Magnetic field of CMEs as represented by 40+ years of analyses

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Introduction

Coronal mass ejections (CMEs) are large magnetized plasma structures that are ejected by the sun into the interplanetary medium. One of the first descriptions of magnetic flux ropes is the uniform twist model, following a paper (Gold & Hoyle 1960) focusing on the magnetic configuration of erupting filaments. With the development of interplanetary probes, various interplanetary data revealed that interplanetary transients had unusual plasma and magnetic field properties.

There were many discussions in the 1970s about the morphology of CMEs. With the definition of magnetic cloud and the development of the force-free fitting in the 1980s, a ***paradigm has taken hold that equates CMEs with highly twisted force-free cylindrical flux ropes with a circular cross-section and closed field lines***. Many observational aspects show that this equivalence is too limiting.

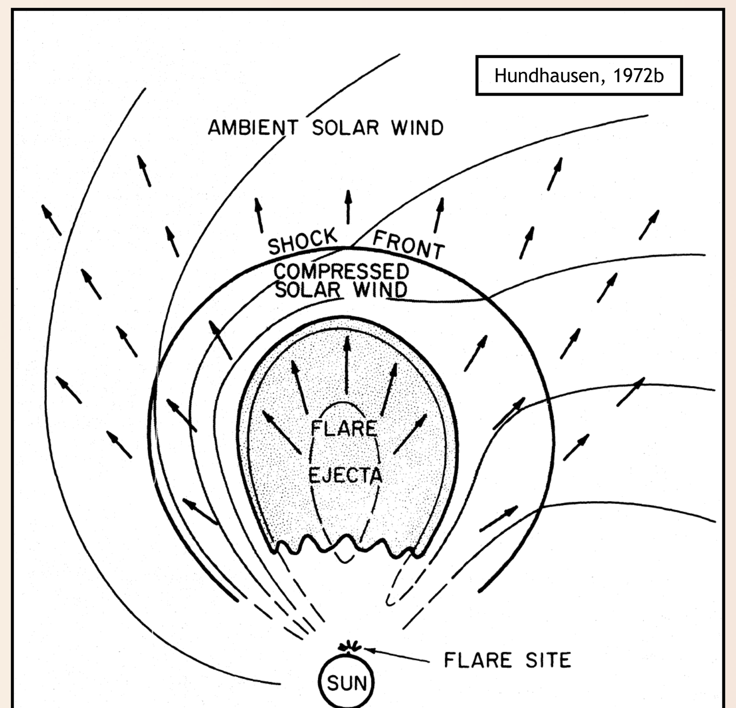


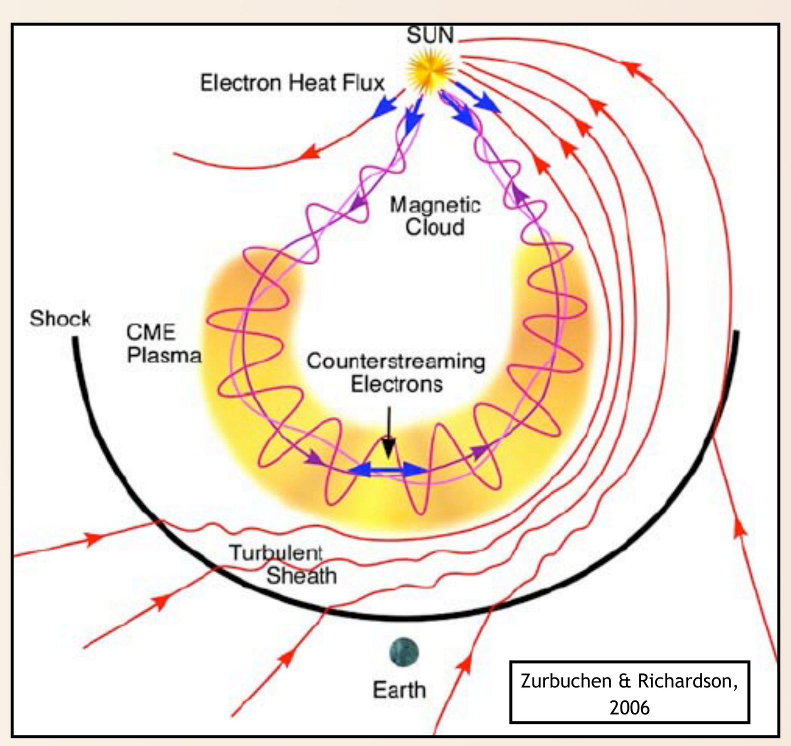
Figure 2. A qualitative sketch, in equatorial cross section, of a flare-produced solar wind disturbance, propagating into an ambient solar wind similar to that shown in figure 1. The arrows again indicate the plasma flow velocity and the light lines indicate the magnetic field. The rotation of the sun has been neglected in drawing a configuration symmetric about the flare site.

