The Importance of Fundamental Research on the Upper Coronal and Heliospheric Evolution of Coronal Mass Ejections

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Synopsis

Coronal mass ejections (CMEs) are a cornerstone of heliophysics research. It is essential to address the evolution of CMEs in the upper corona and interplanetary space (the inner heliosphere), independent of their space weather impact through a comprehensive research program. Such a program should include components of data analysis, theory, model and simulation development and lead to new missions and instrumentation, especially for smallsat/rideshare and Explorer categories. Here, we first detail some of the fundamental science questions that need to be addressed related to CME evolution and propagation, namely the formation of the sheath region ahead of the propagating and expanding CME, the evolution of turbulent plasma within the sheath, the evolution of low-beta plasma inside the magnetic ejecta, and the interaction of successive CMEs, including the propagation of shock waves inside a low-plasma beta, the interaction of propagating shock waves, and the reconnection between successive ejecta. We then discuss the limitations of current approaches, in terms of theory, data analysis and observations. We conclude with several recommendations: 1) the need for missions providing dedicated multi-spacecraft measurements, 2) the availability of heliophysics instruments on planetary missions, 3) the funding for the development of solar-coronal-heliospheric and MHD-kinetic simulations, 4) cross-disciplinary teams.

1 Current Status

In the 2012 Heliophysics Decadal survey, science goals were divided into Key Science Goals (KSGs) and panel's science goals, listed as Solar and Heliopsheric Physics (SHP) goals. All mentions of CME research were (i) associated with their solar origin (SHP2b & SHP3a), (ii) the coupling with the magnetosphere–ionosphere–thermosphere (MIT) system (KSG 2), or (iii) space weather research (KSG 1 and SHP3d). Of particular significance, Key Science Goal 4 is related to fundamental processes. However, the following fundamental processes are not mentioned in KSG4: (1) the stability and evolution of low-beta plasmas and magnetic fields typical of CMEs, (2) the plasma–plasma interaction processes that are central to the formation of CME sheath regions, or (3) the physics associated with magnetic flux ropes, one of the fundamental topological features of plasmas.

This has had significant implications to the field of CME research over the past decade. In order to map to the decadal survey, investigations of CMEs beyond their initiation have not been able to refer to a dedicated science goal. It is unclear what is the difference between research on CME evolution and research on flares or solar energetic particles (SEPs). Flares and SEPs are both identified as areas where fundamental research is a key science goal of the community. As one consequence, none of the three overarching science objectives of the Parker Solar Probe (PSP) mission [Fox et al. 2016] includes CME research, even though the spacecraft's orbit and instrumentation are perfectly suited for investigating CME evolution in a previously unexplored region. In contrast, the second of the four top-level scientific questions of the Solar Orbiter (a mission developed by ESA) reads: "How do solar transients drive heliospheric variability?" including a sub-question of "How do CMEs evolve through the corona and inner heliosphere?" [Müller et al. 2020].

The past decade has nonetheless produced numerous studies on the coronal and interplanetary evolution of CMEs, especially with the availability of heliospheric imaging by STEREO and *in situ* measurements in the inner heliosphere from L1, STEREO and planetary missions (and now from PSP and Solar Orbiter). These studies have focused on CME expansion, deflection, rotation, force balance [see review by Manchester et al. 2017], the formation of CME sheath regions [see review by Kilpua et al. 2017] and the interaction of CMEs with other CMEs [Lugaz et al. 2017] and with stream interaction regions [SIRs, Winslow et al. 2016]. Nevertheless, many of these aspects are heavily understudied or simplified. For example, research on shock formation and sheath development is often based on analogies with magnetospheres. This is not justified since CME-driven sheaths expand, allowing solar wind material to accumulate in a layer adjoining their front boundary [Siscoe & Odstrcil 2008].

