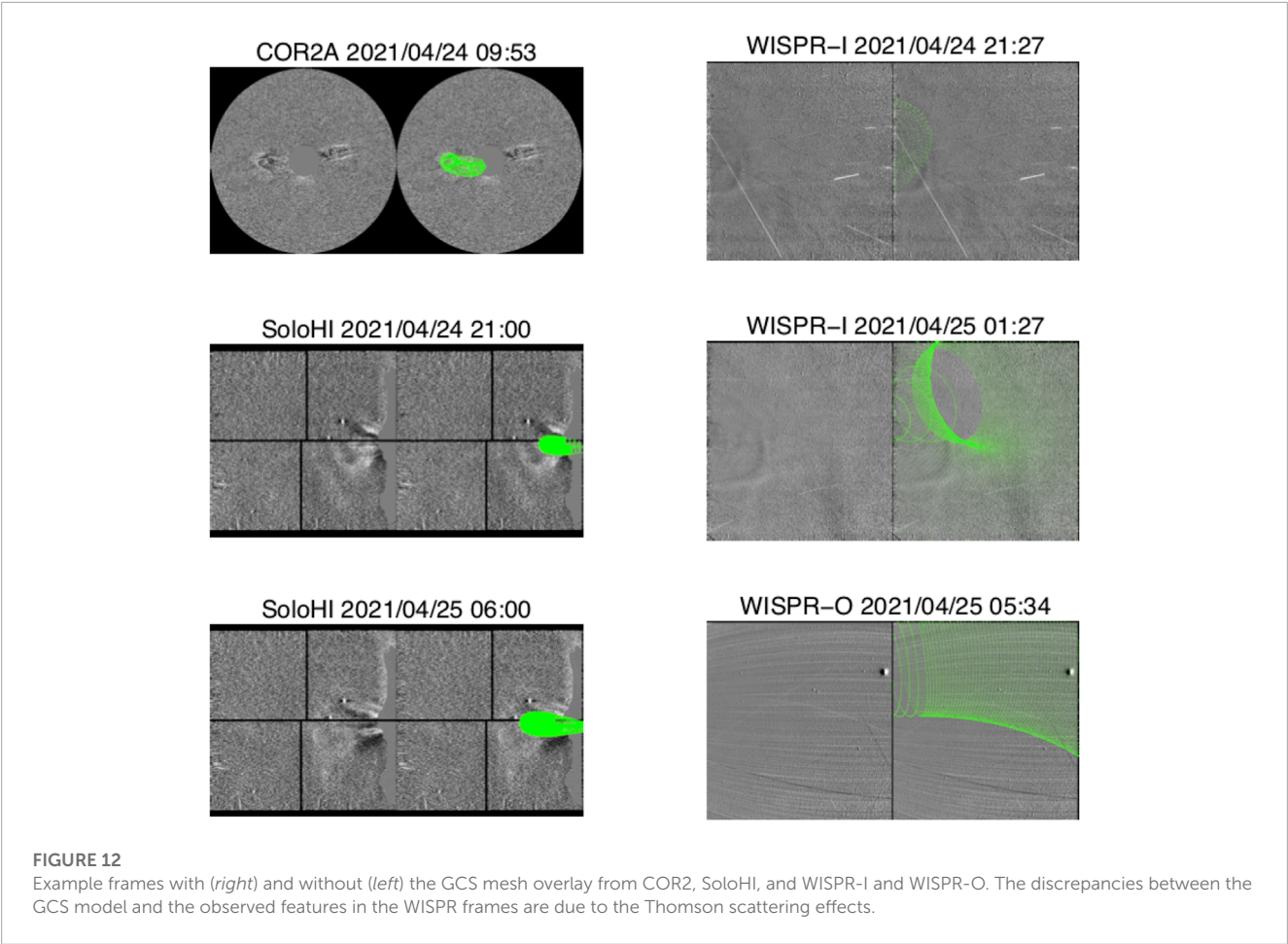




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several consecutive loop structures that continue to be observed after 2021 April 25, 12:00 UT.

Similarly, in WISPR-O, a number of separate distinct outflows are visible throughout 2021 April 25, as seen in Figure 11. This type of repeated outflow has not been seen before or after this event. We believe this is due to a combination of the spacecraft flying through the CME and the different distinct blobs seen in Figure 7F.

4.4 GCS reconstruction

The determined GCS structure (details of the model described in Section 2) is displayed in Figure 12. This structure was determined largely from the COR2 observations, making the geometry more uncertain given the single viewpoint. Later observations from WISPR and SoloHI, while not overlapping with COR2, were used to determine if this GCS structure was plausible.

The parameters of the model are listed in Table 2. Given the relatively faint CME observations and assuming low values of the width and aspect ratio (which controls the minor axis cross-section), we found that the CME nose is almost directly pointed at the PSP spacecraft.

COR2 and SoloHI were optimally positioned to observe the event. However, because the field of views did not overlap and had similar lines of sight, a true multi-viewpoint triangulation

TABLE 2 GCS parameters determined to best recreate the CME. The longitude and latitude have been converted into HEE coordinates for the sake of comparison to Table 1.

