CORONAL MASS EJECTIONS

A Personal Workshop Summary

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Abstract. This workshop summary tries to distill the key difficulties and questions in the art of (I)CME physics and strategies to address them. (I)CMEs are multi-dimensional, multi-parameter, and multi-scale phenomena related to the solar dynamo, corona, and heliosphere. This workshop illustrates the immense progress made in describing and modeling these spectacular energetic solar events, but also shows clear shortcomings in our understanding of them.

Keywords: Coronal mass ejections, flares, solar physics, interplanetary physics, space weather, solar and stellar X-ray luminosity

1. Introduction

Summarizing a workshop that led to the publication of this hefty 500-page volume is a daunting task. So much effort and thought has gone into the individual articles and reports that a summary can hardly do them all justice. From this wealth of material, I have tried to distill the difficulties we face when dealing with coronal mass ejections (CMEs) and their interplanetary manifestations, ICMEs. In one word, (I)CMEs are difficult, because they are "multi-a lot of things": multi-dimensions, multi-parameter, and multi-scale.

It is easy to understand the difficulty with **multi-dimensions**. CMEs are inherently $3 + 1$ dimensional, their spatial properties are linked to their temporal evolution. Obviously, this is difficult, because we are used to drawing two-dimensional sketches and cartoons of CMEs. Figure 2 gives an impression of a dimensional pitfall. Reconnection of the central flux rope with the overlying field lines is topologically impossible in 2-D configuration *a*, but is readily achieved in the 3-D configuration *b*, as shown in *c*. Perhaps less obvious is the problem that many models of CMEs are two (+1) dimensional and that many of our conclusions come from such models. Mikić and Lee (2006, this volume) conclude their introduction to theory and models of CMEs with a list of 10 improvements that are needed to make progress in understanding CME initiation – first of which is the extension of models to 3 (+1) dimensions.

One might be tempted to state that (I)CMEs are even more than 3+1 dimensional. One could argue that e.g. the composition of various parts of an ICME should be

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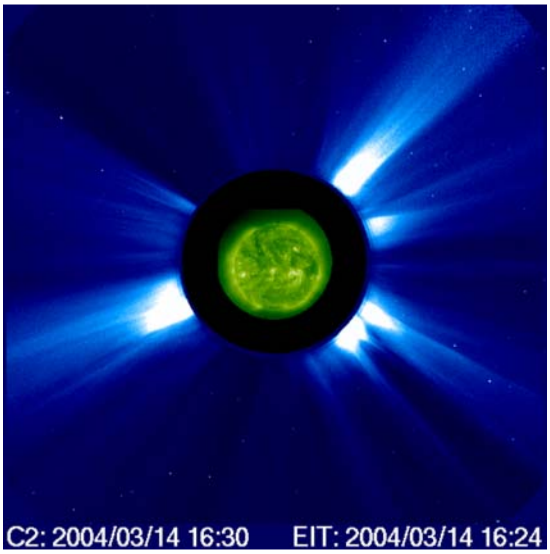

Figure 1. Combined EIT/LASCO image of the "workshop CME" which finally occurred during the final meeting at ISSI. See text for discussion. Image courtesy SOHO (ESA & NASA).

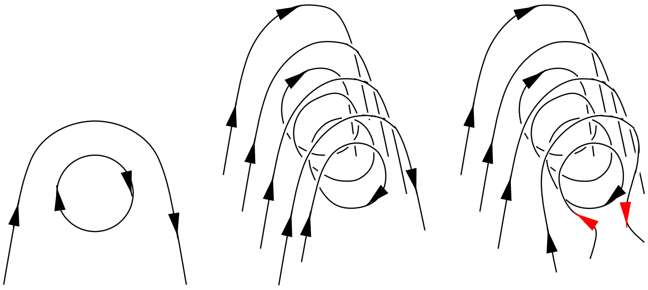
(a) (b) (c)

Figure 2. Dimensional pitfall. No reconnection of the central flux rope with the overlying field lines is possible in 2-D configuration a for topological reasons, while it is in 3-D (b and c).

considered as an extra few dimensions, say one per element or even charge state. One could add three extra dimensions for (I)CME speed and we would end up with an (I)CME phase space, but I'm not sure this is really helpful at our present state of nascent understanding, so I prefer to consider these quantities "parameters".

The **multi parameters** that play a role in the behavior of CMEs constitute the next difficulty. To paraphrase Alexander *et al.* (2006, this volume), "In other words, considering parameters one at a time, as is often done for specific events, is inadequate." This is not only true for models, but also for observations. Zurbuchen and Richardson (2006, this volume) suggest that the most practical approach to identify ICMEs is to "examine as many signatures as possible" or available. Since not all signatures agree and all signatures are (almost?) never present simultaneously, this may well be the only solution we have. As we develop more and more ingenious observational methods, the difficulty in absorbing all the possible observations will increase, adding another dimension to the multi-parameter difficulty.

