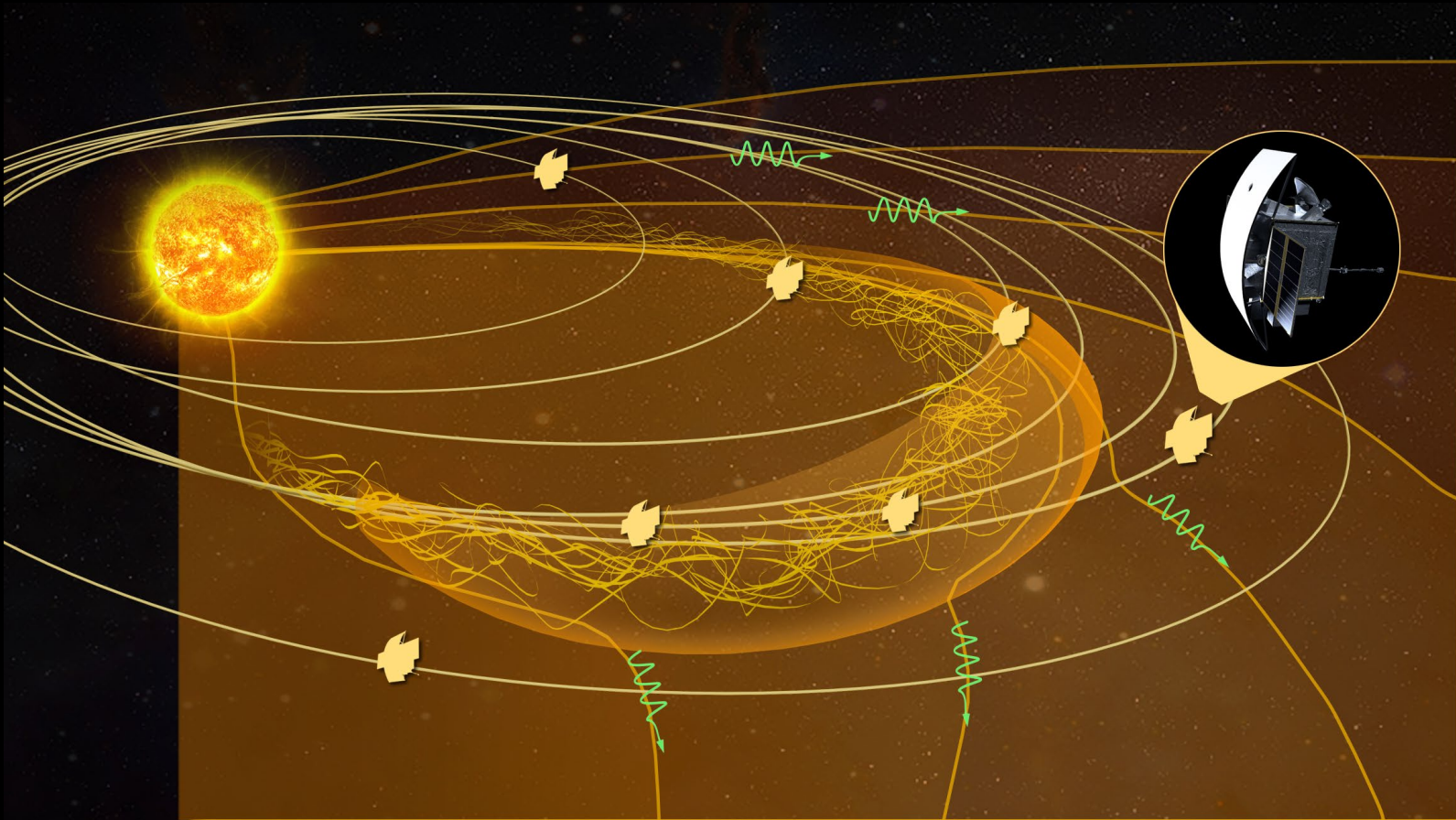


ICME Structure and Evolution in the Inner Heliosphere



Adam Szabo¹

George Ho², Lan Jian¹, David Lario¹, Teresa Nieves-Chinchilla¹

¹NASA Goddard SFC, ²Johns Hopkins U. Applied Physics Laboratory

Synapsys: Interplanetary Coronal Mass Ejections (ICMEs) have been studied for decades using various methods and observational tools; however, their internal structure, transport and evolution in the inner heliosphere remains poorly understood. Similarly, the transport and diffusion of solar energetic particles on their way to 1 AU is surrounded by controversy. This white paper outlines possible next research objectives and a possible multi-spacecraft mission concept (HELIIX) that would provide the measurements to achieve these objectives.

The most energetic manifestations of solar activity and the drivers of the most severe space weather here on Earth are coronal mass ejections (CMEs) and their interplanetary counterparts, also known as interplanetary coronal mass ejections (ICMEs) [Webb & Howard, 2012; Schrijver et al., 2015]. It is now well established that the shocks driven by fast ICMEs are the primary sources of large solar energetic particle (SEP) events. While research during the past decade shed significant light on the initiation and solar release of CMEs, the internal structure, transport and evolution of ICMEs in the inner heliosphere remains poorly understood due to measurements limited to a few vantage points. Similarly, the transport and diffusion of SEPs on their way to 1 AU is surrounded by controversy.

