Current Status:

Coronal mass ejections (CMEs) are a cornerstone of heliophysics science investigations. They are investigated 1) in the solar and heliospheric domains, where they constitute the most energetic and largest-scale objects of study, and 2) in terms of solar wind–magnetosphere coupling, since CMEs subject Earth's and planetary magnetospheres to extreme and sustained forcing. CMEs are the main cause of intense geomagnetic storms (Zhang et al., 2007) and one of the main drivers of the variability of Earth's radiation belts (Kilpua et al., 2015). Fundamental research on CMEs is carried out to investigate their initiation mechanisms at the Sun and the physical processes by which they couple massive amounts of energy and momentum to magnetospheres and influence various regions of the magnetosphere–ionosphere–thermosphere (MIT) system.

In the Heliophysics Decadal survey of 2012, all mentions of CME research are (i) either associated with their solar origin (SHP3a), or (ii) the coupling with the MIT system (KSG 2), or (iii) space weather research (KSG 1: "*predict* the variation in the space environment" and SHP3d: "Develop advanced methods for *forecasting and nowcasting* of solar eruptive events and space weather"). Of particular significance, Key Science Goal 4 is related to fundamental processes; dynamos, the solar wind, magnetic reconnection, collisionless shocks, turbulence and plasma-neutral interactions are specifically mentioned but not the stability and evolution of low-beta plasmas and magnetic fields typical of CMEs nor the plasma-plasma interaction processes that are central to the formation of CME sheath regions or the physics associated with magnetic flux ropes, one of the basic topological features of space plasmas.

These gaps have significant implications to the field of CME research over the past decade, where all investigations of CMEs beyond their initiation have been required to loop back to space weather issues. It is unclear what distinguishes CMEs from flares or SEPs in this respect, although flares and SEPs are both identified as areas where fundamental research is required. As one important consequence, none of the three overarching science objectives of the Parker Solar Probe mission (Fox et al., 2016) includes CME research, even though the spacecraft's orbit and instrumentation would be perfectly suited for investigating CME evolution in a previously unexplored region of the inner heliosphere (the goals are coronal heating and solar wind acceleration, source of the solar wind, energetic particle acceleration and transport). In contrast, the second of the four top-level scientific questions of the Solar Orbiter (a NASA/ESA mission developed by ESA) reads: "How do solar transients drive heliospheric variability?" including two sub-questions of "How do CMEs evolve through the corona and inner heliosphere?" and "How do CMEs contribute to the solar magnetic flux and helicity balance?" (Müller et al., 2013).

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 MESSENGER and STEREO (and now from Parker Solar Probe and Solar Orbiter). Many of these studies, focusing on measurements from NASA missions, have been undertaken in Europe and Asia, where research groups focusing on the heliospheric evolution of CMEs are more prevalent than in the US. These studies have been focusing on CME expansion, deflection, rotation, force balance (Manchester et al., 2017), the formation of CME sheath regions (Kilpua et al., 2017) and the interaction of CMEs with other CMEs (Lugaz et al., 2017) and with stream interaction regions (SIRs, Richardson et al., 2018). Nevertheless, many of these aspects are heavily understudied or simplified. Related research on shock formation and sheath development, for example, is often based on analogies with magnetospheres, even though this is not quite justified since CME-driven sheaths expand, allowing solar wind material to accumulate in a layer adjoining their front boundary (Siscoe & Odstrcil, 2008), or on hydrodynamical processes, as for example the interaction between CMEs and the solar wind in terms of drag (Cargill, 2002).

Desired State:

It is essential to develop a program of fundamental research that addresses the coronal and interplanetary evolution of CMEs, independent of their space weather impact. The focus on understanding and forecasting the geo-effects of CMEs must be grounded in fundamental research that allows one to understand their properties and how they vary on scales ranging from small (~10-100 Earth radii) to large (0.1-0.5 AU). Fundamental research regarding CME initiation and the transfer of mass, momentum and energy from the solar wind to planetary magnetospheres should also continue. In parallel, research on other heliospheric phenomena, such as IP shocks, SIRs and small transients should be pursued in their own right to advance our physical understanding, irrespective of any effort to develop operational and forecasting codes. Overall, fundamental research on CME propagation and evolution should include not only research programs focusing on data analysis, theory and code development but also mission and instrument development, especially in the explorer and smallsat categories.