Lon(°)	Lat(°)	Tilt(°)	Aspect Ratio	Half Angle(°)
162.9	−5.08	13.98	0.125	20.12

was not possible, and the reconstruction should be considered to have significant uncertainties. The SoloHI observations are further limited by the low resolution and cadence of the images due to the larger radial distance of the spacecraft. The WISPR data overlap with the SoloHI data at a much better resolution and cadence, but given that the derived GCS direction is pointing toward the PSP spacecraft, much of the CME front is likely unable to be resolved due to the poor Thompson scattering angle.

It should be noted that the different outflows observed, especially the two apparent flux-rope-like structures seen through Figure 7C, make it challenging to directly and confidently link the *in situ* data to what is imaged remotely. By fitting the GCS to the clearest observed flux-rope seen in COR2, we have produced a plausible geometric and kinematic structure that seems to match the various observations. We do acknowledge the possibility that another structure, such as that seen in front of the structure, fits with the GCS model in Figure 7C and could have been oriented toward PSP and produced the resulting *in situ* signatures. Regardless, the kinematics of the

GCS blob should represent a useful velocity for the various related outflows seen in the imaging.

5 Discussion

To relate features observed in FSI and Metis, COR2, and PSP, we constructed a height–time plot (Figure 13) that combines the FSI and COR2 data, with overlays from measured or extrapolated positions of the eruptions as observed in other instruments. The plot shows the average over a radial cut through the images along the primary propagation direction of the eruption, between about 108° and 122° in the heliocentric radial coordinate system (where 0° is at the Sun's north pole and 90° points due east).

Above 4 $R_{\odot}$, we use COR2 observations to track the motion of the eruption, interpolated to match the spatial and temporal resolution of the FSI observations, and corrected to match the line of sight based on the known spacecraft locations and our 3D reconstruction (see Section 4.1). Note that the timing error introduced by SolO and STEREO-A's different distances from the Sun is about 45 s, which is negligible compared to the uncertainty introduced by the observation cadence of COR2 and the assumptions underpinning the de-projection of the STEREO-A data to match SolO's perspective, and are, therefore, neglected in this plot.

To relate the multiple observations, reconstructions, and extrapolations of the eruption from different instruments to one another and to validate that each tracking method has indeed produced self-consistent results, in a simple, unified view, we overlay our measurements of the position of the eruption on the height–time plot, including FSI (red +), COR2 GCS reconstructions (light blue *), Metis (orange □), and backward extrapolations from PSP's position using the velocities measured *in situ* (first transient in magenta +, constant speed patch in green +, and the second transient in indigo +; these colors are selected to generally correspond to the colors of specific field lines in Figure 2 but must be lightened somewhat to be visible on the dark height–time image).

From the *in situ* observations, we analytically reconstruct the speed values from the PSP location back to 10–20 $R_{\odot}$. We track back three different patches of plasma: the first structure (vertical magenta dash line in Figure 3) that crossed PSP at 412 km s⁻¹, the second at a constant speed of 300 km s⁻¹ (delimit between the two vertical green dash lines), and the third structure at 310 km s⁻¹ (vertical indigo dash line).

We assume steady flows of adiabatic gas in each patch to solve the 1D spherical symmetric Bernoulli's equation (integrated momentum equation) and obtain their speeds at ten different distances between 10 and 20 $R_{\odot}$. We neglect gravity forces, assume a polytropic gas (Shi et al., 2022, in our case, $\gamma = 5/3$), and include the molecular weight μ to consider the He²⁺/H⁺ density ratio measured by SWEAP, to get the following:

$$v^2 = \left(\frac{2\gamma}{\gamma-1} \right) \left(\frac{kT}{\mu m_H} \right) \left[1 - \left(\frac{v_0 r_0^2}{v r^2} \right)^{\gamma-1} \right],$$

where k is the Boltzmann constant, m_H is the proton mass, v_0 and r_0 are the speed and radial distance near the Sun (in this case between 10 and 20 $R_{\odot}$), and v and r are the speed and radial distance at the PSP

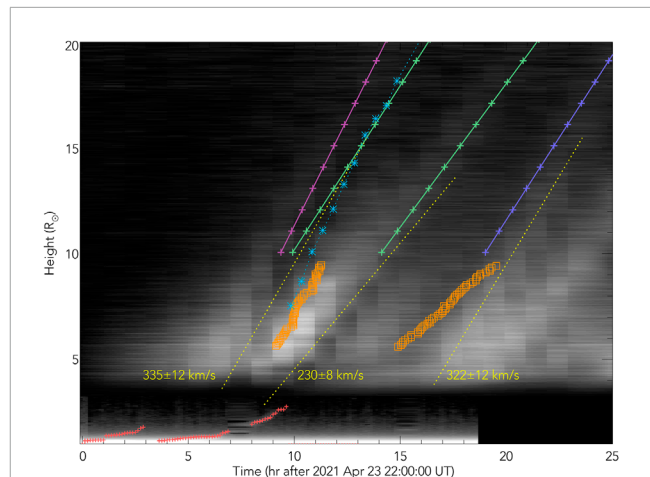


FIGURE 13

Composite FSI and Metis and COR2 height–time plot showing the relationships between erupting features tracked in EU1 (red + symbols), COR2 GCS fits (light blue * symbols), Metis (orange □), and backward extrapolations from PSP *in situ* measurements of three different patches corresponding to those marked with vertical dash lines in Figure 3. The first transient with magenta +, the constant speed patch delimit between the lines marked with green +, and the third transient marked with indigo +. The dashed yellow lines and velocities are fit directly to features in the height–time plot.

location, respectively. We reconstruct analytically the information of the structures back to the Sun by assuming constant speed motion (see Figure 13).

