Coronal Mass Ejections in the Heliosphere

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Plan

• General Properties
• Rate & Solar Cycle Variability
• Relation to Polarity Reversal
• CMEs and Cosmic ray modulation
• SEPs radio bursts
• CMEs and Geomagnetic storms
• Summary
Animation of Halloween 2003 Events

... to illustrate their heliospheric impact
What is a CME?

A prominence eruption that becomes CME core (in microwaves, Nobeyama)

SOHO/LASCO sees the CME Later in the corona with the core

Brightening on the disk is the associated flare
The number of SOHO CMEs is an order of magnitude higher than that of pre-SOHO CMEs.

The average speed and width (of non-halo CMEs) are similar to pre-SOHO values.

The highest speed observed increased significantly to 3347 km/s, but the fraction of CMEs with \( V > 2500 \) km/s is tiny (10^{-4}).

The number of halo CMEs is significantly larger (~3%).

Statistically, faster CMEs decelerate.

The average mass of SOHO CMEs is smaller than pre-SOHO values (due to SOHO's better dynamic range).

\[ a = -0.015 \left( v - 463 \right) \]

\( a = 0 \) when \( v = 463 \), a crude estimate of solar wind speed.

SOHO observed more low-mass CMEs resulting in a smaller average mass.
Solar Cycle Variation of CME Rate and Speed

SOHO CME rate increased from ~0.5/day during solar minimum to ~6/day during maximum. The maximum rate is higher by a factor of 2 (pre-SOHO max rate ~3/day)

The pre-SOHO correlation between sunspot number and CME rate was confirmed, but the correlation was weaker. This seems to be due to the high-latitude CMEs that started in 1999 from polar crown filament region

The solar cycle variation of average CME speed was inconclusive in the pre-SOHO era. SOHO data confirmed the increase from minimum to maximum by a factor of 2. The spikes in the speeds are due to some active regions, which are copious producers of fast CMEs.
CMEs & Prominences

- High latitude prominence eruptions and CMEs during CR 1950-1990 (mid ’99 – early ’02)
- N-S asymmetry
- These CMEs are not associated with sunspot activity
- hence the poor correlation between CME rate & SSN
High & Low latitude CMEs

The average latitude changes significantly over the solar cycle.

2005 distribution looks similar to that in 1998.

Polarity reversal in the northern hemisphere

Polarity reversal in the southern hemisphere

Polarity reversal coincides with the cessation of HL CMEs separately in the northern and southern hemispheres.
Solar magnetic field pattern before reversal

The blue structures (Magnetic field in the polar crown filaments) must be replaced by the red for reversal in the north.

This happens when the high-latitude structures disappear as CMEs.

The red fields represent the future polar crown filament in the north.
CMEs Affecting the Heliosphere

Median 11.4 R
Average 13.1 R

ALL CMEs 9092

Ulysses | LASCO HL | LASCO LL | 1 AU
--- | --- | --- | ---
8 | 101 | 602 | 25
8% | | | 4% (8% excluding Backsided CMEs)

~ 10% of CMEs leaving the Sun seem to reach far into the heliosphere
Consistent with the 11% wide CMEs; Similar fraction reaches the edge of the LASCO FOV

July 10 2000 – February 5, 2001 (7 months); Ulysses poleward of S60 courtesy: J. T. Gosling
The speed distribution of CMEs and ICMEs for 59 pairs (from Gopalswamy et al. 2000 GRL).

\[ a = -0.0054V + 2.193 \]

\[ a = -0.0054 (V - 406) \]

\[ a = 0 \text{ for } V = 406 \rightarrow \text{CMEs riding on the solar wind} \]
The IP acceleration can be used to estimate the CME transit time to Earth. The shock transit time can be obtained from the CME transit time by estimating the standoff distance.

SOHO contributed 2 events to the historical fast transit events compared with a simplified formula for the shock transit time.

\[ t = a \cdot b^V + c \]

Empirical models for shock and CME arrival at Earth.

SOHO CMEs

- 31.8 h
  - 10/26/03
- 27.9 h
  - 7/14/00
  - 10/28/03
- 18.9 h
  - 10/29/03
- 19.7 h
  - 10/29/03

Aug 4, 1972
Sep 1, 1859 Carrington

Diamonds: historical flare-SSC time from Hale 1931, Newton, 1943, Cliver & Svalgaard 2004, Gopalswamy et al 2005

From Gopalswamy et al. 2005 JGR
Relative Number of MCs and ICMEs

Magnetic clouds (MCs) generally originate from close to the disk center, Non-cloud ICMEs (NC) have a large scatter in source locations. shocks (S) without drivers are due to CMEs originating from close to the limb.