2 Desired State and Fundamental Science Questions

It is essential to develop a program for fundamental research that addresses the coronal and interplanetary evolution of CMEs, independent of their relevance for space weather. The focus on understanding and forecasting the geo-effects of CMEs must be grounded in fundamental research that allows one to understand CME properties and how they vary on scales ranging from small ($\sim$10–100 Earth radii) to large (0.2–0.6 AU). We emphasize that the propagation and interplanetary evolution of CMEs should be a science focus of the community over the coming decade (see Fig.1 for the fundamental science questions related to CMEs). Fundamental research on their initiation and early evolution is required as well (see the White Paper "Learn to walk before you run" by Török et al).

In parallel, research on other heliospheric phenomena, such as interplanetary shocks, stream interaction regions (SIRs), heliospheric current and plasma sheets (HCS/HPS), and small transients should be pursued in their own right to advance our physical understanding, irrespective of any efforts to develop operational and forecasting methods of these phenomena. Overall, fundamental research on CME propagation and evolution should include not only research programs focusing on data analysis, theory and numerical model development but also include

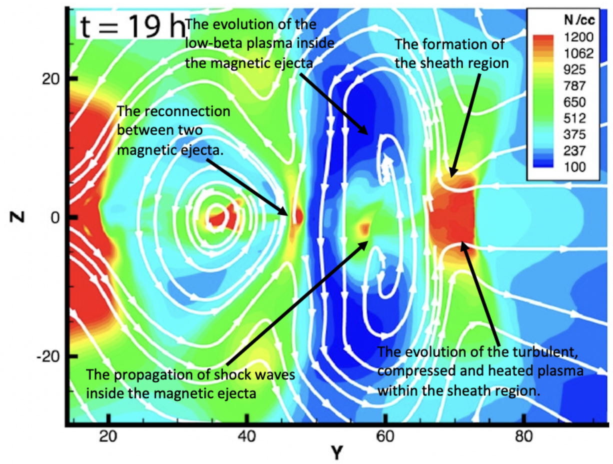

Figure 1: Some of the fundamental processes that occur during CME propagation, as discussed in the text. The plot shows a 2-D cut of the number density for two CMEs at about 0.3 AU from a MHD simulation of Lugaz et al. [2005].

instrument and mission development, especially in the explorer and smallsat categories. These points are developed in Section 4.

A number of fundamental physics questions can best be addressed by studying CMEs, as they constitute a unique space-physics environment that is composed of low-beta (i.e. magnetically dominated), expanding and propagating plasma (referred to hereafter as the magnetic ejecta), preceded by a sheath region formed through a combination of pile-up compression and shock compression. The shock itself is often driven by a combination of the CME bulk propagation and expansion. The fundamental science questions include:

• The formation of the sheath region (importance of pile up vs. shock, importance of CME expansion in the sheath formation).

• The evolution of the turbulent and compressed plasma within the sheath region after its formation, including both highly disturbed region and also well-organized planar structures.

• The evolution of the low-beta plasma inside the magnetic ejecta past the Alfvén surface.

• The interaction of multiple CMEs, in particular the propagation of shock waves inside the unique low-beta plasma environment of magnetic ejecta and the reconnection between two ejecta of low densities and high magnetic fields.

• Additional fundamental science questions include (1) how these phenomena are affected by the interaction of isolated CMEs with solar wind structures, such as HCS, HPS and SIRs, and (2) the formation and morphology of the twisted magnetic flux rope within the magnetic ejecta and are discussed in other white papers.

2.1 The Formation of the CME Sheath Region

The formation of CME sheath regions as they propagate is currently poorly understood and is not being successfully investigated via remote-sensing, in-situ measurements, or numerical modeling. The sheath region of CMEs carry the majority of the ICME mass and expand to reach an average duration of 8–9 hours at 1 AU, being key in the solar wind-magnetospheric coupling.

While CME sheaths are associated with most CMEs, little is still known about the interplay between different processes resulting in their formation. Key differences have been recognized between CME sheaths and planetary magnetosheaths [Siscoe & Odstrcil 2008] due to the importance of CME expansion in addition to propagation. However, slow CMEs without shocks are often associated with a pile-up sheath in the absence of a shock [Salman et al. 2020], and it is therefore clear that the sheaths of moderately fast CMEs are composed of a combination of shocked and piled-up plasma. In addition, the erosion of the magnetic ejecta due to reconnection with the interplanetary magnetic field as the CME propagates, is bound to affect the boundary between the magnetic ejecta and the sheath. This is an additional way, as of yet, mostly unexplored, for sheath region to accumulate more material.