In this case, we did not pursue running MHD numerical simulations (e.g., ENLIL (Odstrcil and Pizzo, 2009), PLUTO (Mignone et al., 2007; Mignone et al., 2012), and EUFORIA (Pomoell and Poedts, 2018) numerical codes) by extrapolating the photospheric fields due to the difficulty of analyzing the event at its source region, observational limitations, and possible prediction of transit times to follow the eruption from the Sun to the PSP location with an analytical approach.

The analytical equations predict between 10 and 20 $R_{\odot}$: the passage of the first structure on 2021 April 24, 08:40 UT, propagating away from the Sun with a speed of 389 km s⁻¹, the constant speed structure on 2021 April 24, 10:00 to 18:00 UT, at 290 km s⁻¹, and the third transient on 2021 April 24, 23:00 UT, at 302 km s⁻¹.

Fitting the slopes of the two eruptions observed in the height–time plot, corresponding to the feature observed near the first sets of orange Metis points, we obtain a velocity of 335 ± 12 km s⁻¹. The second major eruption, around the second set of orange Metis points, has a velocity of 322 ± 12 km s⁻¹. A dark intermediate feature, corresponding to the third set of red points, is probably the trailing edge of the first eruption and has a slower speed, 230 ± 8 km s⁻¹.

The strong agreement between the different sets of observations suggests we are tracking the same features in all of our data. The velocities we measure from these height–time plots also agree well with the PSP-derived velocities, indicating that the propagation of the CME is not strongly influenced by interactions in interplanetary space.

Early in the first eruption, the prominence appears to follow the local magnetic field in the low corona, which is highly non-radial, and thus the radially plotted height–time diagram does not fully capture the prominence's trajectory or velocity. Outside of the FSI field of view, the eruption moves primarily radially, with essentially constant velocity.

By combining the analytical model with the connectivity derived from the MAS model, it is clear that, for much of the propagation of the eruption, the CME is propagating constantly along the open field lines connected to PSP because of the close proximity of the initial prominence to these field lines. While the magnetograms used in the MAS model for the area around the eruption are necessarily somewhat out of date because the eruption occurred on the backside of the Sun with respect to Earth, all of the remote-sensing data supports the notion of a simple propagation originating in the south and following open field lines northward toward the equator.

6 Conclusion

We reported the propagation of a complex prominence eruption that reached PSP on 2021 April 25 at 01:00 UT when the spacecraft was located at $46 R_{\odot}$. To study the full evolution of the event, we combined multi-spacecraft remote-sensing observations with the *in situ* measurements onboard PSP. The structure, as sampled by SPC, was characterized as a low temperature and low-density transient with complex magnetic field configuration and a $\text{He}^{2+}/\text{H}^+ > 8\%$ ratio indicating the presence of alpha particles identified from the clear secondary peak in the 1D reduced distribution functions moving at a velocity ranging between 550 and 650 km s^{-1} . Although the structure lacks a coherent magnetic field configuration, the rest of the characteristics observed are signatures common in magnetic clouds, particularly when related to prominences. We identified the complex prominence eruption as the source by tracking from the Sun to PSP location the propagation of the associated CME, which was only possible due to the nearly perfect quadrature of PSP and SOHO.

We analyzed FSI, Metis, and COR2 images, tracked the structure evolution up to $20 R_{\odot}$, and identified that the eruption occurred in two phases: a smaller outburst beginning in the more southerly part of a prominence and the substantial eruption originated from the more northerly part of the structure. Below $4 R_{\odot}$, the set of remote-sensing observations showed that the structure is complex.

Above $20 R_{\odot}$, the CME kinematics was modeled using the GCS reconstruction method over WISPR and COR2 coronagraph images and by modeling the background magnetic field using the MHD PSI/MAS model and backward analytic reconstruction starting from PSP *in situ* data. The strong agreement between the different sets of observations and models showed that the ICME propagated radially at a constant speed and that it was not strongly influenced by interactions in interplanetary space.

This work highlights the importance of studying the propagation of transients from a multi-spacecraft point of view, as their combination enables a better understanding of the phenomena by closing gaps between the sets, e.g., the distance ranges covered by the different instruments, the image dependence with the spacecraft location which also reverberates on the possibility to model the events from remote-sensing observations, and the limits of the

current reconstruction models back to the Sun from *in situ* data. Particularly in this case, we were able to follow a complex structure that, during the first stages of propagation, it seems to be evolving non-radially before propagating at a constant rate. Moreover, the eruption conserves its plasma and magnetic properties up to $46 R_{\odot}$.