This white paper outlines possible next steps in research objectives and corresponding measurement requirements to make progress in these critical areas. In addition, a multi-spacecraft mission concept responding to these requirements is presented that is technologically ready and fits into a NASA Heliophysics flagship class budget.

ICMEs

ICMEs are traditionally envisioned as expanding magnetic flux ropes [Burlaga et al., 1981; Klein and Burlaga, 1982; Marubashi, 1986; Lepping, Jones, and Burlaga, 1990], attached to the Sun at both ends, expanding outward through the ambient solar wind occasionally driving an interplanetary shock as illustrated in Figure 1. This basic picture of an ICME and its coronal connection has been used for decades to interpret in-situ plasma and magnetic field measurement with considerable success. Moreover, 3D ICME reconstructions have been attempted using 2D plane-of-sky projected white-light observations from heliospheric imagers [e.g., Gopalswamy et al., 2009; Rouillard, 2011; Webb and Howard, 2012], but such methods suffer from line-of-sight integration effects, causing loss of information and ambiguity [e.g., Burkepile et al., 2004; Schwenn et al., 2005; Nieves-Chinchilla et al., 2012, 2013]. However, more recent observations revealed a much more complex picture [e.g., Howard et al., 2022]. Portions of ICMEs plow into slow and dense solar wind streams or into other ICMEs distorting their geometry. The magnetic fields of ICMEs reconnect with the ambient interplanetary magnetic field peeling away layers of the ICME completely changing their magnetic structure. Moreover, recent remote sensing observations even bring into question our understanding of the ICME internal structure (Figure 2). Since it is well established that the speed and magnetic topology (primarily the Southward component of the magnetic field) determine the geo-effectiveness of ICMEs [Gonzalez and Tsurutani, 1987; Wilson, 1987; Russell, 2000], it is essential to determine ICME distortions to be able to accurately forecast their space weather impacts.

Evolution of ICMEs: Sheath and Shock

At its simplest, all ICMEs propagate in and interact with the ambient solar wind. Most ICMEs have piled up solar wind material in front of them, called the sheath. This sheath region contains highly variable magnetic

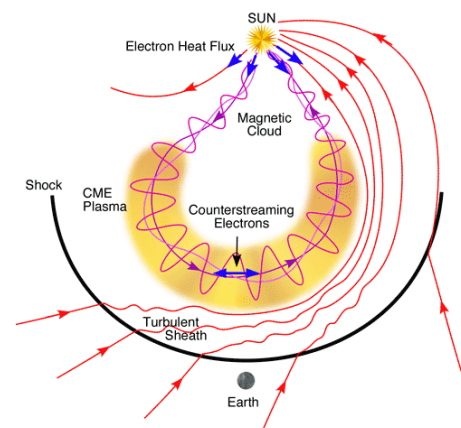


Figure 1. Idealized shape of an ICME.
(from Zurbuchen and Richardson, 2006)

fields that is often more geoeffective than the magnetic flux rope driving it. Davies et al. [2021] reported the in-situ detection of an ICME on April 19, 2020 by Solar Orbiter (SolO) at a heliocentric distance of 0.809 AU. The same ICME was 20.5 hours later observed by the Wind spacecraft near the Sun-Earth Lagrange point L1 at 0.996 AU almost exactly radially lined up with SolO. Figure 3 provides an overview of magnetic field measurements. It is shown that while the SolO-Wind separation was greater than the flux rope cross section, the geometrical expansion factor between SolO and Wind observations of the ICME is close to unity, indicating that the flux rope has undergone little to no expansion as it propagates beyond 0.8 AU to L1. However, the authors also show that the ICME sheath region sharply expands by as much as 64%. This is surprising for a slow moving ICME. The sheath formation of fast moving ICMEs is even less understood.

Fast moving ICMEs drive interplanetary shocks that produce solar energetic particles (SEPs) and enhance the ICME geo-effectiveness when the driven shock compresses the Earth's magnetosphere. While white light images of the ICMEs often reveal a wave boundary ahead of the ICME [e.g., Rodriguez-Garcia et al., 2022], it is impossible to determine if these boundaries are steepened shocks or just pressure pulses. Also, due to momentum conservation, fast ICMEs slow down as they plow up more and more material. Thus, some ICMEs stop driving the preceding shocks, and the shocks start to dissipate. There are very limited number of cases where currently available observations are sufficient to follow this evolution.