A key issue with the investigation of CME sheaths is that global MHD models are not appropriate to study their formation and properties, since they do not account for important small-scale physical processes, while kinetic simulations cannot capture the key large-scale processes such as CME expansion.

As such, little definite is known about how the properties of CME sheath regions reflect the properties of the driving magnetic ejecta, the properties of the shock driven by the magnetic ejecta and the properties of the solar wind, including its turbulence.

2.2 Fundamental Plasma Physics Processes in CME Sheath Regions

Turbulence and reconnection are two of the core fundamental physical processes in space plasma physics. However, they are most often studied in the undisturbed (slow or fast) solar wind rather than in the more unusual conditions of the plasma environment inside CME sheaths. A thorough understanding of these fundamental processes require to study them in a variety of plasma regimes, including in the dense, magnetized plasma of CME sheath regions. A spectacular example is the shock and sheath region of the 2012 July 23 CME as measured by STEREO-A. During this extreme event with a speed near 1 AU in excess of 2000 km s^{-1}, the high-level of energetic particles modulated the interplanetary shock [Russell et al. 2013]. As such, the interaction of the shock with the upstream plasma did not appear to be governed by the fast-mode shock relationship. While such extreme shocks may be common in astrophysical plasma, heliophysics is the only domain where such shocks may be measured *in situ*, and offer the only laboratory to test our understanding of such fundamental plasma processes.

Of particular importance, ultra-low frequency (ULF) waves (with periods of a few minutes) within CME sheaths are known to drive Pc4-Pc5 waves in Earth's magnetosphere, affecting the radiation belts and ring current. Little research has been performed yet on how turbulence within CME sheath region contributes to the formation of these ULF waves and on how turbulence is affected by the compression in the sheath due to the shock and the CME expansion.

Investigating the formation and evolution of CME sheath regions is a key component in understanding the transfer of mass and kinetic energy from the Sun to planetary magnetospheres. As the transient phenomenon with the highest dynamic pressure and the main interplanetary source of ULF waves, CME sheaths are one of the key elements to understand the solar wind-magnetosphere coupling and the disturbed state of magnetospheres and radiation belts. The lack of fundamental research in the formation of CME sheath regions is limiting our long-term ability to advance the entire field of heliophysics.

2.3 Evolution of Low-Beta Plasma

CMEs provide a unique low-beta plasma environment into which to test the limits of fundamental plasma phenomena, such as reconnection, turbulence, and shock physics. Magnetic ejecta (ME) within CMEs consist of some of the most magnetically dominated plasma that we are able to directly measure. The plasma beta (ratio of thermal to magnetic pressure) consistently reaches $\beta = 0.1$ and sometimes $\beta = 0.01$ inside magnetic ejecta, as compared to $\beta \sim 1.0$ in the ambient solar wind at 1 AU. In the solar wind, there is a clear relationship between proton temperature and speed [Lopez 1987]. This relationship breaks inside CMEs, and in fact having a temperature lower than the "expected" temperature is often a criterion used to identify CMEs [e.g., see Richardson & Cane 1995, 2010].

It is known that many fundamental space plasma processes depend significantly on the plasma β, for example magnetic reconnection [Phan et al. 2010]. Most of the investigations of reconnection involving CMEs has focused on erosion [Dasso et al. 2006] or interchange reconnection [Crooker et al. 2000] as they are key for the magnetic flux carried by CMEs and important for the heliospheric magnetic flux balance. However, a few instances of internal reconnection inside the magnetic ejecta have also been reported [Steed et al. 2011] and current sheets are often occurring inside MEs. Little research has focused on how reconnection works in the low-beta regime inside MEs and how it affects the CME magnetic structure.

