energy release on the Sun in a day
CMEs best seen by coronagraphs – LASCO C2
CMEs best seen by coronagraphs – LASCO C3
The three-part white light CME

Vourlidas et al 2013
standard flare-CME model

Forbes-Lin model
1. structure
2. genesis
3. energetics
Brief History of Magnetic Cloud

- 1954 Morrison: unusual magnetized clouds of plasma emitted by the active sun.
- 1958 Cocconi et al.: magnetic loop or bottle anchored in the sun.
- 1958 Piddington: magnetic bubble detached from the sun by reconnection.
- 1959 Gold: shocks preceding these magnetic loops
- 1980–81 Burlaga: first coined “magnetic cloud”
- 1990, 1997, Lepping: magnetic cloud properties

(Burlaga et al, 1981, JGR, 86, 6673–6684)
In-situ measurements of Magnetic Cloud

Tightly wound helix
B: 10 – 100 nT

Low temperature
and plasma density
T: \(10^5\) K, n: 10 – 100 cm\(^{-3}\), \(\beta\): 0.01 – 0.1

Higher speed than
ambient solar wind
v: 300 – 800 km s\(^{-1}\)

Preceded by shocks
and sheaths

(Burlaga et al 1981;
Lepping et al. 1990)
In-situ measurements of Magnetic Cloud

Tightly wound helix

\[ B : 10 \text{ – } 100 \text{ nT} \]

Low temperature and plasma density

\[ T : 10^5 \text{ K, } n : 10 \text{ – } 100 \text{ cm}^{-3}, \beta : 0.01 \text{ – } 0.1 \]

Higher speed than ambient solar wind

\[ v : 300 \text{ – } 800 \text{ km s}^{-1} \]

Preceded by shocks and sheaths

(Burlaga et al. 1981; Lepping et al. 1990)
From in-situ observations, a flux rope may be reconstructed with various methods (Riley et al. 2004, Dasso et al. 2006 for a summary of these methods), assuming a 2d cylindrical structure of the CME flux rope.
MC flux rope: the Lundquist solution

\[ B_0(r) = B_0 \left[ J_0(\alpha r)\hat{z} + J_1(\alpha r)\hat{\phi} \right] \]

\begin{align*}
\text{toroidal flux:} & \quad \Phi_t = \int \int B_z r dr d\phi \\
\text{poloidal flux:} & \quad \Phi_p = \int \int B_\phi dr dl \\
\text{magnetic helicity:} & \quad H_m = \int \vec{A} \cdot \vec{B} \, d^3x \\
& \quad = \frac{1}{\alpha} \int B^2 \, d^3x \\
\text{magnetic twist:} & \quad T = \frac{lB_\phi}{rB_z}, \quad \tau = \frac{T}{2\pi}
\end{align*}

Least-squares fitting of the data points to determine 7 parameters, including the rope axis orientation, radius, and axial field \( B_0 \).

(Lepping et al. 1990, Lynch et al. 2005)
MC flux rope: the Lundquist solution

18 MC flux ropes by Lepping et al. 1990, and 132 MC ropes by Lynch et al. 2005
MC flux rope: the GS solution

2d magnetostatic non-force-free Grad-Shafranov equation

\[ \vec{V}_p = \vec{j} \times \vec{B} \]

\[ \vec{B} = \left( \frac{\partial A}{\partial y}, -\frac{\partial A}{\partial x}, B_z(A) \right) \]

\[ P_t(A) = p(A) + B_z^2 / 2\mu_0 \]

\[ \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0 \frac{dP_t}{dA} \]

\[ \Phi_t = \int \int B_z \, dx \, dy \]

\[ \Phi_p = |A_m - A_b| \]

\[ \tau = 1AU / Lz \]
MC flux rope: the GS solution

MC flux ropes carry an average twist of $\tau > 3$ per AU. Most of them deviate from the Lundquist solution (Hu et al. 2014, 2015; Kahler et al. 2011).

18 MC flux ropes by Hu et al. (2014)
Field line length of MC flux rope

Lengths of MC field lines are also measured from electron travel times, \( L_e = v_e \Delta t \), to compare with models (Larson et al. 1997, Kahler et al. 2011, Hu et al. 2015)
properties of MC flux ropes

<table>
<thead>
<tr>
<th>property</th>
<th>typical values at 1 AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross-sectional radius (a)</td>
<td>0.1 – 0.5 AU</td>
</tr>
<tr>
<td>axial (toroidal) flux</td>
<td>$10^{19-21}$ Mx</td>
</tr>
<tr>
<td>azimuthal (poloidal) flux per AU</td>
<td>$10^{20-22}$ Mx</td>
</tr>
<tr>
<td>magnetic helicity per AU</td>
<td>$10^{40-44}$ Mx$^2$</td>
</tr>
<tr>
<td>magnetic twist per AU</td>
<td>3 – 5 turns, or more</td>
</tr>
</tbody>
</table>


How are flux ropes formed?
CDAW (1996–2005) identified solar source for 88 geomagnetic storms (Dst < -100 nT), 46 being MCs.

<table>
<thead>
<tr>
<th># of MCs (46)</th>
<th>Solar Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 (61%)</td>
<td>Active Regions</td>
</tr>
<tr>
<td>8 (17%)</td>
<td>Quiet Sun</td>
</tr>
<tr>
<td>10 (22%)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Zhang et al. (2007)
genesis of a flux rope

The debate on nature or nurture: the flux rope is born from below the photosphere (emerging flux rope), or is made in the corona, by reconnection, during its eruption (in-situ formed flux rope), or a hybrid of the two.