Evolution of ICMEs: Interaction and Distortion

Even early global MHD models predicted that the shape of ICMEs would be significantly distorted by their interaction with the structured ambient solar wind [e.g., Odstreil and Pizzo, 1999]. Only more recent fortuitous remote sensing observations of an ICME demonstrated how significant this distortion can be [Savani et al., 2010] (See Figure 4). However, even with the two STEREO spacecraft the 3D reconstruction of ICME geometry is very ambiguous due to their semi-transparent nature and line-of-sight effects. In situ observations also suggest that not only the shape but also the ICME internal magnetic structure is impacted by these interactions [Nieves-Chinchilla et al., 2018]. However, reconciling the in situ

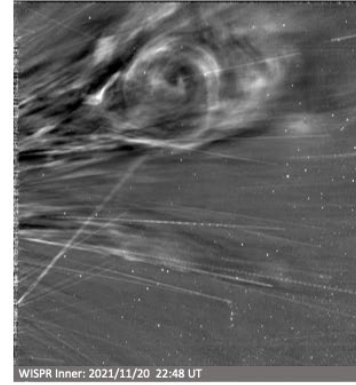


Figure 2. ICME with complex internal structure observed by PSP WISPR on November 20, 2021. [Howard et al., 2022]

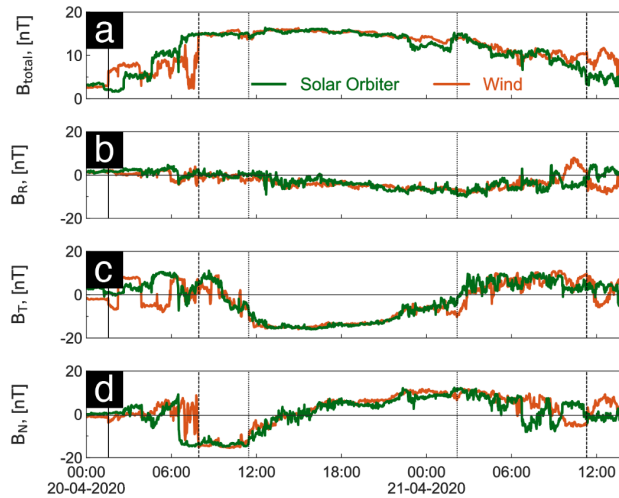


Figure 3: (a-d) Magnetic field measurements at Wind (orange), overlaid with the scaled magnetic field measurement of Solar Orbiter (green) of an ICME observed at two radial positions. Note that while the flux ropes are nearly identical, the sheath region is significantly thicker at Wind. (From Davies et al., 2021).

measurements with remote sensing observations remains a challenge.

Even more significant ICME distortions are likely when two or more ICMEs run into each other when ICMEs can even completely merge by the time they reach 1 AU [Gopalswamy et al., 2001, Palmerio et al., 2021a, Nieves-Chinchilla et al., 2022]. A particularly dramatic multi ICME interaction was recently captured by the WISPR imager on Parker Solar Probe (PSP) (Figure 5). Kilpua et al. [2012] suggested that the majority of small ICMEs merge with each other before reaching the orbit of Earth. However, we have limited number in-situ observations where the evolution of ICME-ICME interaction is captured resulting in our poor understanding of the physical processes involved.

Evolution of ICMEs: Magnetic Erosion

Another way ICMEs interact with the ambient solar wind is through magnetic reconnection both at their front and back sides that effectively peel away layers of the magnetic flux rope, disrupting the magnetic topology of the structures (Figure 6) [Ruffenach et al., 2012]. Reconnection is particularly frequent in low- β ICME plasma, even for low magnetic shear [Gosling and Szabo, 2008]. Lauvraud et al. [2014] showed, using both in-situ observations and models, that magnetic erosion in ICMEs due to magnetic reconnection can reduce the geo-effectiveness of a storm by up to 30%, adding that 50% of the erosion likely takes place between Mercury's and Earth's orbits. Similarly Ruffenach et al. [2014], analyzing a larger group of 50 ICMEs, found evidence of magnetic erosion for almost all cases, on average removing 40% of their azimuthal magnetic flux before reaching 1 AU. These findings highlight that ICMEs undergo significant changes between the Sun and 1 AU, requiring significant new observations to fully understand.

ICME Internal Structure

All of the above-mentioned studies assume that at their coronal origins ICMEs have a simple magnetic flux rope topology. However, recent observations brought even this assumption into question. For example, Howard et al., [2022] reported Parker Solar Probe observations of an ICME with an unexplained internal structure (Figure 2). Similarly, Nieves-Chinchilla et al. [2020], demonstrated that using current models to interpret the in-situ measurements of some ICMEs with a single flux rope geometry is impossible. This illustrates that single spacecraft observations are insufficient to fully describe the true internal structure of ICMEs.

