4. Solar Fireworks: Flares, CMEs, shock waves
- History, examples, definition of terms
- Balloon type CMEs and halos
- Typical CME properties during the activity cycle
- The relationship between CMEs and flares
- Where is the shock in coronagraph data?
- CMEs, shocks, ejecta clouds: a strange metamorphosis!
- Open questions about flares, CMEs, and shock waves

Lectures at the
International Max-Planck-Research School
Oktober 2002
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Flares and the begin of space weather research

A solar flare, as observed by TRACE

Carrington was the first man who happened in 1859 to observe a flare and also to notice the connection with the strong geomagnetic storm 15 hours later. Note what the "father of space weather" noted at the end of his report:

"...one swallow does not make a summer!"

"Collisionless" shocks in the heliosphere?

The famous battle Gold vs Parker about shocks in the heliosphere: piston driven shocks vs blast waves?

It began in the late 1950s, i.e. 3 years before the experimental proof of the existence of a solar wind.

Skylab in 1973 initiated CME research

The most popular astronomical picture in history:
a huge prominence, seen in the He I line (30.4 nm)

Some CMEs are spectacular, indeed!

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A unique observation by LASCO-C2.
Note the helical structure of the prominence filaments!

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A very fast interplanetary shock wave, as seen by Helios in 1978.

A look into the history of some terms:
Morrison, 1954    diffuse clouds of ionized hydrogen bearing a turbulent magnetic field
Piddington, 1958  diffuse clouds, “Gold’s bottles”
Gold, 1959       plasma clouds
Parker, 1959     coronal magnetic bottle
Schatten, 1970    bright plasma clouds
Brueckner et al., 1972 dense plasma cloud within a closed magnetic loop
Pinter, 1973     electron clouds leaving 10 Rs
Tousey, 1973     white light cloud
Shea et al., 1974 coronal transient phenomena
Gosling et al., 1974 mass ejections from the sun
Gosling et al., 1975 coronagraph observed mass ejections, coronal mass ejection events
Gold, 1976       solar mass ejection events
Hildner et al., 1976 CME for Cold Magnetic Enhancement (!)
Munro et al., 1979 mass ejection events
Munro et al., 1979 mass ejection events
Munro et al., 1979 mass ejection events
Michalski et al., 1980 solar mass ejection
Burlaga et al., 1981 magnetic loop, magnetic cloud
Burlaga et al., 1982 CME for Coronal Mass Ejection
Handshouse et al., 1984 definition of coronal mass ejection

A unique observation by LASCO-C2.
Note the helical structure of the prominence filaments!

Two small comets were evaporating near the Sun. A few hours later a huge ejection occurred. Coincidence?
A unique observation by LASCO-C2.
Note the helical structure of the prominence filaments!

Some CMEs are spectacular, indeed!

Most big CMEs show a characteristic 3-part structure:
- bright outer loop,
- dark void
- bright inner kernel

Fast CMEs drive interplanetary shock waves

A very fast interplanetary shock wave, as seen by Helios in 1978.

These are typical CME products in the interplanetary medium:
- no more 3-part structure,
- just shocked “sheath” plasma (compressed and heated),
- and sometimes “driver gas”

What, actually, is a CME?
Definition of terms:
1. A coronal mass ejection (CME) is an observable change in coronal structure that
   occurs on a time scale of a few minutes and several hours and
2. involves the appearance (and outward motion, RS) of a new, discrete, bright, white-light
   feature in the coronagraph field of view.” (Handshouse et al., 1984, similar to the
   definition of “mass ejection events” by Munro et al., 1979).

The term “CME” was not introduced until 10 years after their discovery. I would prefer to call them SMEs, that avoids confusion...
Here comes a "balloon-type" CME, observed by LASCO-C1, on June 21, 1998. It also shows the characteristic 3-part structure: bright outer loop, dark void, bright inner kernel. This balloon took some 30 hours to finally take off! It was the offspring of an eruptive prominence. It ran away at about the slow wind speed, probably no shock was associated with it.

Initiation of a balloon type CME

It is hard to tell when this event really started!

Limb CMEs and „halo” CMEs

A series of dramatic CMEs observed by LASCO C3 on SOHO. Halo CMEs, if pointed towards (not away from!) the Earth, may cause disturbances of the Earth’s geomagnetism: Geomagnetic Storms, Space Weather.

Front or backside: a new quality from SOHO

Towards or away from Earth? That can only be decided using simultaneous disk observations.

In H-alpha, similar features had been seen long ago: "Moreton-waves". They are not the same.

Properties of CMEs, 1979 to 1981

A pressure wave (EIT wave) in the solar atmosphere, pushed by a flare on 7.4.1997. In conjunction, there was a halo CME launched towards Earth.