Similarly, the formation and amplification of waves and turbulence inside the low-beta environment of MEs is understudied but MEs provide a directly measured and unique environment, for which to test theories and advance our fundamental understanding of plasmas.

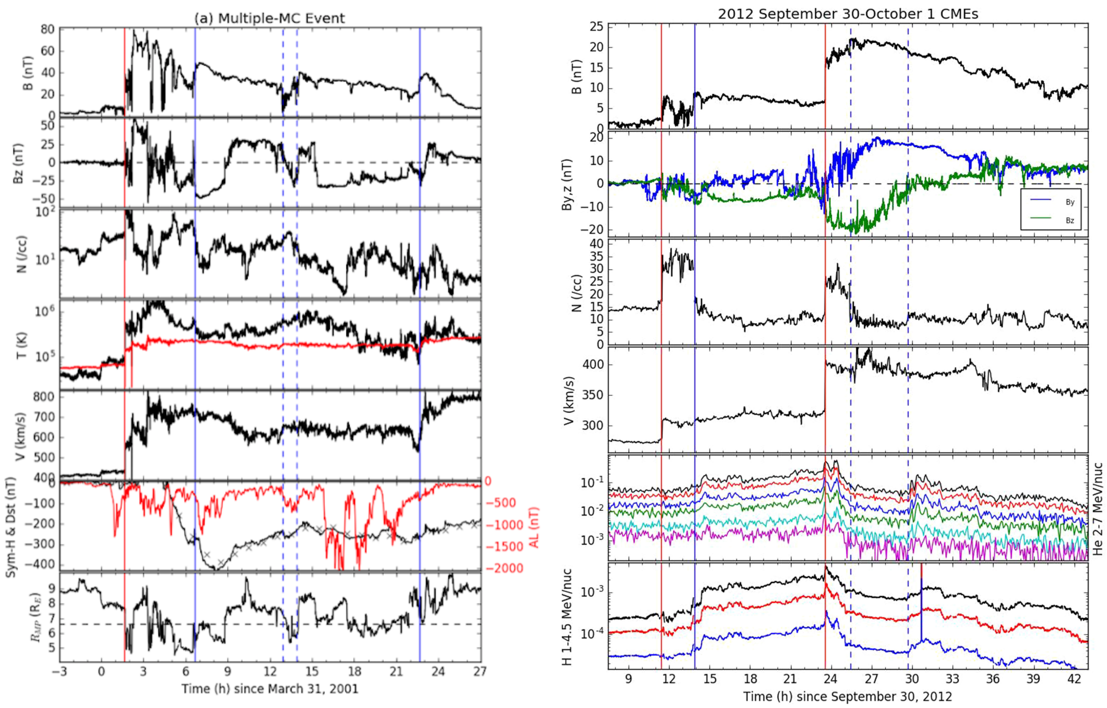

Figure 2: Left: Multi-MC event of 2001 March 31. The shock (red line) has one of the largest compression ever measured for a CME-driven shock with a magnetic field compression of 6 and a density compression of 2. This shock is likely associated with the merging of two shocks. The period between the two dashed blue lines has been analyzed as associated with reconnection between the two MEs. Right: Shock inside the CME of 2012 September 30. The second red line marks the shock propagating inside a previous eruption. Particles with energies up to 5 MeV are filling up the ejecta (last panel). Li & Lugaz [2020] showed that explaining their acceleration is not straight-forward.

2.4 CME–CME Interaction

The interaction of successive CMEs provide the most extreme environment for which we have direct measurements useful to test our fundamental understanding of plasma physics. The topics described above become even more complex when more than one CME is involved. While CME–CME interactions are often investigated due to their associated geo-effectiveness, it also provides a unique laboratory for extreme conditions in space plasma.

• *Shocks propagating in low-beta, low Mach number medium*: CME-driven shocks tend to be relatively weak, as compared to planetary bow shocks, with Mach number in the IP space of 2–4 and an average near 1 AU of about 2 [Kilpua et al. 2015]. During instances of CME–CME interaction, the faster, overtaking CME often drives a shock that propagates inside the slower, overtaken ME. In these cases, shocks are often fast but weak with Mach numbers below 1.5 [Lugaz et al. 2015], due to the high upstream speed and Alfvén speed inside the ME. The physics of such shocks, for example their ability to compress the magnetic field of the ME, is still poorly understood. See right panel of Figure 2.