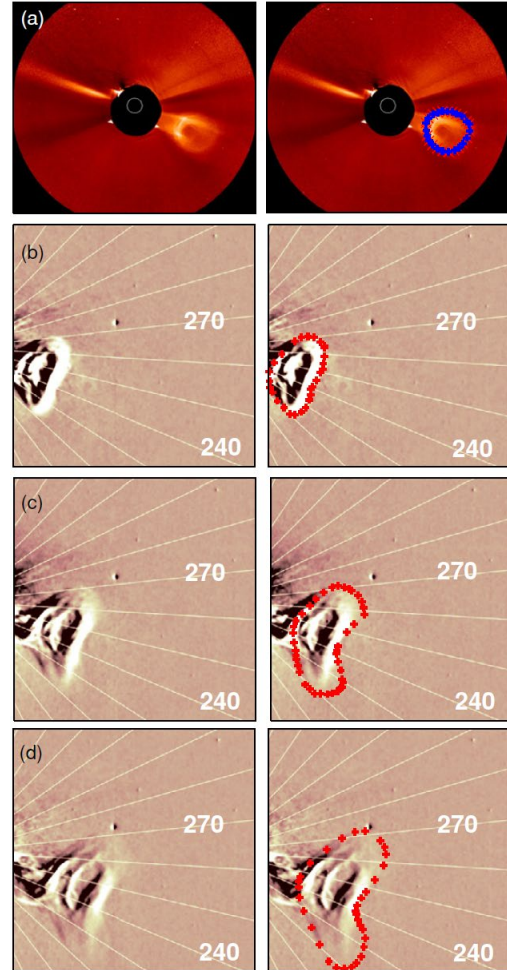


Figure 4. COR-2 and HI-1 STEREO spacecraft images of the 2007 November 15 CME without (left column) and with an overplot of manual tracing of the envelop of the CME (right column). Note the significant distortion from a cylindrical geometry. (From Savani et al., 2010)

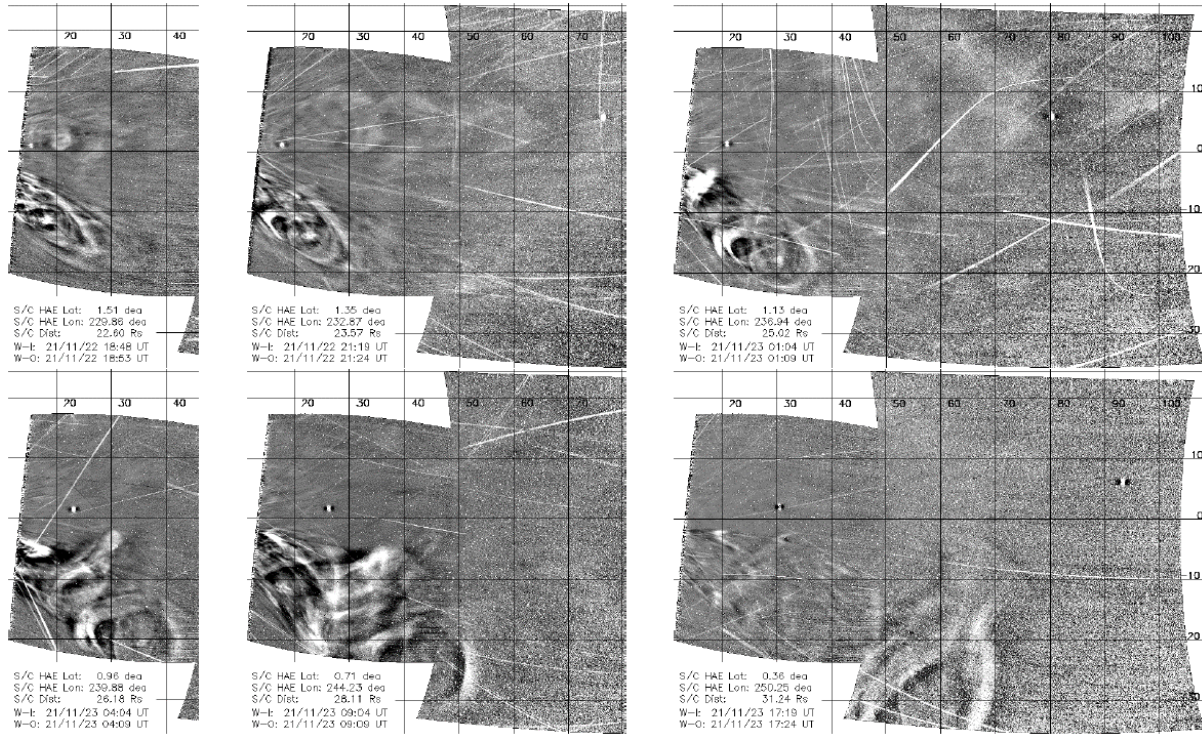


Figure 5. PSP WISPR composite images from November 22-23, 2021 showing the complex interaction of three consecutive ICMEs, possibly leading to their merging. (From *Howard et al.*, 2021)

SEPs

ICME driven shocks are the most efficient accelerators of SEPs that endanger astronauts and spacecraft alike particularly outside the protection of the Earth's magnetosphere. Improving our understanding of ICME propagation/evolution in the inner heliosphere will also improve our forecasting/nowcasting SEP events. Although the acceleration and transport of energetic particles in the heliosphere have been studied extensively [e.g., Reames, 1999; Mewaldt, 2006; Raymond et al., 2012; Drake and Swisdak, 2012], models tend to assume that particles transport in an idealized nominal Parker spiral interplanetary magnetic field configuration. ICMEs