Non-cloud: deviation from 3
CMEs play a role in the modulation of galactic cosmic rays (GCRs). Solar cycle dependent cosmic ray modulation can be explained by the presence of CME-related magnetic inhomogeneities in the heliosphere.

Pre-SOHO:
Rate was not high enough
Min to max variation was too low
CMEs and GCR Modulation

CME rate high enough
Min to max variation high enough
Contribution from High-latitude CMEs
Impact of Plasmas & Particles

A CME headed Earthwards
SEPs acceleration starts when the
CME is close to the Sun (a few Rs)

SEPs reach SOHO (located along the
SUN-Earth line at L1) in 10s of minutes

SOHO detectors blinded by SEPs

SOHO’s performance in imaging the corona
is temporarily affected
--Sometimes fatal
The CME kinetic energy (speed, width) decides the wavelength range of type II bursts. Speed, width, & deceleration progressively increase for CMEs associated with metric, Decameter-hectometric (dh) and metric to kilometric (m-to-km) Type II bursts. km type IIIs have positive acceleration → shock formation at large distances from the Sun. CMEs with m-to-km type II bursts are also associated with SEP events (same shock accelerates electrons & protons).
SEP Associated CMEs

- CMEs have very high speed (Avg ~ 1500 km/s) compared to 480 km/s
- Most CMEs are halos (72%); non-halos are wide (avg ~186 deg) : 45 deg
- Most CMEs decelerating (sign of high speed) – drag: ~0 m/s²
- Generally western source (Avg ~38 deg); many behind west limb (18%)
CME Interaction

Interacting CMEs result in enhanced radio emission in the IP medium → additional electrons accelerated (Gopalswamy et al., 2001ApJL)

SEP-related CMEs seem to be launched into a medium distorted and disturbed by preceding CMEs.

CMEs with preceding CMEs (P,O) from the same AR result in higher SEP intensity compared to those without (NP).

The scatter in the SEP intensity vs. CME speed plot is also reduced when P and NP events are separated.

High intensity SEP events are 3 times more likely to be preceded by wide CMEs within a day.

Gopalswamy et al. 2004 JGR
CMEs and Geomagnetic storms

Disk

FLimb

Backside

GOES 10 X-Rays:

GOES 8 X-Rays:

GOES 10 X-Rays:
Halo CMEs

- Halos known for a long time (Howard et al. 1982, but routinely observed only by SOHO)
- Front-sided halos are likely to impact Earth
- The high kinetic energy of the halos allows them to travel far into the interplanetary medium and impact on Earth causing geomagnetic storms.

- Halos are >2 times faster on the average
- Halos are associated with bigger flares
59 strong (Dst ≤ -100 nT) storms (1996-2003) were analyzed (Gopalswamy, 2006)

- 55 were CME-associated
- 3 were probably CIR-related
- 1 probably CIR

Geoeffective CMEs are faster and wider on the average.

Mostly full halos (69%) and partial halos (31%)
Geoeffectiveness of Halos

378 halos of cycle 23 analyzed for Geoeffectiveness (Dst < -40 nT)

- Source longitude $\Lambda < 45$ deg
  - Highly geoeffective
- Source Ion $45 < \Lambda \leq 90$ deg
  - Moderately geoeffective
- Source Ion $\Lambda > 90$ deg
  - Not geoeffective

- Random Dst values
  - Similar to Backside halos

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**Frontside Halo**
- Med -97 nT
- Ave -117 nT
- 167 CMEs

**Limb Halo**
- Med -50 nT
- Ave -62 nT
- 90 CMEs

**Backside Halo**
- Med -36 nT
- Ave -41 nT
- 80 CMEs

**Random**
- Med -37 nT
- Ave -47 nT
- 120 Intervals
Significant CMEs

CMEs of heliospheric consequences $V \geq 1000$ km/s
Summary

- CME rate increases by an order of magnitude from minimum to maximum: solar max rate a factor of 2 higher than pre-SOHO estimates
- The mean CME speed is higher by a factor of 2 during solar maximum (this was not established before SOHO era).
- ~10% CMEs important for heliospheric impact
- Only 1-2% of CMEs are important for SEPs
- Halo CMEs are faster than average (and wider); 3%
- Geoeffective CMEs form a subset of front-side halos
- Direct CME impact is essential for geoeffectiveness
- Source location and speed differ for Geo- and SEPeffective CMEs
- Poor correlation between CME rate and SSN is due to high-latitude CMEs
- Polarity Reversal coincides with the cessation of high-latitude CMEs
- High-latitude CME rate has a better (anti)correlation with GCR intensity during A>0 cycle than with the low-latitude rate.
- The opposite is true for the A<0 cycle
Summary

SOHO has observed CMEs almost over a solar cycle, yielding an extensive and uniform data set for a better understanding the CME phenomenon.