• *Particle acceleration by shocks propagating in low-beta, low Mach number medium*: It has been reported that shocks inside ME can sometimes accelerate particles to high energies (10s of MeV) [Shen et al. 2008]. These particles often fill the entire ME into which these shocks propagates [Xu et al. 2019]. Theoretical considerations based on diffusive shock acceleration reveal that these shocks do not spend enough time inside the ME to accelerate the particles to these high levels [Li & Lugaz 2020]. Closed field line inside MEs are favorable to particle acceleration by enabling multiple shock crossing, the low level of turbulence, very cold proton temperature and very low density, all hinder efficient particle acceleration. While experimentally well documented, the ability of CME-driven shocks to accelerate particles to high-energy inside MEs is still a mystery [see also Lario et al. 2021]. See right panel of Figure 2.

• *Shock–Shock Interaction*: Shock–shock interaction is a relatively rich field within fluid dynamics. In space plasma physics, most studies have either been purely theoretical, or focusing on the interaction of a planetary bow shock (a stationary, high-Mach number shock) and propagating IP shocks [e.g., see Samsonov et al. 2007]. During CME–CME interaction, there are sometimes instances of two propagating shocks that interact and merge. The physical mechanisms occurring during these interactions are poorly understood, but the resulting discontinuities can show extreme jumps in plasma and magnetic field quantities, as is the case for example for the 2001 March 31 shock. See left panel of Figure 2.

• *Reconnection and Interaction between two MEs involving low-beta, high Alfvén speed regimes*: The reconnection between two MEs is still poorly understood. As compared to smaller flux tubes, they cannot be successfully simulated using particle-in-cell (PIC) simulations due to their large-size and the combination of propagation and expansion makes it even hard to determine the relative speed at the interface between two MEs. Cases of elevated temperature, depressed and turbulent magnetic fields at the interface between two MEs have been analyzed as the result of their reconnection. This provides, once again, an extreme regime into which to test our understanding of reconnection with an asymmetry between the two sides reconnecting but low-beta, high Alfvén speed in both sides. See left panel of Figure 2.

Additionally, CME–CME interaction has been reported as being associated with super-elastic collisions [Shen et al. 2012, 2013], where the total kinetic energy of the system increases during the collision (a result that was the cover of *Nature Physics*). This result needs confirmation as both simulations and the analysis of remote-sensing images come with high uncertainties.

3 Current Limitations

3.1 Simulation and Theory Limitations

While the ability to forecast the arrival time and speed of CMEs in operational settings with reasonable accuracy as highlighted in the previous Decadal Survey (p. 56) is one of the major achievements in heliospheric physics of the past twenty years, it should not obscure the fact that there are numerous physical phenomena that the simulations and associated numerical codes used for these forecasts do not and cannot capture: the CME magnetic field, CME expansion, the turbulent nature of the sheath, the small and meso-scale structures within CMEs, etc. There is in fact a community-wide consensus that incomplete physics in first-principle models is one of the major bottlenecks towards reliable space weather forecasting as highlighted in the recent "Roadmap for Reliable Ensemble Forecasting of the Sun–Earth System". Some of these features (the CME sheath region, for example) are not accurately captured by research simulations either. Efforts to include more physics into existing codes (MHD or otherwise) are essential. In fact, there exists but a handful of numerical simulations where a CME is initiated with a realistic model **AND** propagated to 1 AU to provide simulated in-situ measurements. A recent example [Török et al. 2018, see Figure 3] highlights how critical CME propagation is in modifying CME properties, and how neglecting their coronal and interplanetary evolution inevitably results in major gaps along the Sun–Earth chain.