Finally, the physics of (I)CMEs is truly **multi-scale**. For example, the acceleration of particles at ICME-driven shocks requires understanding the overall global structure of the shock and the ambient solar wind, e.g., the magnetic connection to the shock, the intermediate scales such as local curvature, bumps, and dents, on the scale of several ion gyroradii, as well as the microphysics involved in escaping particles generating upstream turbulence on which other particles can scatter. On the Sun, CMEs are driven by or drive small- and large-scale reconnection. Large-scale subsurface flows influence the emergence and appearance of active regions, while small-scale photospheric motions "wiggle" the overlying field lines in the corona which can form large-scale structures that may or may not act as tethers for underlying (buoyant or not) flux ropes. Forbes *et al.* (2006, this volume) illustrate the enormous range of scales in their Figure 1 and Hudson *et al.* (2006, this volume) stress the consequences for modeling.

These few and incomplete examples of the complexity of (I)CMEs demonstrate that "(I)CME-ology" is not an easy field to work in. It is a challenge to understand (I)CMEs and we need to break this challenge down into manageable chunks or questions that we can address.

2. What do We Need to Understand?

There are several ways of dividing up questions that need to be addressed to make progress in the understanding of (I)CMEs. A traditional way is to begin with CME initiation, its propagation through the corona and interplanetary medium, and the consequences of (I)CMEs such as particle acceleration and their influence on cosmic rays. Another way would be to look at some properties or conditions that we believe are crucial to the processes just mentioned, such as the roles of flux emergence, cancellation, or shear, of helicity in (I)CMEs. Other properties or conditions associated with (I)CMEs are flux ropes, seed populations, and their magnetic connection back to the Sun. I have tried to combine both ways inTable I.

The ejection of coronal mass requires energy and we generally agree that it is the magnetic field that supplies this energy. The emergence of magnetic flux alone is insufficient, it appears that flux needs to be sheared, with twisting often injecting helicity and increasing the available energy. How this flux and helicity is injected is unclear. Is it the result of subsurface processes or of photospheric footpoint motions or of rotating sunspots? Both Gopalswamy *et al.* (2006, this volume) and Schwenn *et al.* (2006, this volume) in this volume consider this an important question to answer. Is the increasing helicity important or is it the accompanying increase

TABLE I

Properties or conditions associated with various (I)CME stages.

	Flux emerg./ cancel./shear and helicity	Reconnection/ flares	Flux ropes	Particle populations	Magnetic connection
CME initiation	•	•	•	•	
Coronal propagation	•	•	•	•	•
Interpl. propagation	•	•	•	•	•
Shocks/particles		•	•	•	•

in stored energy that makes active regions with sigmoids more likely to produce CMEs? How does this affect the overall helicity budget of the Sun?

The eruption of CMEs is accompanied by a major reconfiguration of the coronal magnetic field, thereby converting stored magnetic energy into kinetic and thermal energy. However, we still do not fully understand how this conversion occurs (Schwenn *et al.*, 2006, this volume). We all agree it happens by the process of reconnection, but it is very hard to observe because it occurs on such small scales and because of its fundamentally 3-D nature. For instance, we do not understand whether reconnection initiates a CME or whether it is merely a consequence of a CME. Does it trigger a flare or is it triggered by a flare (Pick *et al.*, 2006, this volume; Schwenn *et al.*, 2006, this volume)? Where is the filament with respect to the reconnection site? As the CME moves through the corona into interplanetary space, it interacts with the ambient solar wind and is accelerated or decelerated. Is this the only process or does ongoing reconnection also affect CME propagation speed by converting kinetic energy into thermal energy (Forsyth *et al.*, 2006, this volume)?

A related question is where the flux ropes are formed (Gopalswamy *et al.*, 2006, this volume). Are they already present in the subsurface and then emerge from it, or do they form in the atmosphere? If the latter, do they form before or during the eruption and what is their relation to reconnection? The question whether all CMEs are fluxropes is quite fundamental and of practical purpose (Gopalswamy *et al.*, 2006, this volume). If all CMEs are fluxropes, then our models already incorporate that property. If not, then more work will be required to model non-flux-rope CMEs. The difficulty in settling this question is observational. It is hard to determine whether a CME is a flux rope from remote-sensing observations. Definitely, not all ICMEs are flux ropes (Wimmer-Schweingruber *et al.*, 2006, this volume; Zurbuchen and Richardson, 2006, this volume), but we do not truly understand the relationship between CMEs and ICMEs (Forsyth *et al.*, 2006, this volume). The spacecraft trajectory may simply not be intersecting the flux-rope part of the ICME, or this part has dissolved due to ongoing reconnection, or, indeed, there may well be non-flux-rope ICMEs.