The ***goal*** of this work is to review studies made possible by the wealth of data over the past 25-40 years and ***to lay out a model that provide a more up-to-date visual of the structure of CMEs***. We show common visualization of CMEs and point out the lack of clear evolution in these sketches to reflect a better understanding of the complex nature of CMEs, in term of their non-force-free nature, the field line length and twist distribution, the open/closed nature of the field lines within CMEs, the shape and coherence of the CMEs, and the form of helicity within CMEs, the stability of force-free field. At the end, we present an updated sketch of a magnetic ejecta that incorporates the majority of these aspects.

Standard Models of CMEs

***In situ* measurements**

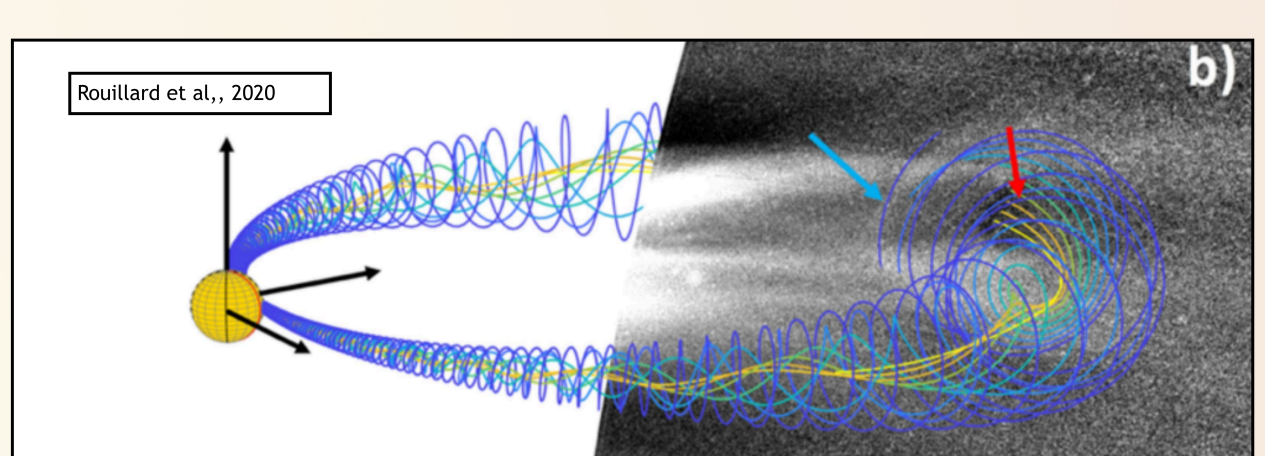
Due to the variety of CME profiles observed *in situ*, they have been classified into different categories: magnetic cloud, following the definition of Burlaga et al. (1981), magnetic cloud-like or magnetic ejecta, exhibiting some or most, but not all, of the characteristics of magnetic clouds, various manifestations of interacting CMEs and other complex ejecta, which primarily encompass events with low and high amount of rotation of the magnetic field vector.



The cartoon by Zurbuchen & Richardson (2006) is often used to introduce CMEs and present a highly twisted flux rope with a circular cross-section, closed field lines in a quasi-2D configuration. This model is used for all CME profiles, with the understanding that more complex profiles are associated with crossings away from the nose/axis.