Separating the CME rate into high and low latitude rates helps understand the correlation with sunspot numbers, solar polarity reversal, and galactic cosmic ray modulation.

The relation between CMEs and Prominence Eruptions is confirmed and recent doubts have been clarified.

The combination of SOHO and wind/WAVES data has helped observe direct CME interactions and study their implications for radio bursts and SEP events.

The coupling between CMEs and the solar wind has been possible by combining SOHO data with in situ data resulting in models for estimating the arrival times of CMEs and shocks.

A hierarchical relationship between CMEs and type II bursts has been found, confirming that the most energetic CMEs produce type II bursts over the longest wavelength range and responsible for the large SEP events.
Tylka jan 20 05

- GLE onset 6:48:40 +/-10s (NM)
- E-folding rise 25 s
- CRNE on IMP8: 06:51:48, probably 06:50
- Electron onset at 6:50:12 +/- 5 s
- 3DP: 6:49 electrons
- For all GLEs, typical delay of e is < 2 min
- Cliver et al. (1982) found 5 min delay, may be an artifact of limited sensitivity
### SOHO and Pre-SOHO CMEs

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1 Tousey (1973)
2 MacQueen et al 1974
3 Michels et al 1980
4 Brueckner et al., 1995; Gopalswamy 2004
CME-Flare Association

- The CME association rate clearly increases with
  - (1) Flare size (20% for C-class, 49% for M-class and 92% for X-class)
  - (2) Longitude of the solar source

- The center-to-limb variation of CME association

- Rate is important only for weak flares

- There are some X-class flares (8%) with no CME association.

- ~20% of CMEs may not have been detected by LASCO

Estimated CME Visibility function assuming that all limb CMEs are detected by LASCO
Impulsive SEP Events and CMEs

Impulsive SEP events were thought to be not associated with CMEs. Recent study using SOHO data shows that ~40% of the impulsive SEP events are associated with CMEs. However, the type II burst association is rather poor (~13%).

CMEs associated with impulsive SEP events are slightly faster on the average, but the widths are similar to the general population.

Study based on a small sample (38 events). Needs further investigation.

Yashiro et al. 2004
Acceleration

The dependence of acceleration $a$ on speed $V$ is similar in the LASCO FOV and over the Sun-Earth distance.

- Very slow CMEs accelerate.
- Very fast CMEs decelerate.
- CMEs near slow wind speed show little acceleration.
- Near the Sun, $a$ has propelling, gravity & drag components.

$$a = -0.023 \ (V - 506)$$

Comparing the speeds of CMEs near the Sun and ICMEs (magnetic clouds) at 1 AU.

Gopalswamy et al., 2000; 2001
Yashiro et al., 2004,
Gopalswamy, 2004

$$a = -0.0054\ V + 2.193$$

$$a = -0.0054 \ (V - 406)$$

$a = 0$ for $V=406 \rightarrow$ CMEs riding on the solar wind.
CMEs and Prominence Eruptions

- Prominence eruptions from Nobeyama radioheliograph and SOHO CMEs confirmed the high-degree (83%) of association between CMEs and PEs.
- CMEless PEs were much slower (20 km/s), attained very low heights and mostly moving horizontally.
- North-south asymmetry in CME and PE rate.
- The latitude distributions of CMEs & PEs were different because of non-radial motion of CMEs during solar minimum.


PE latitudes are closer to the poles than CME latitudes during solar minimum.
An interesting consequence of the HL CME rate and polarity reversal is the connection to the modulation of galactic cosmic rays (GCRs). Newkirk et al. (1981) had identified CMEs as the solar origin of the low-frequency power in the interplanetary magnetic field fluctuations and suggested that the solar-cycle dependent modulation of GCRs can be explained by the presence of the fluctuations in the heliosphere. For effective modulation, a higher and more cycle-dependent CME occurrence rate (varying by factors up to 10) was required than pre-SOHO data indicated (Wagner, 1984). SOHO has demonstrated the higher and more cycle-dependent rate (when HL CMEs are considered), and hence the GCR modulation should be possible.

Cross-correlation between GCR intensity and high-latitude (HL) and low-latitude (LL) CME rates for (left) the A< 0 epoch of cycle 21 and (right) the A>0 epoch of cycle 23. Note the switching of the dominant correlation between cycles 22 (A<0) and 23 (A>0).

Gopalswamy, 2004