Statistical analysis of about 1000 CMEs observed by SOLWIND
Note the small number of slow CMEs! The increased sensitivity of the modern instrumentation has NOT increased the number of slow, faint CMEs.

Histogram of apparent front speeds of 640 CMEs, observed by LASCO on SOHO.

Properties of CMEs, 1996 to 1998

- The average width of all LASCO-CMEs is about 50°.
- If non-limb events were sorted out, the scatter would be less.
- Very few limb CMEs with widths of up to 180° occur. These are the real fast and dangerous "biggies".
- The average angular size did not change much with rising solar activity.

Apparent angular size of 840 CMEs

CMEs and shock rates during 2 solar cycles

- There is a clear maximum of CME and shock occurrence at maximum activity.
- Between minimum and maximum, the rates of both: shocks and CMEs vary by a factor of 10.
- The shock rate shows a double peak: maximum occurrence before and after the maximum.
- The ratio between CME and shock rates is 10.

The angular extent of shock fronts

- We can calculate the average cone angle $\alpha_{sh}$ of a shock front. It is
  \[
  \cos \frac{\alpha_{sh}}{2} = 1 - \frac{S}{2\pi R^2}
  \]
  with $S$ as the shock front surface at distance $R$ to the sun.

- We found that, on the long term average, $S$ is one tenth of the full solid angle $4\pi R^2$, thus, the ratio $S/(2\pi R^2)$ is 0.2, yielding
  \[
  \alpha_{sh} = 75°
  \]

Result: The average cone angle $\alpha_{sh}$ of shock fronts amounts to about 75°.

The daily rate of all CMEs and shocks seen by an in-situ observer.

The relationship between flares and CMEs

- Flares are localized short-duration explosions in the solar atmosphere, seen in visible light, EUV, X- and Gamma-rays.
- CMEs are large-scale expulsions of huge plasma clouds that may drive shock waves.
- Flares and CMEs often occur in close temporal context.

The simple but important conclusions from these studies:
Flares occurring after their associated CMEs cannot be their cause, quite logically.

Flares and CMEs are probably symptoms of a more basic "magnetic disease" of the sun.
Results from correlations between CMEs and interplanetary shocks:
- An observer within the angular span of a fast (>400 km/s) CME has a 100% chance to be hit by a fast shock wave,
- Every shock (except at CIRs) can be traced back to a fast CME.

These shocks and the driver gases following them have a near 100% chance of becoming geo-effective, if ejected towards Earth.

Note: no such statement applies to flares!

Indeed: there are flares without CMEs (and geo-effects) and there are CMEs (and geo-effects) without flares.

The modern paradigm

CAUSE AND EFFECT IN SOLAR-TERRESTRIAL PHYSICS
- Evolving solar magnetic field
- Instability, buoyancy?
- Coronal mass ejection
- Unstable mass ejection
- Interplanetary shock
- Particle acceleration
- Magnetic cloud
- Geomagnetic storm
- Auroral event
- Delay: 1-4 days

However, the very big events have everything: flares, radio bursts, CMEs, shock waves, energetic particles, etc., within a few minutes. Causes and effects? Remain to be disentangled...

Models, sketches, ideas on CME onset...

There are several scenarios being sketched. In order to decide which one applies, we need precisely timed multi-wavelength (interdisciplinary?) observations!

Ejected plasma clouds in space

Model showing the possible large-scale geometry of the MC observed by Helios 2 and IMP/SEE in April 1979.
This cloud contains "bidirectional electrons", evidence for magnetic cut-off

A typical "magnetic cloud" following a fast shock wave.

Typical CME products in the interplanetary medium:
- just shocked "sheath" plasma (compressed and heated),
- and sometimes "driver gas", incl. magnetic clouds,
- no more signs of 3-part structure, in general.

The signatures of plasma clouds/driver gas with respect to the ambient solar wind:
- ion and electron temperature depressions,
- tangential discontinuities in density, temperatures, and field,
- helium abundance enhancements (up to 30 \%),
- unusual ionization states (Fe$^{16+}$, He$^+$, etc.),
- counterstreaming of energetic electrons and protons,
- magnetic cloud signatures: anomalous field rotation, strong magnetic field, very low plasma beta, low variance of the magnetic field.

Usually, only a subset of these signatures is observed.

Open questions about flares, CMEs, and shock waves

A catalog of ignorance...

- What are the warning signs of an upcoming CME?
- What is the role of reconnection: trigger, driver, or consequence?
- Are there different types of CMEs?
- What are the relative roles of the CME shock and the flare shock?
- Solar energetic particles: are they transported around the Sun or are they locally accelerated?
- Where and how is the 3-part structure (often seen at CMEs but rarely in-situ) lost?
- How far around the sun do shocks reach, and why?
- ...
- and many others!