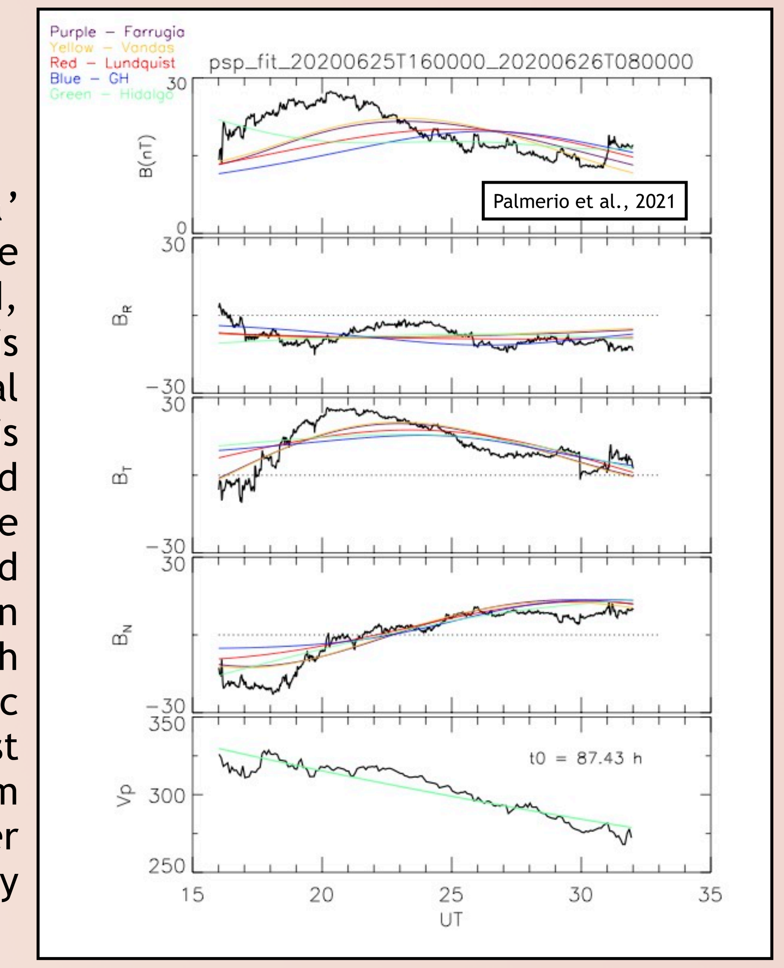
Remote Sensing

CMEs are observed during their eruptions using remote-sensing imagers, such as coronagraphs measuring the Thomson scattered light, or extreme-ultraviolet imager. The figure below shows a CME erupting in a coronagraph. While this is often described and analyzed as a flux rope, what is observed is a direct measure of the electron density along the observer-Sun line of sight. As such, one observes primarily a high density structure emerging from the lower corona. A cavity of low density might or might not be present, and has been analyzed as corresponding to the magnetic ejecta.



Limitations: Force Free Model

The simplest representation of ejecta' magnetic fields is force-free field, where the current is parallel to the magnetic field, meaning that $\nabla \times B = \alpha B$. Solutions to this equation have been presented for a cylindrical configuration assuming a constant α. Even this simplest approximation of a force-free field does not imply that α is a constant. While the Lundquist/Lepping force-free fit is widely used in the solar-terrestrial community, the variation of the magnetic field components are much better fitted by it than the total magnetic field. The Lundquist model, in its simplest form, always "predicts" the maximum magnetic field strength to occur in the center of the magnetic cloud, whereas this is rarely observed.



Limitations: Field Line Length and Twist Distribution

Lundquist fitting model as it is applied in most cases, implies that the twist is to be maximum on the outer boundaries of the magnetic ejecta and minimum in the middle. Kahler et al. (2011), using impulsive energetic electrons associated with flares to determine the field lines, found that the magnetic filed lines are nearly uniformly twisted inside MCs (see Figure to the right).

