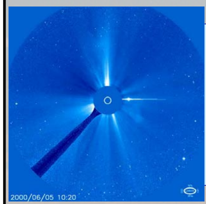
Physics of the heliosphere: an introduction

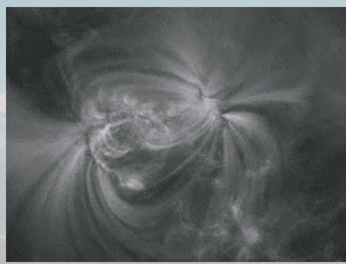
Lectures at the
International Max-Planck-Research School
Oktober 2002
by Rainer Schwenn, MPAe Lindau



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

Flares and the begin of space weather research

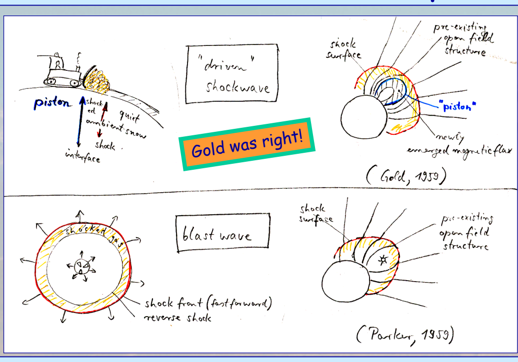


A solar flare, as observed by **TRACE**

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:

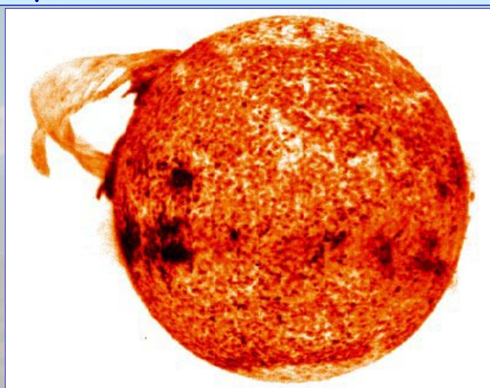
"...one swallow does not make a summer!"

„Collisionless" shocks in the heliosphere?



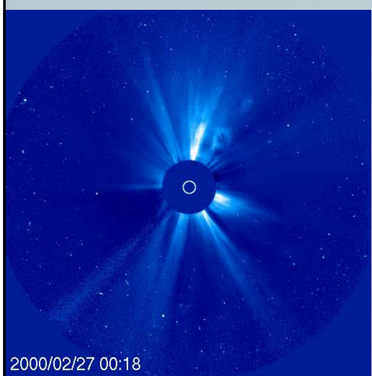
The famous battle Gold vs Parker about shocks in the heliosphere: piston driven shocks vs blast waves?
It began in the late 1950s, i.e. 3 years before the experimental proof of the existence of a solar wind!

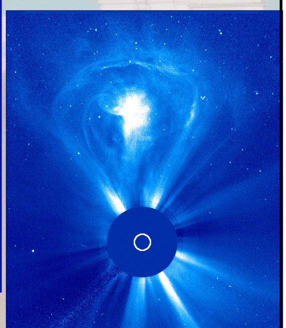
Skylab in 1973 initiated CME research



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

Some CMEs are spectacular, indeed!