Relatively simple models may be useful to investigate some of the problems in a dedicated manner, which would allow for an approach close to a parametric study (for example, the effect of CME orientation on CME–CME interaction), while other problems require code development

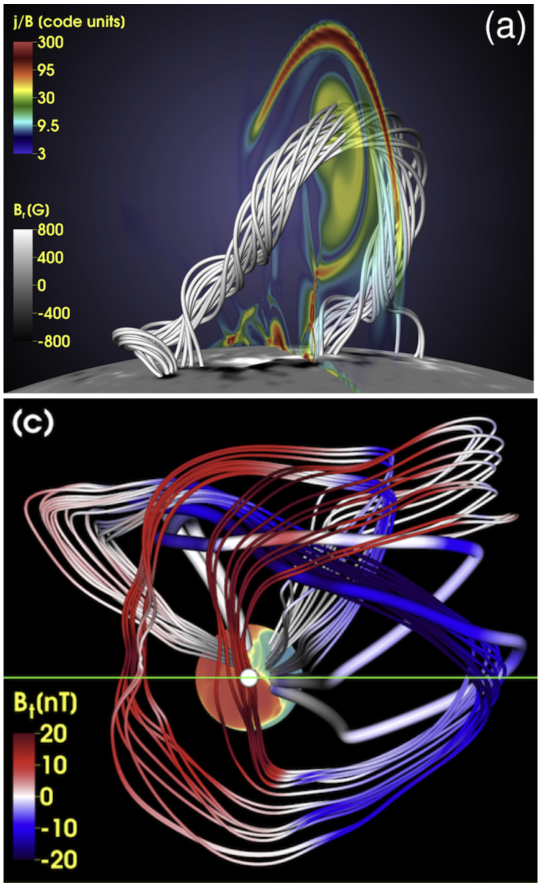

Figure 3: The morphology of the CME changes and the complexity of the magnetic field increases during the propagation from the Sun (panel a) to near 1 AU (panel c), as shown in this simulation from Török et al. [2018].

to include new physics, often at sub-grid scales (turbulence). This is the case, for example, to investigate sheath formation and properties.

In addition, all fitting and reconstruction techniques used to determine CME properties in the IP space from single-spacecraft measurements, assume 2-D invariance along an axis, which critically leads to results that can always be interpreted as a flux rope [Al-Haddad et al. 2013]. There is little incentive to develop more advanced techniques that do not assume invariance, as there are few multi-spacecraft data to test these methods. Such methods [Möstl et al. 2008] were developed early in the STEREO mission, as the spacecraft were close to each other, but the depth of the solar minimum in 2008 resulted in almost no CMEs.

3.2 Data Analysis and Tools

We have decades of *in situ* and remote-sensing observations of CMEs that need to be analyzed with as few assumptions as possible to better understand these phenomena. This data analysis should also be used to identify which major observational limitations remain to our understanding of CMEs, for example systematic multi-spacecraft measurements or coronal and heliospheric magnetic field observations. These will guide instrument and mission development for the next decades. If space weather forecasting is the ultimate goal, existing tools, such as the Graduated Cylindrical Shell or force-free approaches, might work well enough; however, this bears the risk that no fundamental research is undertaken to better understand the 3-D shape of CME fronts as seen in coronagraphs or non-force-free configurations inside CMEs. If fundamental research on the evolution of CMEs remains underfunded in comparison to space weather research, it is clear that, soon, the lack of fundamental understanding of CMEs will be the limiting factor for any forecast.

3.3 Observations

With PUNCH set to provide new remote-sensing observations of the corona and heliosphere in the near-future, and PSP and SolO providing single-spacecraft measurements in the innermost heliosphere, **the clear gap in observations for interplanetary research of large-scale structures, is primarily with multi-spacecraft in situ measurements.** The discovery of magnetic clouds [Burlaga et al. 1981] was made possible by the fact that five spacecraft crossed the same CME within about 1 AU from each other. This revealed the global nature of the magnetic ejecta. This event, measured in 1978, remains the best observed CME event in the inner heliosphere to date. The very small separations (typically of the order of 0.1°) of spacecraft at L1 doesn't allow to investigate the global structures of CMEs and shocks. Currently, a very well observed event would be observed by three spacecraft (say, Solar Orbiter, STEREO-A and L1).