<table>
<thead>
<tr>
<th></th>
<th>Pre-existing rope</th>
<th>In-situ formed rope</th>
</tr>
</thead>
<tbody>
<tr>
<td>idea</td>
<td><strong>Formed in convection zone, emerges to the corona, or formed in the corona, but prior to eruption</strong></td>
<td><strong>Formed in-situ during eruption by magnetic reconnection</strong></td>
</tr>
<tr>
<td>models</td>
<td>Chen89, Low96, Gibson98, Fan04, Forbes-Priest-Isenberg-Lin, VanBallegooijen89</td>
<td>Moore80, Mikic88, Mikic94, Choe96, Demoulin96, Titov99, Antiochos99, Amari03, Longcope07</td>
</tr>
<tr>
<td>observations</td>
<td>filaments, sigmoids, other indirect signatures.</td>
<td>sheared arcades, other indirect signatures.</td>
</tr>
<tr>
<td>problems</td>
<td>cannot measure magnetic field in the corona</td>
<td>cannot measure magnetic field in the corona</td>
</tr>
</tbody>
</table>
examples of a pre-existing flux rope

Filaments and sigmoids are magnetized plasma structures present prior to eruption with higher chance of MC occurrence.
infer flux rope properties from surface signatures

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Surface signatures</th>
<th>research</th>
</tr>
</thead>
<tbody>
<tr>
<td>dynamics</td>
<td>CME speed</td>
<td>Gopalswamy01</td>
</tr>
<tr>
<td>orientation, handedness</td>
<td>global magnetic field</td>
<td>Mulligan00</td>
</tr>
<tr>
<td></td>
<td>loop arcade</td>
<td>McAllister98</td>
</tr>
<tr>
<td></td>
<td>filament</td>
<td>Rust94, Bothmer98</td>
</tr>
<tr>
<td></td>
<td>Sigmoid dimming</td>
<td>Canfield99, Pevtsov01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Webb00</td>
</tr>
<tr>
<td>axial (toroidal) flux</td>
<td>active region</td>
<td>Leamon04</td>
</tr>
<tr>
<td></td>
<td>filament</td>
<td>Lepping97</td>
</tr>
<tr>
<td></td>
<td>dimming</td>
<td>Webb00</td>
</tr>
<tr>
<td>azimuthal (poloidal) flux, electric</td>
<td>active region</td>
<td>Demoulin02, Nindos03,</td>
</tr>
<tr>
<td>current, helicity</td>
<td>dimming</td>
<td>Leamon04</td>
</tr>
<tr>
<td></td>
<td>CME flare</td>
<td>Mandrini05, Attrill06</td>
</tr>
<tr>
<td></td>
<td>flare</td>
<td>Moore07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longcope07, Qiu07,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kazachenko09,12</td>
</tr>
</tbody>
</table>
Flux ropes formed by magnetic reconnection of a sheared arcade, transferring shear to twist.
poloidal or azimuthal magnetic flux $\Phi_p$: the amount of twist along the field lines

The helical structure, or the twist, results from magnetic reconnection.
reconnection is “visible” in disk observations

Flare loops and their foot-points are bright because of plasma heating along post-reconnection flux tubes.
reconnection is measured from flare ribbons

\[ \frac{d\Phi_B}{dt} = -\oint \vec{E} \cdot d\vec{l} = \frac{d}{dt} \left( \int B_{in} dA_{in} \right) = \frac{d}{dt} \left( \int B_R dA_R \right) \]  

(forbes & priest 1984)
by mapping ribbons on the magnetogram

\[ \Phi_B = \int B_{in} \, dA_{in} = \int B_R \, dA_R \]
reconnection flux is a good fraction of the AR flux

Qiu et al, 2002-2010, Kazachenko et al. (2017)
The erupting rope causes coronal dimming at the two feet, with which the axial flux of the rope is estimated.

Moore et al. (2001)
handedness of reconnection formed flux rope

compare MC and solar signatures

<table>
<thead>
<tr>
<th>parameters</th>
<th>Solar surface signatures</th>
<th>MC flux rope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected orientation</td>
<td>45° NE of equator 30° - 55° NE (range) 55° axis of dimmings Filament rotates toward E-W</td>
<td>-11° ecliptic latitude, 108° ecliptic longitude S-E-N type</td>
</tr>
<tr>
<td>handedness</td>
<td>left</td>
<td>left</td>
</tr>
<tr>
<td>Magnetic flux</td>
<td>1.0x10^{21} Mx (dimmings)</td>
<td>7.35x10^{20} Mx (axial)</td>
</tr>
<tr>
<td>speed</td>
<td>600 km/s (CME front)</td>
<td>430-500 km/s</td>
</tr>
</tbody>
</table>

Figure 3. (Top) EIT difference image (0507 UT-0450 UT) and (bottom) MDI image (0454 UT). Superposed are the area masks which were used to estimate total magnetic flux at the assumed footpoints of erupting loop system. Masks used for the southwest (left) and northeast (right) dimming regions.

An event on 1997 May 12-15 analyzed by Webb et al. (2000)
reconnection flux and MC flux

(Qiu et al. 2007, Hu et al. 2014)
reconnection flux and MC flux

\( \Phi_p = 2.8 \Phi_t^{0.7} \)

\( \Phi_p = 0.68 \Phi_r^{0.61} \)

(Qiu et al. 2007, Hu et al. 2014)
dimming flux and MC flux

(Qiu et al. 2007)
flare configuration and MC twist

An event with decreasing twist (Hu et al. 2014)
flare configuration and MC twist

An event with flat twist (Hu et al. 2014)
flare configuration and MC twist

Which one is correct? What do we see in MC flux rope and flare? (Priest et al. 2016, 2017)
Summary

MC measurements provide evidence of flux ropes, which probably carry a large amount of twist.

MC flux ropes are formed in the Sun, and reconnection plays an important role in its formation, as well as its energetics.