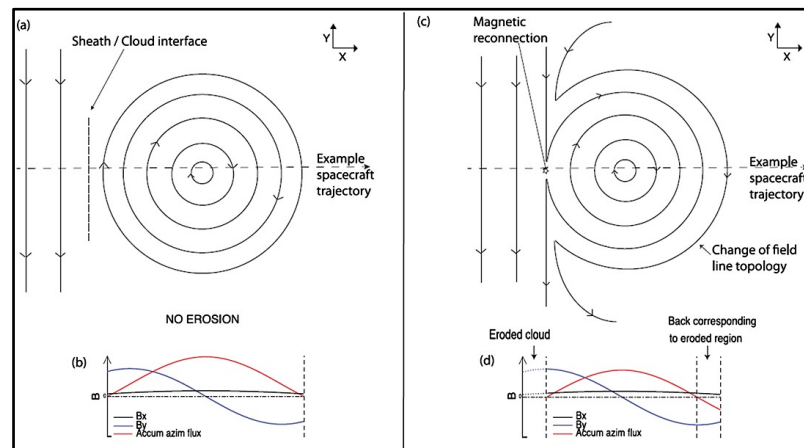


Figure 6. The magnetic structure of (a) non-eroded and (c) eroded MCs together with (b and d) the expected variations in the magnetic field components and accumulated azimuthal magnetic flux. Large portions of ICMEs can erode via this process. (From *Ruffenach et al.*, 2012)

significantly disrupt this simple magnetic topology changing magnetic connections and rates of cross-field diffusion [e.g., Palmerio et al., 2021b]. Furthermore, the presence of ICMEs in interplanetary space has an influence on the peak intensities and fluences of the SEP events [Lario and Karelitz, 2014]. A consequence of better understanding ICME propagation and evolution is that global magnetic field line geometries would be better determined, and thus improving our SEP propagation models and forecasting capabilities.

Measurement Requirements

In order to determine the inner heliospheric structure and evolution of ICMEs, multi-point, in situ measurements of the magnetic field and solar wind plasma properties are necessary. The same ICME has to be observed simultaneously by at least four spacecraft at different azimuth angles to detect deformations from the traditional symmetric horse-shoe shaped geometry. In addition, ICMEs have to be observed at different radial distance from the Sun to detect evolutionary changes. This would require at least two more spacecraft. All of these six spacecraft would have to be in a 90 degree wedge corresponding to the average angular size of ICMEs. Since orbital mechanics does not allow for such a long-term configuration, a larger spacecraft fleet is needed that would form different 4-6 spacecraft configurations at different times. The HELEX notional mission concept described below was developed with this requirement in mind.

The HELIX Mission Design

The HELiospheric eXplorers (HELIX) concept was studied by a Johns Hopkins University Applied Physics Laboratory (JHUAPL) engineering team not as a point design but as a number of different trades that included different number of spacecraft, different instrumentation, and different orbits. This allows the later fine-tuning of this concept to reflect emerging scientific objectives and fiscal realities. The study concluded that this concept is technologically feasible and would lead to significant and quantifiable improvements in forecasting space weather phenomena.

Orbit Design

The HELIX constellation envisions a heliocentric orbit via a single launch, with a ~ 7.5 -month orbit periodicity (1:1 resonance with Venus). A Venus encounter occurs after ~ 0.5 revolution about the Sun (roughly 3.7–5.7 months). A launch in 2032–2033 is assumed with C_3 of ≤ 15 km^2/s^2 . Upon arrival at Venus, each spacecraft experiences a Venus gravity assist (VGA) that disperses the constellation into distinct science orbits. A single deterministic Venus spacing maneuver (VSM) is performed for most spacecraft 10–80 days after launch (optimal timing depends on the Venus transfer geometry) to enable a minimum time-spacing between each

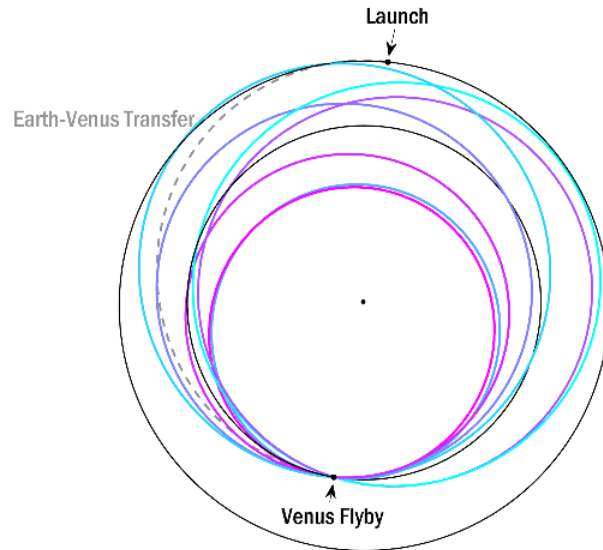


Figure 7. Globally optimal seven-spacecraft orbit.

sequential Venus encounter. A “central” spacecraft in the constellation encounters Venus at the nominal epoch with no VSM required, while the other spacecraft are spaced away from the central spacecraft (e.g., for a seven-spacecraft constellation with a minimum spacing of one flyby per 8 hours) (Figure 7).

A variable constellation with the number of spacecraft varying from four to ten was considered. The desirability of a particular constellation was evaluated based on the fraction of mission time when three, four, or five spacecraft occupied a 60° or 90° wedge with maximum radial separation. It was established that beyond seven or eight spacecraft, the improvement was minimal (i.e., wedges with five spacecraft or more with radial separations reaching between 0.25 and 0.3 AU were not improved).