As the CME propagates outwards through the corona, it can drive a shock, depending on its speed and the local magnetosonic speed (Forbes *et al.*, 2006, this volume). These shocks may accelerate particles of various origins in the corona and beyond, but it is unclear from observations where the shocks form (and possibly disappear) relative to the heights where SEPs are accelerated (Cane and Lario, 2006, this volume). Furthermore, the roles of the various seed populations, such as flare suprathermals, shock geometry, and transport processes in determining the properties of individual events are unclear (Klecker *et al.*, 2006, this volume). For instance, the relation of the various systematic dependencies such as m/q, charge-state, and spectral properties, to the local and possibly global plasma and shock properties is unclear. Are flare-accelerated particles, "normal" coronal particles, and possibly inner-source pick-up ions the only seed populations? What do they tell us about shock and hence CME evolution? Are scatter-free particles truly scatter-free, i.e. are the injection delays true delays, implying shock acceleration, or are transport processes affecting flare-produced particles (Cane and Lario, 2006, this volume)? When moving out of the corona into interplanetary space, ICMEs continue to accelerate particles, but intriguingly also can contain particles within. Where do they come from and what do they tell us about ICME topology (Klecker *et al.*, 2006, this volume; Wimmer-Schweingruber *et al.* 2006, this volume)? Even farther out in the heliosphere large ICMEs may compress the solar wind or multiple ICMEs may merge to form Merged or even Global Merged Interaction Regions (MIRs or GMIRs). These regions contribute to the modulation of cosmic rays (Gazis *et al.*, 2006, this volume) by serving as "diffusion barriers". The relation of the constituting ICMEs and these barriers is unclear.

The various particle populations accessible to modern space-based instrumentation have greatly enhanced our possibilities to understand (I)CMEs, be it to detect them in-situ (Wimmer-Schweingruber *et al.*, 2006, this volume; Zurbuchen and Richardson, 2006, this volume; von Steiger and Richardson, 2006, this volume; Gazis *et al.*, 2006, this volume), but also to relate processes involved in CME initiation (Wimmer-Schweingruber *et al.*, 2006, this volume; Zurbuchen and Richardson, 2006, this volume) and particle acceleration (Cane and Lario, 2006, this volume; Klecker *et al.*, 2006, this volume). This workshop certainly drove home the point that there is a richness of information in these measurements that is still waiting to be exploited. Nevertheless, some observations, such as the simultaneous measurement of elevated and low charge states in the bulk plasma of ICMEs, are still puzzling and await explanation (Wimmer-Schweingruber *et al.*, 2006, this volume; Zurbuchen and Richardson, 2006, this volume).

Another group of questions may be summarized under magnetic connection. We have already touched upon the subject of flare-related energetic particles inside flux ropes. How do they get into the interior of the flux-rope ICME (Klecker *et al.*, 2006, this volume; Cane and Lario, 2006, this volume)? Do they leak into the

ICME from the shock it is driving, are they connected along open field lines back to the ejection site, or to some other flaring active region? While the signatures of bidirectional electrons are understood in terms of magnetic connection back to the Sun, those of bidirectional ions are not (Wimmer-Schweingruber *et al.*, 2006, this volume). This magnetic connection may also be a clue to the observation that the kinetic temperature inside ICMEs decreases less quickly with heliocentric distance than that of the solar wind. What keeps on heating ICMEs (Forbes *et al.*, 2006, this volume) once they have been ejected? How long are these open field lines maintained and how are they disconnected? This has immediate implications for the question of the open magnetic flux of the Sun which is strongly influenced by ICMEs (Crooker and Horbury, 2006, this volume), but also on the removal of helicity from the Sun (Hudson *et al.*, 2006, this volume).

3. What is Needed?

In order to further our emerging understanding of (I)CMEs, we need to make progress in the areas of observations/measurements, theory and modeling, and, last but not least, in breaking down our knowledge and understanding to a level manageable for operational use in space weather forecasting (see paper by Siscoe and Schwenn (2006) in this volume). We could also summarize the needs in other ways, along the lines discussed in the introduction. First of all, we need to measure (I)CMEs in 3 (+1) dimensions: This requires 3-D magnetic field measurements in the photosphere, chromosphere, and corona. We are also waiting for the first 3-D images of CMEs from STEREO and are also excited about the opportunities of observing ICMEs while in quadrature with other spacecraft. STEREO, together with Wind, SOHO, and ACE will also allow us multi-point observations of ICMEs and the shocks they drive. Nevertheless, these 3-D measurements are likely to be at the wrong scales or certainly not at all the scales needed. Short of a dedicated multi-scale mission, we should combine the data from Wind, SOHO, ACE, and STEREO with those of ESA's Cluster when it is in the solar wind. In the farther future, we need to investigate the evolution of ICMEs in the inner heliosphere, making use of ESA's Solar Orbiter with its unique orbit, and the multi-point measurements offered by NASA's Sentinels. These missions will no doubt enhance our understanding of (I)CMEs and related phenomena.