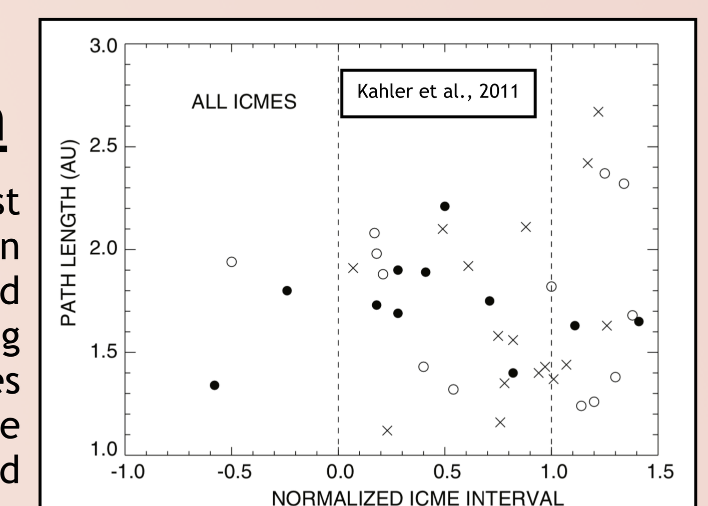


Figure 5. Superposed epoch plot of *Le* for all ICMEs, combining 16 EPAM NR electron events ⩽12 hr from ICME boundaries (vertical dashed lines) and the 24 events inside the boundaries. Open circles, solid circles, and crosses are class 0, 1, and 2 ICMEs, respectively.

Most fitting models are based on a predetermined twist distribution, and therefore cannot be used to investigate the twist distribution inside MEs. Möstl et al. (2009) determined that the twist of the 2007 May 23 CME observed simultaneously by Wind and STEREO-A was about 1.5 turns per AU and uniform throughout the ejecta. The authors noted that this is inconsistent with the circular cross-section linear force-free fittings. Other examples with higher twist are shown in the Figure on the right.

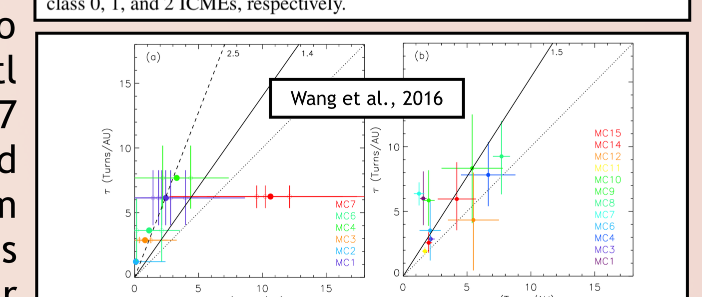


Figure 5. Comparison of the number of turns per astronomical unit, τ, derived by the velocity-modified GH model with (a) that by the electron probe method and (b) that by the GS model. Each circle in Figure 5a indicates an energetic electron event, and each dot marks the mean value of the twists of a MC. The solid lines are the linear fits to the solid dots in Figures 5a and 5b. The dashed line in Figure 5a is the linear fit to the solid dots excluding MC7. The numbers on the top of the panels give the slopes of the linear fitting lines.

Limitations: Open-Closed Field Lines

The possibility that the magnetic field lines inside CMEs are open was already noted by Burlaga et al (1981). All models and representations assume that the magnetic field lines are closed. Investigations have focused on the erosion of the outer layer of the magnetic field of the MC (e.g., see Ruffenach et al., 2012), which still leaves the core of the "flux rope" composed of closed field lines.

However, the most direct measurements of the topology of magnetic field lines are obtained from suprathermal electrons: bidirectional electrons (BDEs) are signatures of closed field lines and single strahls are signatures of open field lines (although they have also been explained as being associated with asymmetric closed field lines). Measurements (see Figures, and e.g., work by Crooker et al) indicate that MCs are typically composed of a mix of open and closed field lines with the "core" being as likely composed of open or closed field lines.