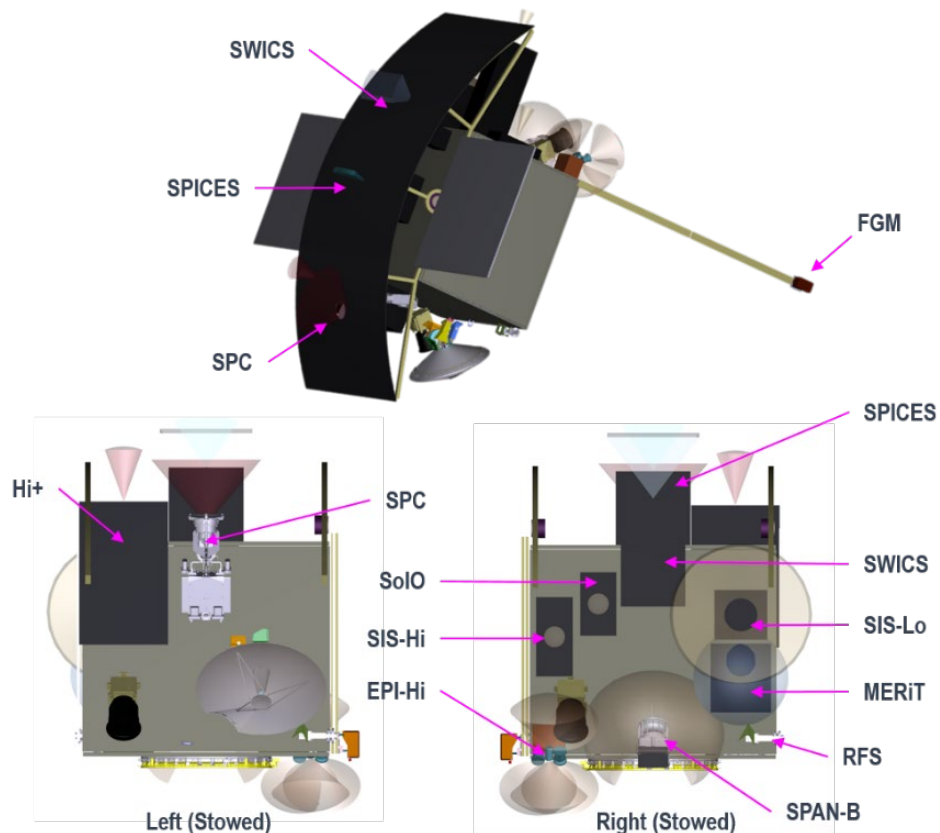


Figure 8. Notional HELIX spacecraft design. The full, aspirational instrument complement is shown with FC a Faraday Cap, FGM the fluxgate magnetometer, SWICS and SPICES solar wind composition instruments, SPAN-B a solar wind electron detector, SIS-Lo and SIS-Hi suprathermal ion instruments, MERIT an SEP detector, HI+ a heliospheric imager. Four of these spacecraft could be attached to a single ESPA ring.

HELIX Instrumentation

Three different instrument suites were evaluated: (1) a threshold configuration with the minimum number of instruments (all in situ) to address the highest-priority questions, (2) a baseline mission (all in situ instruments) that would be able to provide closure regarding the main science objectives, (3) and an aspirational mission that would add one of five remote solar sensing instruments—a different one for different spacecraft—to also address solar-heliospheric

connections. The threshold option includes dual magnetometers, solar wind plasma and composition instrumentations, suprathermal ion and SEP detectors. The baseline mission adds radio waves and solar wind electron detection capability along with upgraded solar wind composition and energetic particle instruments. Finally, the aspirational option adds one remote sensing instrument rotating between a coronagraph/heliospheric imager, vector magnetograph, EUV imager, and an X-ray spectrometer.

HELIX Mission Implementation.

All three payload configurations, with example instruments, were fitted into a small volume-constrained spacecraft that can be attached to an ESPA Grande carrier, which is the secondary payload adapter for Evolved Expendable Launch Vehicles (EELV). Thus, eight spacecraft could be launched with two ESPA Grande rings, and, in theory, a primary payload still could be added to the top of the stack, enabling a wide range of launch options.

The three-axis stabilized spacecraft could generate 380 W of power and had a dry mass of 313/438/485 kg each depending on the payload option. A possible spacecraft design is shown in Figure 8. Assuming a Class C+ mission class, an ELV-class launch vehicle (e.g., Falcon, Vulcan, New Glenn), and a 3-year primary mission, the total estimated cost of this mission is ~\$1B.

Required Technology Development

The telemetry requirements of each spacecraft are very modest, and with new onboard storage technology, a week's worth of science data can be easily stored. This significantly reduces the Deep Space Network (DSN) requirements of the mission, but it also introduces a number of challenges, such as orbit determination and maintenance as well as autonomous recovery from some failure modes. A beacon ping probably would have to be implemented on X-band and sent on the low-gain antenna to provide simple health updates.

Further details of the HELIX mission can be found in the NASA Living With a Star (LWS) Architecture Report (2022) under the mission concept FMT-2 (<https://lws-ac.jhuapl.edu>).