Data availability statement

PSP SWEAP and FIELDS data are publicly available and can be found at: <https://cdaweb.gsfc.nasa.gov/>. The SoloHI data will be accessible at https://solohi.nrl.navy.mil/so_data/L1/ while WISPR at <https://wispr.nrl.navy.mil/data/rel/fits/L3/orbit08/> and SECCHI at https://stereo-ssc.nascom.nasa.gov/data/ins_data/secchi/L0/a. Metis data will become available through the Solar Orbiter Archive (SOAR) by the end of 2023. Data are in any case available from the instrument Principal Investigator, prof. Marco Romoli (marco.romoli@unifi.it) upon request. EUH data is available through the Solar Orbiter Archive (SOAR, <https://soar.esac.esa.int/>). Our MAS model results are all available online at www.predsci.com.

Author contributions

TN, DS, PH, DB, VA, KK and MS contributed to conception, design of the study and writing of the first draft of the manuscript. TN carried out the PSP *in situ* data analysis and backward reconstruction models. MS performed the alpha ratio estimation and *in situ* data analysis. DS carried out height–time analysis for the near-sun observations and contributed to the characterization of the magnetic topology of the eruption's source region. PH performed analysis of the WISPR, SoloHI and COR2 images, including the GCS reconstruction of the CME on those data sets. DB contributed the EUH image processing and the visualization of the magnetic field lines. CV was the science planner and campaign leader for EUH that produced the EUH data analyzed in this paper. VA performed analysis of Metis data, including the determination of Metis height–time curves. PR and KR performed and worked the magnetic field simulations. FL and CS worked with the Metis observation plan that produced the Metis data analyzed in this paper. RS worked with the Metis observation plan and processed the resulting data analyzed in this paper. MU performed Metis UV data processing. All authors contributed to manuscript revision, and approved the submitted version. TN would like to thank Kristoff Paulson and Anthony Case for all their helpful discussions.

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Conflict of interest

PR is employed by Predictive Science Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Alterman, B. L., Kasper, J. C., Stevens, M. L., and Koval, A. (2018). A comparison of alpha particle and proton beam differential flows in collisionally young solar wind. *ApJ* 864, 112. doi:10.3847/1538-4357/aad23f
- Andretta, V., Bemporad, A., De Leo, Y., Jerse, G., Landini, F., Mierla, M., et al. (2021). The first coronal mass ejection observed in both visible-light and UV H I Ly- α channels of the Metis coronagraph on board Solar Orbiter. *AAP* 656, L14. doi:10.1051/0004-6361/202142407
- Antonucci, E., Romoli, M., Andretta, V., Fineschi, S., Heinzel, P., Moses, J. D., et al. (2020). Metis: The solar orbiter visible light and ultraviolet coronal imager. *AAP* 642, A10. doi:10.1051/0004-6361/201935338
- Bale, S. D., Goetz, K., Harvey, P. R., Turin, P., Bonnell, J. W., Dudok de Wit, T., et al. (2016). The FIELDS instrument suite for solar Probe plus. Measuring the coronal plasma and magnetic field, plasma waves and turbulence, and radio signatures of solar transients. *SSR* 204, 49–82. doi:10.1007/s11214-016-0244-5
- Biondo, R., Bemporad, A., Mignone, A., and Reale, F. (2021). Reconstruction of the parker spiral with the reverse *in situ* data and MHD Approach - rimap. *J. Space Weather Space Clim.* 11, 7. doi:10.1051/swsc/2020072