The community has been resourceful, utilizing measurements from numerous planetary missions, such as Pioneer Venus Orbiter, MESSENGER, MAVEN, Juno, to investigate the propagation of CMEs [e.g., see Jian et al. 2008; Winslow et al. 2015; Davies et al. 2021] and to obtain multi-spacecraft conjunction events [e.g., see Salman et al. 2020; Palmerio et al. 2021]. However, many of the problems listed above would be best solved by having multi-spacecraft measurements combining radial and longitudinal alignment to distinguish propagation and 3-D effects. While such multi-spacecraft missions have been relatively common for the magnetosphere (THEMIS, Cluster, MMS), and are planned for Earth's perigeospace with HelioSwarm, no such mission is operating, under formulation or consideration for the interplanetary space.

There is a risk that missions focusing on in-situ measurements and remote-sensing observations of CMEs, shocks (and CIRs) move towards space weather operations (as is the case for some of the L5 European proposals, coronagraphic observations, or some near-Earth beyond L1 monitors) rather than research-focused missions. As detailed above, there are numerous open science questions that require investment not only in modeling but also observations to move forward. Making these investments in science missions is also the only way to ensure that future operational missions are designed in the most appropriate way (for example by limiting the separation from the Sun-Earth line to no more than a few degrees, although the exact maximum acceptable separation is yet unknown).

4 Way Forward: Recommendations

We focus here on high-level recommendations about measurements and some recommendations related to numerical models that can be easily implemented.

• **Dedicated multi-spacecraft measurements**: real progress in our understanding of CMEs require dedicated multi-spacecraft measurements, both in radial and longitudinal alignments. Many recent studies have focused on CME magnetic field due to instrument limitations. Having joint plasma and magnetic field measurements for satellites in radial alignment will enable investigations of CME evolution, including the formation of the sheath and changes in the expansion, but also the interaction of CMEs with other solar wind structures. Having most or all CMEs that impact Earth being measured *in situ* by 3–10 spacecraft at a range of 5–20° would go a long way in our understanding of issues related to the sheath relation to the ejecta, the ejecta magnetic structure, etc. Details about which measurements are best adapted to answer these science questions related to CMEs are discussed in the WP by Palmerio et al.

(i) Such measurements may be easily provided with smallsats launched as rideshare. The Heliophysics division should ensure that no launch mass to interplanetary space is wasted.

(ii) The Heliophysics division should be pro-active in funding smaller missions, following the example of the SIMPLEX program of the Planetary division (15–60 M$ and launched as rideshare), for which Phase A/B are funded before down-selection. This enables concepts to mature, and lowers the bar for new PIs to propose missions, hence diversifying the pool of PIs.

(iii) Missions to the inner planets should ideally have at least one instrument (plasma, field, energetic particles) that can be used by Heliophysics researchers. MESSENGER and MAVEN have led the way with dedicated heliophysics science goals and this should be extended to more missions to provide more measurements of CMEs and IP structures for a low cost.

• Efforts should be made to ensure that magnetized CMEs initiated through data-driven models are propagated from the solar surface to 1 AU. This is the only way to combine our knowledge gained from active region evolution and CME eruption with the knowledge from in-situ measurements. The model-data comparison made possible by this approach will further test our understanding of CMEs.

• Investment should be made by NSF and NASA to fund cross-disciplinary teams within space science, for example to study reconnection inside CMEs. The NSF/SHINE call, started in 2022, shows one example of such a program but it should be extended. Longer funding periods may be necessary for fundamental research. Currently, the only grants longer than 3 years tend to be for larger programs. Having even relatively small funding (∼100 k$ per year) but for 5 years would allow PIs to invest in some of these science questions.