References

- Burkepile, J.T., Hundhausen, A.J., Stanger, A.L., St Cyr, O.C., and Seiden, J.A., 2004, Role of projection effects on solar coronal mass ejection properties: 1. A study of CMEs associated with limb activity, *J. Geophys. Res.*, *109*, A03103, doi:10.1029/2003JA010149
- Burlaga, L.F., Sittler, E., Mariani, F., Schwenn, R.: 1981, Magnetic loop behind an interplanetary shock: Voyager, Helios and IMP-8 observations. *J. Geophys. Res.* *86*, 6673, doi:10.1029/JA086iA08p06673
- Davies, E.E., Möstl, C., Owens, M.J., Weiss, A.J., Amerstorfer, T., Hinterreiter, J., Bauer, M., Bailey, R.L., Reiss, M.A., Forsyth, R.J. and Horbury, T.S., 2021. In situ multi-spacecraft and remote imaging observations of the first CME detected by Solar Orbiter and BepiColombo. *Astronomy & Astrophys.*, *656*, p.A2, doi:10.1051/0004-6361/202040113
- Drake, J.F. and Swisdak, M., 2012, Ion heating and acceleration during magnetic reconnection relevant to the corona, *Space Sci. Rev.*, *172*, 1-4, 227, doi:10.1007/s11214-012-9903-3
- Gonzalez, W.D. and Tsurutani, B.T., 1987. Criteria of interplanetary parameters causing intense magnetic storms ($Dst < -100$ nT), *Planetary and Space Sci.*, *35*(9), pp.1101-1109, doi:10.1016/0032-0633(87)90015-8
- Gopalswamy, N., Yashiro, S., Kaiser, M.L., Howard, R.A. and Bougeret, J.L., 2001. Radio signatures of coronal mass ejection interaction: Coronal mass ejection cannibalism?, *Astrophys. J.*, *548*(1), p.L91, doi:10.1086/318939
- Gopalswamy, N., et al., 2009. CME interactions with coronal holes and their interplanetary consequences, *J. Geophys. Res.*, *114*, A00A22, doi:10.1029/2008JA013686
- Gosling, J.T. and Szabo, A., 2008. Bifurcated current sheets produced by magnetic reconnection in the solar wind. *J. Geophys. Res.*, *113*, A10, doi:10.1029/2008JA013473
- Howard, R.A., et al., 2022, Overview of the remote sensing observations from PSP solar encounter 10 with perihelion at 13.3 Rs, arXiv:2207.12175v1
- Kilpua, E.K.J., Jian, L.K., Li, Y., Luhmann, J.G., and Russell, C.T., 2012, Observations of ICMEs and ICME-like solar wind structures from 2007-2010 using near-Earth and STEREO observations, *Solar Phys.*, *281*, 391, doi:10.1007/s11207-012-9957-0
- Klein, L.W., and Burlaga, L.F.: 1982, Interplanetary magnetic clouds at 1 AU. *J. Geophys. Res.* *87*, 613, doi:10.1029/JA087iA02p00613
- Lario, D., and Karelitz, A., 2014. Influence of interplanetary coronal mass ejections on the peak intensity of solar energetic particle events. *J. Geophys. Res.*, *119*, pp.4185-4209, doi: 10.1002/2014JA019771
- Lavraud, B., Ruffenach, A., Rouillard, A.P., Kajdic, P., Manchester, W.B. and Lugaz, N., 2014. Geo-effectiveness and radial dependence of magnetic cloud erosion by magnetic reconnection, *Journal of Geophysical Research: Space Phys.*, *119*, 1, 26-35, doi:10.1002/2013JA019154
- Lepping, R.P., Jones, J.A. and Burlaga, L.F., 1990. Magnetic field structure of interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, *95*, A8, 11957-11965, doi:10.1029/JA095iA08p11957
- Nieves-Chinchilla, T., R. Colaninno, A. Vourlidas, A. Szabo, R. P. Lepping, S. A. Boardsen, B. J. Anderson, and H. Korth, 2012, Remote and in situ observations of an unusual Earth-