- Borovsky, J. E. (2008). Flux tube texture of the solar wind: Strands of the magnetic carpet at 1 AU? *J. Geophys. Res. (Space Phys.)* 113, A08110. doi:10.1029/2007JA012684
- Borini, G., Gosling, J. T., Bame, S. J., and Feldman, W. C. (1982). Helium abundance enhancements in the solar wind. *JGR* 87, 7370–7378. doi:10.1029/JA087iA09p07370
- Bothmer, V., and Schwenn, R. (1994). Eruptive prominences as sources of magnetic clouds in the solar wind. *SSR* 70, 215–220. doi:10.1007/BF00777872
- Braga, C. R., Vourlidas, A., Liewer, P. C., Hess, P., Stenborg, G., and Riley, P. (2022). Coronal Mass Ejection Deformation at 0.1 au Observed by WISPR. *ApJ* 938, 13. doi:10.3847/1538-4357/ac90bf
- Brueckner, G. E., Howard, R. A., Koomen, M. J., Korendyke, C. M., Michels, D. J., Moses, J. D., et al. (1995). The large angle spectroscopic coronagraph (LASCO). *Sol. Phys.* 162, 357–402. doi:10.1007/BF00733434
- Burlaga, L., Fitzenreiter, R., Lepping, R., Ogilvie, K., Szabo, A., Lazarus, A., et al. (1998). A magnetic cloud containing prominence material: January 1997. *JGR* 103, 277–285. doi:10.1029/97JA02768
- Burlaga, L. F., Klein, L., Sheeley, J., Michels, D. J., Howard, R. A., Koomen, M. J., et al. (1982). A magnetic cloud and a coronal mass ejection. *GRL* 9, 1317–1320. doi:10.1029/GL009i012p01317
- Case, A. W., Kasper, J. C., Stevens, M. L., Korreck, K. E., Paulson, K., Daigneau, P., et al. (2020). The solar Probe cup on the parker solar Probe. *ApJS* 246, 43. doi:10.3847/1538-4365/ab5a7b
- DeForest, C. E., Howard, T. A., and McComas, D. J. (2013). Tracking coronal features from the low corona to Earth: A quantitative analysis of the 2008 december 12 coronal mass ejection. *ApJ* 769, 43. doi:10.1088/0004-637X/769/1/43
- Domingo, V., Fleck, B., and Poland, A. I. (1995). SOHO: The solar and heliospheric observatory. *SSR* 72, 81–84. doi:10.1007/BF00768758
- Fox, N. J., Velli, M. C., Bale, S. D., Decker, R., Driesman, A., Howard, R. A., et al. (2016). The solar Probe plus mission: Humanity's first visit to our star. *SSR* 204, 7–48. doi:10.1007/s11214-015-0211-6
- Freeland, S. L., and Handy, B. N. (1998). Data analysis with the SolarSoft system. *Sol. Phys.* 182, 497–500. doi:10.1023/A:1005038224881
- Gibson, S. E. (2018). Solar prominences: Theory and models. Fleshing out the magnetic skeleton. *Living Rev. Sol. Phys.* 15, 7. doi:10.1007/s41116-018-0016-2
- Gopalswamy, N., Shimojo, M., Lu, W., Yashiro, S., Shibasaki, K., and Howard, R. A. (2003). Prominence eruptions and coronal mass ejection: A statistical study using microwave observations. *ApJ* 586, 562–578. doi:10.1086/367614
- Hess, P., Howard, R. A., Stenborg, G., Linton, M., Vourlidas, A., Thernisien, A., et al. (2021). In-flight calibration and data reduction for the WISPR instrument on board the PSP mission. *Sol. Phys.* 296, 94. doi:10.1007/s11207-021-01847-9
- Hess, P., Rouillard, A. P., Kouloumvakos, A., Liewer, P. C., Zhang, J., Dhakal, S., et al. (2020). WISPR imaging of a pristine CME. *ApJS* 246, 25. doi:10.3847/1538-4365/ab4ff0
- Hess, P., and Zhang, J. (2017). A study of the earth-affecting CMEs of solar cycle 24. *Sol. Phys.* 292, 80. doi:10.1007/s11207-017-1099-y
- Hirshberg, J., Bame, S. J., and Robbins, D. E. (1972). Solar flares and solar wind helium enrichments: July 1965 July 1967. *SolPhys* 23, 467–486. doi:10.1007/BF00148109