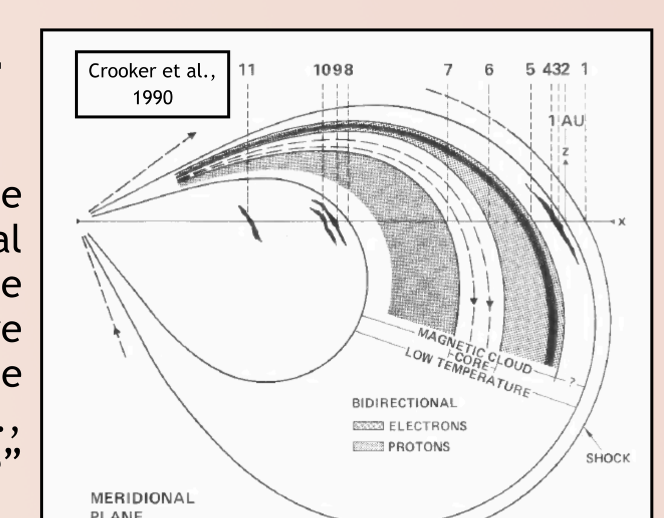


Fig. 2. Coronal mass ejection structure based on observations and assumed flux rope topology.

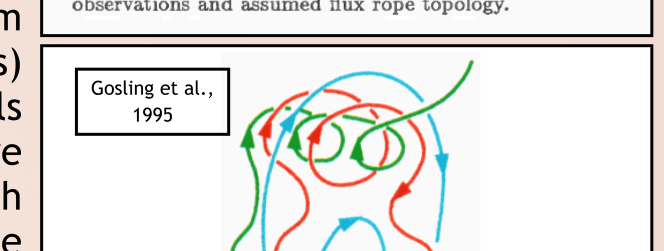
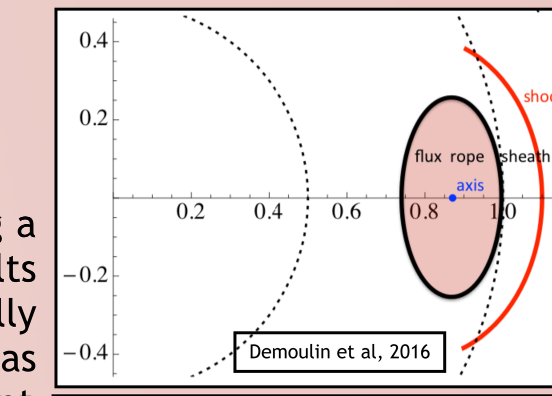
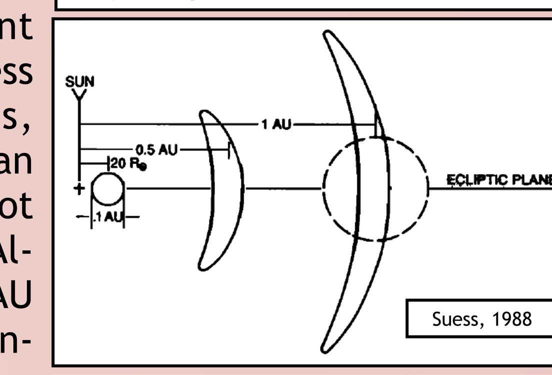


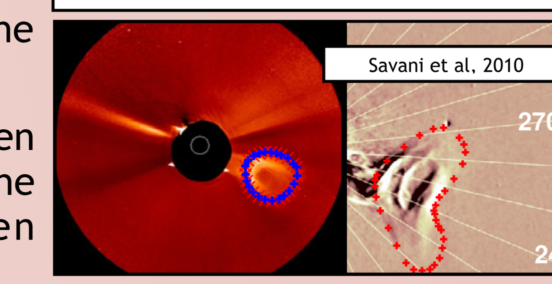
Figure 4. An example of several different magnetic topologies possible in a CME that has undergone 3-dimensional reconnection. The sketch is not to scale and not all possible topologies are represented.

Limitations: Elliptical Shape & Pancaking

CMEs have been assumed to propagate while maintaining a constant angular width. This is supported by early results from LASCO (StCyr et al., 1998) but hasn't been carefully investigated with heliospheric imagers. Recently, this has led to the conclusion that CMEs are not coherent structures (Owens, 2017), reviving an argument that Suess (1988) addressed. Based on in-situ measurements, Demoulin et al. (2016) have concluded that CMEs have an elliptical cross-section with a 3:1 ratio, which is not consistent with an extreme elliptical cross-section. Al-Haddad et al. (2022) used plasma measurements near 1 AU to test these different scenarios and found moderate non-radial flows, with directions not consistent with any of the typical scenarios.