- directed coronal mass ejection from multiple viewpoints, *J. Geophys. Res.*, *117*, A06106, doi:10.1029/2011JA017243
- Nieves-Chinchilla, T., Vourlidas, A., Stenborg, G., Savani, N. P., Koval, A., Szabo, A., & Jian, L. K., 2013, Inner heliospheric evolution of a “Stealth” CME derived from multi-view imaging and multipoint in situ observations. I. Propagation to 1 AU. *Astrophys. J.*, *779*(1), 55, doi:10.1088/0004-637X/779/1/55
- Nieves-Chinchilla, T., A. Vourlidas, Raymond, J.C., Linton, M. G., Al-haddad, N., Savani, N. P., Szabo, A., Hidalgo, M.A, 2018, Understanding the Internal Magnetic field configuration of ICMEs using more than 20 years of *Wind* observations. *Solar Physics*, doi: 10.1007/s11207-018-1247-z
- Nieves-Chinchilla, T., Szabo, A., Korreck, K.E., Alzate, N., et al., 2020, Analysis of the internal structure of the streamer blowout observed by the Parker Solar Probe during the first solar encounter, *Astrophys. J., Supp. Ser.*, *246*:63, doi:10.3847/1538-4365/ab61f5
- Nieves-Chinchilla, T., Alzate, N., Cremades, H., Rodríguez-García, L., Dos Santos, L.F., Narock, A., Xie, H., Szabo, A., Palmerio, E., Krupar, V. and Pulupa, M., 2022, Direct First Parker Solar Probe Observation of the Interaction of Two Successive Interplanetary Coronal Mass Ejections in 2020 November. *Astrophys. J.*, *930*(1), 88, doi:10.3847/1538-4357/ac590b
- Marubashi, K., 1986, Structure of the interplanetary magnetic clouds and their solar origins. *Adv. Space Res.* *6*, 335, doi:10.1016/0273-1177(86)90172-9
- Mewaldt, R.A., 2006, Solar energetic particle composition, energy spectra, and space weather, *Space Sci. Rev.*, *124*, 1-4, 303, doi:10.1007/s11214-006-9091-0
- Odstroil, D. and Pizzo, V.J., 1999, Three-dimensional propagation of coronal mass ejections (CMEs) in a structured solar wind flow 2. CME launched adjacent to the streamer belt, *J. Geophys. Res.*, *104*, A1, 493, doi:10.1029/1998JA900038
- Palmerio, E., Nieves-Chinchilla, T., Kilpua, E. K. J., Barnes, D., Zhukov, A. N., Jian, L. K., et al. 2021a, Magnetic structure and propagation of two interacting CMEs from the Sun to Saturn. *J. Geophys. Res.*, *126*, doi:10.1029/2021JA029770
- Palmerio, E., Kilpua, E. K. J., Witasse, O., Barnes, D., Sanchez-Cano, B., Weiss, A. J., et al. 2021b. CME magnetic structure and IMF preconditioning affecting SEP transport. *Space Weather*, *19*, doi:10.1029/2020SW002654
- Reames, D.V., 1999, Particle acceleration at the Sun and in the heliosphere, *Space Sci. Rev.*, *90*, 3-4, 413, doi:10.1023/A:1005105831781
- Raymond, J.C, Krucker, S., Lin, R.P., and Petrosian, V., 2012, Observational aspects of particle acceleration in large solar flares, *Space Sci. Rev.*, *173*, 1-4, 197, doi:10.1007/s11214-012-9897-x
- Rodriguez-Garcia, L., et al., 2022, Evidence of a complex structure within the 2013 August 19 coronal mass ejection, *Astron & Astrophys.*, *662*, doi:10.1051/0004-6361/202142966
- Rouillard, A.P., 2011, Relating white light and in situ observations of coronal mass ejections: A Review, *J. Atmos. and Solar-Terr. Phys.*, *73*, 10, 1201, doi:10.1016/j.jastp.2010.08.015
- Ruffenach, A., Lavraud, B., Owens, M.J., Sauvaud, J.A., Savani, N.P., Rouillard, A.P., Démoulin, P., Foullon, C., Opitz, A., Fedorov, A. and Jacquey, C.J., 2012, Multispacecraft observation of magnetic cloud erosion by magnetic reconnection during propagation. *Journal of Geophysical Research: Space Physics*, *117*(A9), doi:10.1029/2012JA017624
- Ruffenach, A., et al. 2015, Statistical study of magnetic cloud erosion by magnetic reconnection, *J. Geophys. Res.*, *120*, 43–60, doi:10.1002/2014JA020628

- Russell, C.T., 2000, The solar wind interaction with the Earth's magnetosphere: A tutorial, *IEEE Trans. On Plasma Sci.*, 28, 6, 181, doi:10.1109/27.902211
- Savani, N.P., Owens, M.J., Rouillard, A.P., Forsyth, R.J., and Davies, J.A., 2010, Observational evidence of a coronal mass ejection distortion directly attributable to a structured solar wind, *Astrophys. J. Lett.*, 714, L128, doi:10.1088/2041-8205/714/1/L128
- Schrijver, C.J., Kauristie, K., Aylward, A.D., Denardini, C.M., Gibson, S.E., Glover, A., Gopalswamy, N., Grande, M., Hapgood, M., Heynderickx, D. and Jakowski, N., 2015, Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS. *Advances in Space Research*, 55(12), 2745-2807, doi:10.1016/j.asr.2015.03.023
- Schwenn, R., Dal Lago, A., Huttunen, E., Gonzalez, W.D., 2005, The association of coronal mass ejections with their effects near the Earth, *Ann. Geophys.*, 23, 3, 1033, doi:10.5194/angeo-23-1033-2005
- Webb, D.F., and Howard, T.A., 2012, Coronal mass ejections: Observations, *Living Reviews in Solar Physics*, 9, 3. doi: 10.12942/lrsp-2012-3
- Wilson, R.M., 1987, Geomagnetic response to magnetic clouds. *Planetary and Space Sci.*, 35(3), 329-335, doi:10.1016/0032-0633(87)90159-0
- Zurbuchen, T.H., and Richardson, I.G., 2006, In-situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections, *Space Sci. Rev.*, 123, doi:10.1007/s11214-006-9010-4