- Horbury, T. S., O'Brien, H., Carrasco Blazquez, I., Bendyk, M., Brown, P., Hudson, R., et al. (2020). The solar orbiter magnetometer. *AAP* 642, A9. doi:10.1051/0004-6361/201937257
- Howard, R. A., Moses, J. D., Vourlidas, A., Newmark, J. S., Socker, D. G., Plunkett, S. P., et al. (2008). Sun Earth connection coronal and heliospheric investigation (SECCHI). *SSR* 136, 67–115. doi:10.1007/s11214-008-9341-4
- Howard, R. A., Stenborg, G., Vourlidas, A., Gallagher, B. M., Linton, M. G., Hess, P., et al. (2022). Overview of the remote sensing observations from PSP solar encounter 10 with perihelion at 13.3 R_☉. *ApJ* 936, 43. doi:10.3847/1538-4357/ac7ff5
- Howard, R. A., Vourlidas, A., Colaninno, R. C., Korendyke, C. M., Plunkett, S. P., Carter, M. T., et al. (2020). The solar orbiter heliospheric imager (SoloHI). *AAP* 642, A13. doi:10.1051/0004-6361/201935202
- Howard, T. A., and DeForest, C. E. (2012). Inner heliospheric flux rope evolution via imaging of coronal mass ejections. *ApJ* 746, 64. doi:10.1088/0004-637X/746/1/64
- Inhester, B. (2006). *Stereoscopy basics for the STEREO mission*. arXiv e-prints, astro-ph/0612649.
- Kaiser, M. L. (2005). The STEREO mission: An overview. *Adv. Space Res.* 36, 1483–1488. doi:10.1016/j.asr.2004.12.066
- Kasper, J. C., Abiad, R., Austin, G., Balat-Pichelin, M., Bale, S. D., Belcher, J. W., et al. (2016). Solar wind electrons alphas and protons (SWEAP) investigation: Design of the solar wind and coronal plasma instrument suite for solar Probe plus. *SSR* 204, 131–186. doi:10.1007/s11214-015-0206-3
- Kilpua, E. K. J., Good, S. W., Palmerio, E., Asvestari, E., Lumme, E., Ala-Lahti, M., et al. (2019). Multipoint observations of the June 2012 interacting interplanetary flux ropes. *Front. Astronomy Space Sci.* 6, 50. doi:10.3389/fspas.2019.00050
- Landau, L. D., and Lifshitz, E. M. (1987). *Fluid mechanics*. Butterworth-Heinemann, Elsevier.
- Lepri, S. T., and Rivera, Y. J. (2021). Elemental abundances of prominence material inside ICMes. *ApJ* 912, 51. doi:10.3847/1538-4357/abea9f
- Lionello, R., Linker, J. A., and Mikić, Z. (2001). Including the transition region in models of the large-scale solar corona. *ApJ* 546, 542–551. doi:10.1086/318254
- Lionello, R., Linker, J. A., and Mikić, Z. (2009). Multispectral emission of the sun during the first whole sun month: Magnetohydrodynamic simulations. *ApJ* 690, 902–912. doi:10.1088/0004-637X/690/1/902
- Livi, R., Larson, D. E., Kasper, J. C., Abiad, R., Case, A. W., Klein, K. G., et al. (2022). The solar Probe Analyzer-ions on the parker solar Probe. *ApJ* 938, 138. doi:10.3847/1538-4357/ac93f5
- Luhmann, J. G., Gopalswamy, N., Jian, L. K., and Lugaz, N. (2020). ICME evolution in the inner heliosphere. *Sol. Phys.* 295, 61. doi:10.1007/s11207-020-01624-0
- MacQueen, R. M., Csoeke-Poeckh, A., Hildner, E., House, L., Reynolds, R., Stanger, A., et al. (1980). The high altitude observatory coronagraph/polarimeter on the solar maximum mission. *Sol. Phys.* 65, 91–107. doi:10.1007/BF00151386
- MacQueen, R. M., Eddy, J. A., Gosling, J. T., Hildner, E., Munro, R. H., Newkirk, J., et al. (1974). The outer solar corona as observed from Skylab: Preliminary results. *ApJL* 187, L85. doi:10.1086/181402
- Mampaey, B., Verbeeck, F., Stegen, K., Kraaikamp, E., Gissot, S., Auchère, F., et al. (2022). *Solo/eui data release 5.0 2022-04*. Published by Royal Observatory of Belgium (ROB). doi:10.24414/2qfw-tr95
- Marsch, E., Schwenn, R., Rosenbauer, H., Muehlhaeuser, K. H., Pilipp, W., and Neubauer, F. M. (1982). Solar wind protons: Three-dimensional velocity distributions and derived plasma parameters measured between 0.3 and 1 AU. *JGR* 87, 52–72. doi:10.1029/JA087iA01p00052
- Mierla, M., Seaton, D. B., Berghmans, D., Chifu, I., De Groof, A., Inhester, B., et al. (2013). Study of a prominence eruption using PROBA2/SWAP and STEREO/EUVI data. *Sol. Phys.* 286, 241–253. doi:10.1007/s11207-012-9965-0
- Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., et al. (2007). Pluto: A numerical code for computational Astrophysics. *ApJS* 170, 228–242. doi:10.1086/513316
- Mignone, A., Zanni, C., Tzeferacos, P., van Straalen, B., Colella, P., and Bodo, G. (2012). The PLUTO code for adaptive mesh computations in astrophysical fluid dynamics. *ApJS* 198, 7. doi:10.1088/0067-0049/198/1/7
- Müller, D., Cyr, St. O. C., Zouganelis, I., Gilbert, H. R., Marsden, R., Nieves-Chinchilla, T., et al. (2020). The Solar Orbiter mission. Science overview. *AAP* 642, A1. doi:10.1051/0004-6361/202038467
- Munro, R. H., Gosling, J. T., Hildner, E., MacQueen, R. M., Poland, A. I., and Ross, C. L. (1979). The association of coronal mass ejection transients with other forms of solar activity. *Sol. Phys.* 61, 201–215. doi:10.1007/BF00155456
- Ness, N. F., and Burlaga, L. F. (2001). Spacecraft studies of the interplanetary magnetic field. *JGR* 106, 15803–15817. doi:10.1029/2000JA000118
- Nieves-Chinchilla, T., Alzate, N., Cremades, H., Rodríguez-García, L., Dos Santos, L. F. G., Narock, A., et al. (2022). Direct first parker solar Probe observation of the interaction of two successive interplanetary coronal mass ejections in 2020 november. *ApJ* 930, 88. doi:10.3847/1538-4357/ac590b