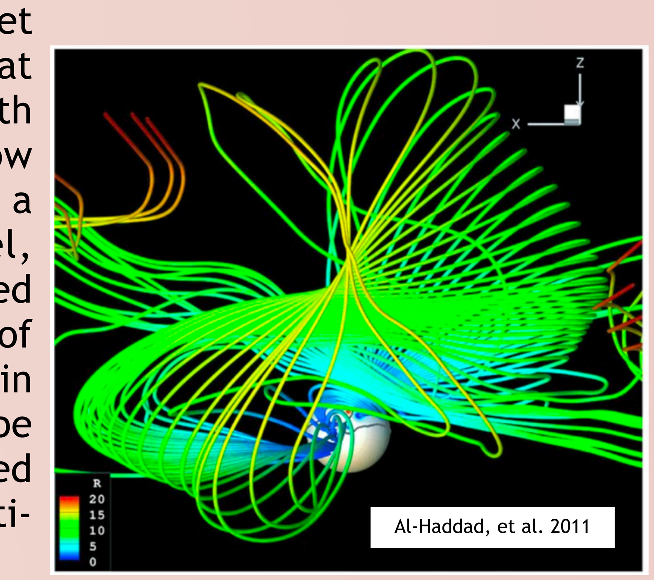




CME pancaking due to the structured solar wind has been imaged a few times (e.g., Savani et al., 2010) but the consequences for fitting models have not been investigated.

Limitations: Writhe and Complex Structures

The possibility for more complex (or different) magnetic structures has been discussed for more than 30 years. Riley et al. (2004) used MHD simulations to show that fitting techniques do not work well for large impact parameters and that "result from techniques to infer global morphology must be viewed with caution." Al-Haddad et al. (2011, 2019) showed that a 3-D magnetic field with significant writhe but low twist can be well fitted by a twisted flux rope model, which will return a twisted flux rope. The assumption of axial invariance is key in returning twisted flux rope but has not been well tested due to the lack of multi-spacecraft measurements.



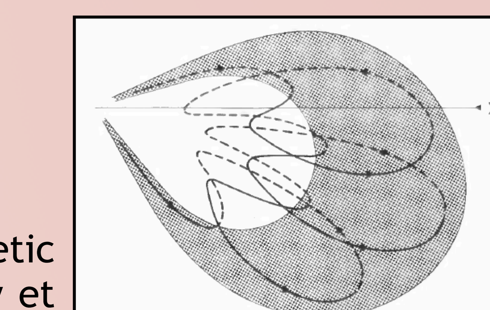


Fig. 3. Helical portion of the flux rope magnetic field, drawn separately as if it were an overlay for Figure 2, for clarity. The shaded area is the meridional cross-section of the rope and fits between discontinuities 5 and 8. The solid (dashed) curves trace the distorted helix in front (back) of the shaded plane. The helix is distorted according to the ecliptic cross-sectional shape in Figure 4.

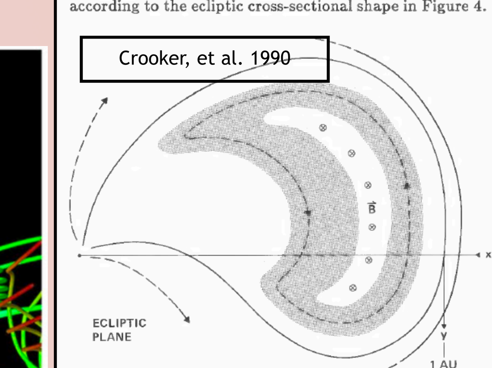


Fig. 4. Cross-section of the Figure 2 structure. The shaded region is the helical portion of the flux rope, between discontinuities 5 and 8. The core of the rope, between discontinuities 6 and 7, is unshaded, and the southward direction of the magnetic field is indicated there. The dashed contour inside the shaded region is a projection of one turn in the helical magnetic field. The dashed curves spiraling out from the sun indicate the IMF polarity.

Summary: A more Physical Sketch of Magnetic Ejecta

While many of these points may be known by CME researchers, the common sketch and visualization as highlighted in the first column do not capture this physics. Developing a more realistic sketch that captures these processes is essential to properly convey the complexity of CMEs and the depth of physical processes which are still active areas of research. We propose one such sketch here.