References

Al-Haddad, N., Nieves-Chinchilla, T., Möstl, C., et al. 2013, Sol. Phys., 284, 129

Burlaga, L., Sittler, E., Mariani, F., & Schwenn, R. 1981, J. Geophys. Res., 86, 6673

Crooker, N. U., Shodhan, S., Gosling, J. T., et al. 2000, Geophys. Res. Lett., 27, 3769

Dasso, S., Mandrini, C. H., Démoulin, P., & Luoni, M. L. 2006, Astron. Astrophys., 455, 349

Davies, E. E., Forsyth, R. J., Winslow, R. M., Möstl, C., & Lugaz, N. 2021, Astrophys. J., 923, 136

Fox, N. J., Velli, M. C., Bale, S. D., et al. 2016, Space Sci. Rev., 204, 7

Jian, L. K., Russell, C. T., Luhmann, J. G., Skoug, R. M., & Steinberg, J. T. 2008, Sol. Phys., 249, 85

Kilpua, E., Koskinen, H. E. J., & Pulkkinen, T. I. 2017, Liv. Rev. Sol. Phys., 14, 5

Kilpua, E. K. J., Lumme, E., Andreeova, K., Isavnin, A., & Koskinen, H. E. J. 2015, J. Geophys. Res. Space Phys., 120, 4112

Lario, D., Richardson, I. G., Palmerio, E., et al. 2021, Astrophys. J., 920, 123

Li, G., & Lugaz, N. 2020, Astrophys. J., 905, 8

Lopez, R. E. 1987, J. Geophys. Res., 92, 11189

Lugaz, N., Farrugia, C. J., Smith, C. W., & Paulson, K. 2015, J. Geophys. Res. Space Phys., 120, 2409

Lugaz, N., Manchester, W. B., & Gombosi, T. I. 2005, Astrophys. J., 634, 651

Lugaz, N., Temmer, M., Wang, Y., & Farrugia, C. J. 2017, Sol. Phys., 292, 64

Manchester, W., Kilpua, E. K. J., Liu, Y. D., et al. 2017, Space Sci. Rev., 212, 1159

Möstl, C., Miklenic, C., Farrugia, C. J., et al. 2008, Ann. Geophys., 26, 3139

Müller, D., St. Cyr, O. C., Zouganelis, I., et al. 2020, Astron. Astrophys., 642, A1

Palmerio, E., Nieves-Chinchilla, T., Kilpua, E. K. J., et al. 2021, J. Geophys. Res. Space Phys., 126, e2021JA029770

Phan, T. D., Gosling, J. T., Paschmann, G., et al. 2010, Astrophys. J. Lett., 719, L199

Richardson, I. G., & Cane, H. V. 1995, J. Geophys. Res., 100, 23397

Richardson, I. G., & Cane, H. V. 2010, Sol. Phys., 264, 189

Russell, C. T., Mewaldt, R. A., Luhmann, J. G., et al. 2013, Astrophys. J., 770, 38

Salman, T. M., Winslow, R. M., & Lugaz, N. 2020, J. Geophys. Res., 125, e2019JA027084

Samsonov, A. A., Sibeck, D. G., & Imber, J. 2007, J. Geophys. Res., 112, A12220

Shen, C., Wang, Y., Ye, P., & Wang, S. 2008, Sol. Phys., 252, 409

Shen, C., Wang, Y., Wang, S., et al. 2012, Nat. Phys., 8, 923

Shen, F., Shen, C., Wang, Y., Feng, X., & Xiang, C. 2013, Geophys. Res. Lett., 40, 1457

Siscoe, G., & Odstrcil, D. 2008, J. Geophys. Res., 113, A00B07

Steed, K., Owen, C. J., Démoulin, P., & Dasso, S. 2011, J. Geophys. Res., 116, 1106

Török, T., Downs, C., Linker, J. A., et al. 2018, Astrophys. J., 856, 75

Winslow, R. M., Lugaz, N., Philpott, L. C., et al. 2015, J. Geophys. Res. Space Phys., 120, 6101

Winslow, R. M., Lugaz, N., Schwadron, N. A., et al. 2016, J. Geophys. Res. Space Phys., 121, 6092

Xu, M., Shen, C., Chi, Y., et al. 2019, Astrophys. J., 885, 54