- Odstrčil, D., and Pizzo, V. J. (2009). Numerical heliospheric simulations as assisting tool for interpretation of observations by STEREO heliospheric imagers. *Sol. Phys.* 259, 297–309. doi:10.1007/s11207-009-9449-z
- Ogilvie, K. W., and Desch, M. D. (1997). The wind spacecraft and its early scientific results. *Adv. Space Res.* 20, 559–568. doi:10.1016/S0273-1177(97)00439-0
- O'Hara, J. P., Mierla, M., Podladchikova, O., D'Huys, E., and West, M. J. (2019). Exceptional extended field-of-view observations by PROBA2/SWAP on 2017 April 1 and 3. *ApJ* 883, 59. doi:10.3847/1538-4357/ab3b08
- Owen, C. J., Bruno, R., Livi, S., Louarn, P., Al Janabi, K., Allegrini, F., et al. (2020). The solar orbiter solar wind analyser (SWA) suite. *AAP* 642, A16. doi:10.1051/0004-6361/201937259
- Palmerio, E., Nieves-Chinchilla, T., Kilpua, E. K. J., Barnes, D., Zhukov, A. N., Jian, L. K., et al. (2021). Magnetic structure and propagation of two interacting CMEs from the sun to saturn. *J. Geophys. Res. (Space Phys.)* 126, e2021JA029770. doi:10.1029/2021JA029770
- Parenti, S. (2014). Solar prominences: Observations. *Living Rev. Sol. Phys.* 11, 1. doi:10.12942/lrsp.2014-1
- Parker, E. N. (1958). Dynamics of the interplanetary gas and magnetic fields. *ApJ* 128, 664. doi:10.1086/146579
- Patel, R., Majumdar, S., Pant, V., and Banerjee, D. (2022). A simple radial gradient filter for batch-processing of coronagraph images. *Sol. Phys.* 297, 27. doi:10.1007/s11207-022-01957-y
- Pesnell, W. D., Thompson, B. J., and Chamberlin, P. C. (2012). The solar dynamics observatory (SDO). *Sol. Phys.* 275, 3–15. doi:10.1007/s11207-011-9841-3
- Pizzo, V. J. (1981). On the application of numerical models to the inverse mapping of solar wind flow structures. *JGR* 86, 6685–6690. doi:10.1029/JA086iA08p06685
- Pomoell, J., and Poedts, S. (2018). Euhforia: European heliospheric forecasting information asset. *J. Space Weather Space Clim.* 8, A35. doi:10.1051/swsc/2018020
- Priest, E. R., Hood, A. W., and Anzer, U. (1989). A twisted flux-tube model for solar prominences. I. General properties. *ApJ* 344, 1010. doi:10.1086/167868
- Reeves, K. K., Linker, J. A., Mikić, Z., and Forbes, T. G. (2010). Current sheet energetics, flare emissions, and energy partition in a simulated solar eruption. *ApJ* 721, 1547–1558. doi:10.1088/0004-637X/721/2/1547
- Reva, A. A., Ulyanov, A. S., and Kuzin, S. V. (2016). Current sheet structures observed by the TESIS EUV telescope during a flux rope eruption on the sun. *ApJ* 832, 16. doi:10.3847/0004-637X/832/1/16
- Richardson, I. G., Cliver, E. W., and Cane, H. V. (2000). Sources of geomagnetic activity over the solar cycle: Relative importance of coronal mass ejections, high-speed streams, and slow solar wind. *JGR* 105, 18203, 203–18213, 213. doi:10.1029/1999JA000400
- Riley, P., Linker, J. A., and Arge, C. N. (2015). On the role played by magnetic expansion factor in the prediction of solar wind speed. *Space weather*. 13, 154–169. doi:10.1002/2014SW001144
- Riley, P., Linker, J. A., and Mikić, Z. (2001). An empirically-driven global MHD model of the solar corona and inner heliosphere. *JGR* 106, 15889–15901. doi:10.1029/2000JA000121
- Riley, P., Lionello, R., Caplan, R. M., Downs, C., Linker, J. A., Badman, S. T., et al. (2021). Using Parker Solar Probe observations during the first four perihelia to constrain global magnetohydrodynamic models. *AAP* 650, A19. doi:10.1051/0004-6361/202039815
- Rochus, P., Auchère, F., Berghmans, D., Harra, L., Schmutz, W., Schühle, U., et al. (2020). The solar orbiter EUV instrument: The extreme ultraviolet imager. *AAP* 642, A8. doi:10.1051/0004-6361/201936663
- Rodríguez, L., Warmuth, A., Andretta, V., Mierla, M., Zhukov, A. N., Shukhobodskaya, D., et al. (2023). The eruption of 22 April 2021 as observed by solar orbiter: Continuous magnetic reconnection and heating after the impulsive phase. *SolPhys* 298, 1. doi:10.1007/s11207-022-02090-6
- Romoli, M., Antonucci, E., Andretta, V., Capuano, G. E., Da Deppo, V., De Leo, Y., et al. (2021). First light observations of the solar wind in the outer corona with the Metis coronagraph. *AAP* 656, A32. doi:10.1051/0004-6361/202140980
- Rouillard, A. P. (2011). Relating white light and *in situ* observations of coronal mass ejections: A review. *J. Atmos. Solar-Terrestrial Phys.* 73, 1201–1213. doi:10.1016/j.jastp.2010.08.015
- Schatten, K. H. (1971). Current sheet magnetic model for the solar corona. *Cosm. Electrody.* 2, 232–245.
- Schou, J., Scherrer, P. H., Bush, R. I., Wachter, R., Couvidat, S., Rabello-Soares, M. C., et al. (2012). Design and ground calibration of the helioseismic and magnetic imager (HMI) instrument on the solar dynamics observatory (SDO). *Sol. Phys.* 275, 229–259. doi:10.1007/s11207-011-9842-2
- Scolini, C., Chané, E., Temmer, M., Kilpua, E. K. J., Dissauer, K., Veronig, A. M., et al. (2020). CME-CME interactions as sources of CME geoeffectiveness: The formation of the complex ejecta and intense geomagnetic storm in 2017 early september. *ApJS* 247, 21. doi:10.3847/1538-4365/ab6216