On the modeling side, there are probably "only" two wishes, one very difficult, one easier to achieve. The easy goal is to make current and future models more readily available to researchers, thus greatly simplifying data interpretation. The Michigan group is making a promising start in this respect. The other Need (with a capital N) is simply for more realistic models. Almost all papers in this volume call for more realistic modeling. More accurate treatment of the coronal energy balance, inclusion of realistic seed particle populations and composition in models,

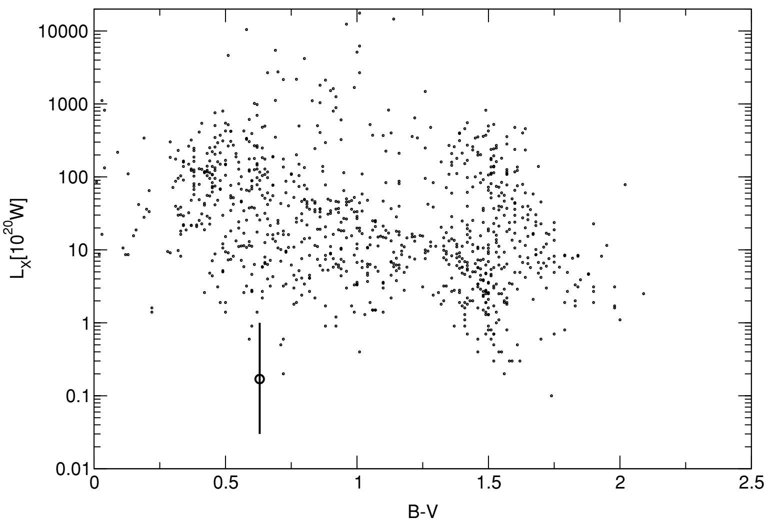

Figure 3. X-ray luminosities of stars in the solar neighborhood vs. B-V color index. The large circle with the vertical solid line indicate the Sun and its X-ray variability. Data: http://vizier.u-strasbg.fr/cgi-bin/VizieR.

relaxation of simplifying assumptions, fully 3-D time-dependent models, inclusion of all relevant scales (kinetic to MHD), self-consistent treatments of CME initiation and evolution, modeling of observable quantities, and inclusion of cross-scale coupling are just a few examples of the many wishes uttered at this workshop. There is still alot of work ahead.

4. The Sun as a Star

The relation of CME initiation and flares is still unclear, yet if we want to apply our understanding of CMEs to other stars and estimate mass loss due to CMEs (e.g. during early evolutionary stages), then we probably need to revert to flares as indicators of CME activity. To me, one of the greatest puzzles in this respect is the extremely low X-ray activity of the Sun when compared to other stars, even solar-type stars.Figure 3 shows X-ray luminosity of a volume-limited Rosat all-sky survey of the solar vicinity vs. B-V color index. The Sun has a B-V index of 0.63, the large circle shows average solar X-ray luminosity, the solid vertical line indicates its variability. The data are from the Vizier Service at Centre de Données astronomiques de Strasbourg (`http://vizier.u-strasbg.fr/cgi-bin/VizieR`). Clearly, the Sun lies at the lower extreme of X-ray activity for all Sun-like stars. Are we just lucky to live with a star that is benigningly X-ray inactive? Or is it a prerequisite for life?

Figure 4. The castle of Elmau in February 2003. Photograph courtesy J. Schmidt.

Figure 5. Group photograph in Elmau. Courtesy J. Schmidt.

5. Final Remarks

The series of workshops leading up to the publication of this volume saw changes in the way we view coronal mass ejections and related coronal and interplanetary phenomena. During the first workshop at the wonderful castle of Elmau (see Figure 4) in the snow-covered Bavarian hills, we were still absorbing the richness of the visual impressions offered by SOHO (and, of course, the more immediate surroundings). For instance, one topic of discussion that came up repeatedly at the first workshop was the relation of slow and fast CMEs to gradual and impulsive solar particle events. Was there a one-to-one correspondence? Was there no relation at all? Today we know that there is a continuum of CME speeds (see, e.g., Figure 1.5 of Schwenn *et al.* (2006, this volume)), then we were still under the impression of a two-class distribution. As we have seen in this workshop, a lot of progress has been made. As is usual in the science business, every question solved generates at least one additional new question – a few selected ones have been mentioned in this summary.

At the last workshop, at the International Space Science Institute, ISSI, we finally got our "workshop CME". It is an utterly unspectacular CME emerging from the upper streamer in the south-western quadrant of Figure 1. May this workshop stand out as more spectacular than its CME!

Acknowledgements

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