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 codes 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 the CME is initiated with a realistic model **AND** propagated to 1 AU to provide simulated in-situ measurements. A recent example (Török et al.,

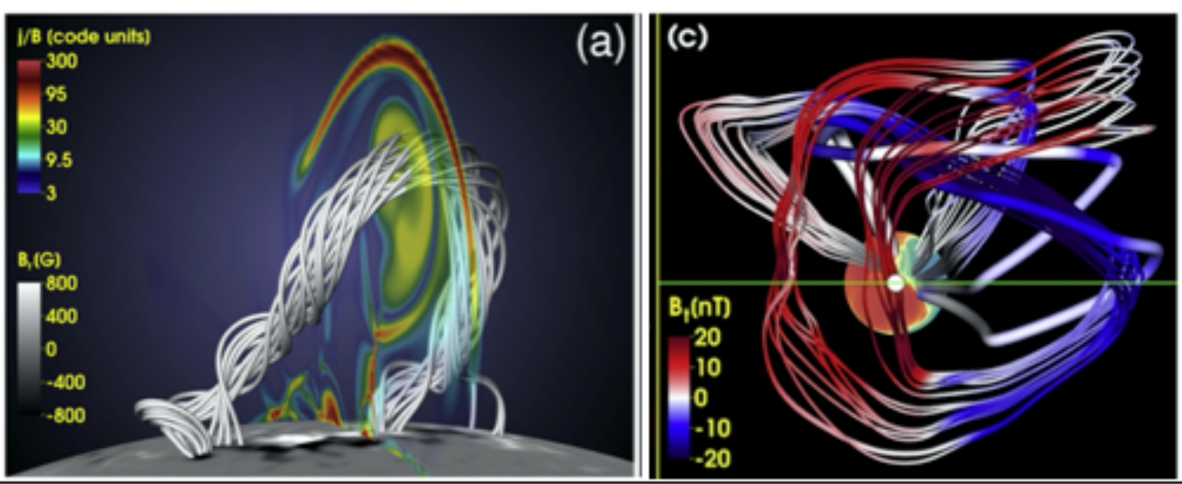

Figure 1: View of the simulated CME initial (left) and final (right, at 1 AU) magnetic configuration. The changes are due to the CME propagation. Adapted from Török et al. (2018).

2018; see also Fig. 1) 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.

We have decades of in-situ and remote-sensing observations of CMEs that need to be analyzed with as few assumptions as possible and can be used 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 future mission and instrument development to be launched in 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, for example, the 3-D shape of CME fronts as seen in coronagraphs, including dimples and waves or non-force-free configurations inside CMEs. If fundamental research on the coronal and heliospheric evolution of CMEs remains underfunded in comparison to space weather research, it is clear that in 2050 the lack of fundamental understanding of CMEs will be the limiting factor for any forecast.

Way Forward:

<table>
<tr><th>Objective</th><th>Open Science Questions</th><th>Required Programs</th></tr>
<tr><td rowspan="4">Determine how CMEs and other IP structures evolve in the corona and heliosphere</td><td>What is the role that CMEs play in the transfer of magnetic flux and energy from the Sun to the heliosphere?</td><td rowspan="4">Active data analysis of existing missions.
Development and validation of first-principle simulation models.
New IP science missions.</td></tr>
<tr><td>What is the 3-D magnetic structure of CMEs and how does it evolve during propagation?</td></tr>
<tr><td>How do CME sheaths form, what determine their properties and how do they affect planetary magnetospheres?</td></tr>
<tr><td>How does the interaction of CMEs with other CMEs, coronal and heliospheric structures affect their properties in the heliosphere?</td></tr>
</table>

Science Investigations and New Mission/Instrumentation Timelines	
2020-2030	Fundamental research on CME structure, evolution, and sheath formation through active and enhanced ROSES programs – Identification of existing observational gaps – Development of rideshare and explorer missions to fill these gaps – Pathfinder missions
2030-2050	Launch of additional missions on IP and space weather research – Associated analysis and model development – Development, selection and launch of new operational space weather missions – Active fundamental research on CME evolution being incorporated into first-principle space weather models
2050	Active fundamental research on CME evolution – First-principle space weather models – Fleet of IP and space weather missions

References:

Cargill et al., *AnGeo*, **20**, 879–890, 2002. – Fox et al., *SSRv*, **204**, 7–48, 2016. – Kilpua et al., *GRL*, **42**, 3076–3084, 2015. – Kilpua et al., *LRSP*, **14**:5, 2017. – Lugaz et al., *SoPh*, **292**:64, 2017. – Manchester et al., *SSRv*, **212**, 1159-1219, 2017. – Müller et al., *SoPh*, **285**, 25–70, 2013. – Richardson et al., *LRSP*, **15**:1, 2018. – Siscoe & Odstrcil, *JGR*, **113**:A00B07, 2008.– Török et al., *ApJ*, **856**:75, 2018.– Zhang et al., *JGR*, **112**:A10102, 2007.