- Seaton, D. B., Hughes, J. M., Tadikonda, S. K., Caspi, A., DeForest, C. E., Krimchansky, A., et al. (2021). The Sun's dynamic extended corona observed in extreme ultraviolet. *Nat. Astron.* 5, 1029–1035. doi:10.1038/s41550-021-01427-8
- Sheeley, J., Michels, D. J., Howard, R. A., and Koomen, M. J. (1980). Initial observations with the SOLWIND coronagraph. *ApJL* 237, L99–L101. doi:10.1086/183243
- Shi, C., Velli, M., Bale, S. D., Réville, V., Maksimović, M., and Dakeyo, J.-B. (2022). Acceleration of polytropic solar wind: Parker Solar Probe observation and one-dimensional model. *Phys. Plasmas* 29, 122901. doi:10.1063/5.0124703
- Stone, E. C., Frandsen, A. M., Mewaldt, R. A., Christian, E. R., Margolies, D., Ormes, J. F., et al. (1998). The advanced composition explorer. *SSR* 86, 1–22. doi:10.1023/A:1005082526237
- Tasnim, S., Cairns, I. H., and Wheatland, M. S. (2018). A generalized equatorial model for the accelerating solar wind. *J. Geophys. Res. (Space Phys.)* 123, 1061–1085. doi:10.1002/2017JA024532
- Thernisien, A. F. R., Howard, R. A., and Vourlidas, A. (2006). Modeling of flux rope coronal mass ejections. *ApJ* 652, 763–773. doi:10.1086/508254
- Thernisien, A., Vourlidas, A., and Howard, R. A. (2009). Forward modeling of coronal mass ejections using STEREO/SECCHI data. *Sol. Phys.* 256, 111–130. doi:10.1007/s11207-009-9346-5
- Tousey, R., Bartoe, J. D. F., Bohlin, J. D., Brueckner, G. E., Purcell, J. D., Scherrer, V. E., et al. (1973). A preliminary study of the extreme ultraviolet spectroheliograms from Skylab. *Sol. Phys.* 33, 265–280. doi:10.1007/BF00152418
- Velli, M., Harra, L. K., Vourlidas, A., Schwadron, N., Panasenco, O., Liewer, P. C., et al. (2020). Understanding the origins of the heliosphere: Integrating observations and measurements from Parker Solar Probe, solar orbiter, and other space- and ground-based observatories. *AAP* 642, A4. doi:10.1051/0004-6361/202038245
- Vourlidas, A., Howard, R. A., Plunkett, S. P., Korendyke, C. M., Thernisien, A. F. R., Wang, D., et al. (2016). The wide-field imager for solar Probe plus (WISPR). *SSR* 204, 83–130. doi:10.1007/s11214-014-0114-y
- Wang, J., Feng, H., and Zhao, G. (2018). Cold prominence materials detected within magnetic clouds during 1998–2007. *AAP* 616, A41. doi:10.1051/0004-6361/201731807
- Webb, D. F., and Howard, T. A. (2012). Coronal mass ejections: Observations. *Living Rev. Sol. Phys.* 9, 3. doi:10.12942/lrsp-2012-3
- Weber, E. J., and Davis, J. (1967). The angular momentum of the solar wind. *ApJ* 148, 217–227. doi:10.1086/149138
- Whittlesey, P. L., Larson, D. E., Kasper, J. C., Halekas, J., Abatcha, M., Abiad, R., et al. (2020). The solar Probe ANalyzers—electrons on the Parker Solar Probe. *ApJS* 246, 74. doi:10.3847/1538-4365/ab7370
- Wood, B. E., Hess, P., Howard, R. A., Stenborg, G., and Wang, Y.-M. (2020). Morphological reconstruction of a small transient observed by Parker Solar Probe on 2018 November 5. *ApJS* 246, 28. doi:10.3847/1538-4365/ab5219
- Wood, B. E., Wu, C.-C., Lepping, R. P., Nieves-Chinchilla, T., Howard, R. A., Linton, M. G., et al. (2017). A STEREO survey of magnetic cloud coronal mass ejections observed at Earth in 2008–2012. *ApJS* 229, 29. doi:10.3847/1538-4365/229/2/29
- Yermolaev, Y. I., Lodkina, I. G., Yermolaev, M. Y., Riazantseva, M. O., Rakhmanova, L. S., Borodkova, N. L., et al. (2020). Dynamics of large-scale solar-wind streams obtained by the double superposed epoch analysis: 4. Helium abundance. *J. Geophys. Res. (Space Phys.)* 125, e27878. doi:10.1029/2020JA027878
- Zhao, X., Liu, Y. D., Hu, H., and Wang, R. (2019). Quantifying the propagation of fast coronal mass ejections from the sun to interplanetary space by combining remote sensing and multi-point *in situ* observations. *ApJ* 882, 122. doi:10.3847/1538-4357/ab379b
- Zurbuchen, T. H., and Richardson, I. G. (2006). *In-situ* solar wind and magnetic field signatures of interplanetary coronal mass ejections. *SSR* 123, 31–43. doi:10.1007/s11214-006-9010-4
- Zurbuchen, T. H., Weberg, M., von Steiger, R., Mewaldt, R. A., Lepri, S. T., and Antiochos, S. K. (2016). Composition of coronal mass ejections. *ApJ* 826, 10. doi:10.3847/0004-637X/826/1/10