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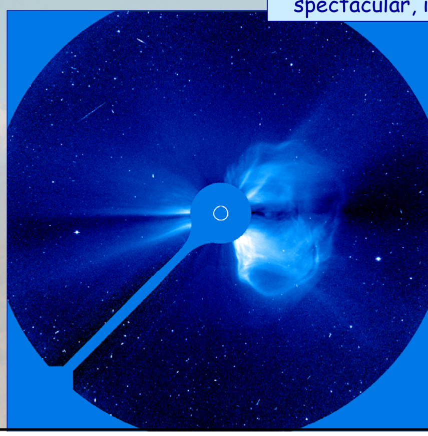
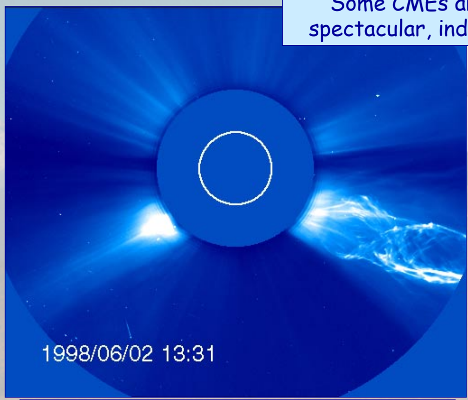
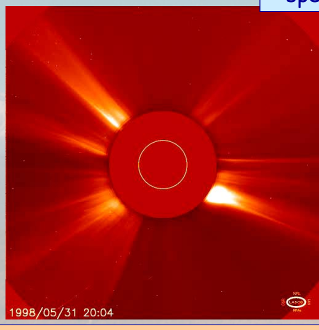


Some CMEs are spectacular, indeed!



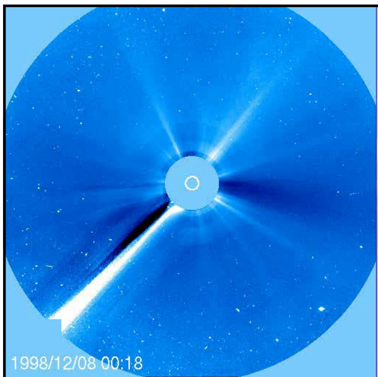
A unique observation by **LASCO-C2**.
Note the helical structure of the prominence filaments!

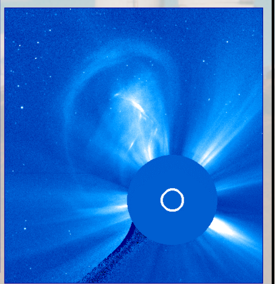
Some CMEs are spectacular, indeed!



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!

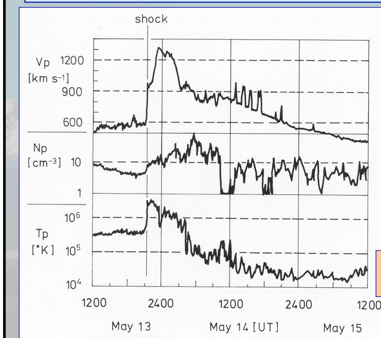




Most big CMEs show a characteristic 3-part structure:

- bright outer loop,
- dark void
- bright inner kernel

Fast CMEs drive interplanetary shock waves



Some shocks literally shake up the whole heliosphere!

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"

A look into the history of some terms:

Morrison, 1954	diffuse **clouds** of ionized hydrogen bearing a turbulent magnetic field
Piddington, 1958	ejected **magnetic clouds**
Gold, 1959	magnetized clouds, "Gold's bottles"
Parker, 1959	plasma clouds
Schatten, 1970	coronal magnetic bottle
Brueckner et al., 1972	bright plasma clouds
Pinter, 1973	dense plasma cloud within a closed magnetic loop
Tousey, 1973	electron clouds leaving 10 Rs
Stewart et al., 1974	white light cloud
MacQueen, 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**
Hildner et al., 1975	mass ejection coronal transients
Gosling, 1976	**solar mass ejection events**
Burlaga et al., 1978	CME for Cold Magnetic Enhancement **(!)**
Munro et al., 1979	mass ejection events
Michels et al., 1980	solar mass ejections
Burlaga et al, 1981	magnetic loop, magnetic cloud
Burlaga et al., 1982	**CME for Coronal Mass Ejection**
Hundhausen et al., 1984	definition of coronal mass ejection

The term "CME" was not introduced until 10 years after their discovery!

The definition of a CME

What, actually, is a CME?

Definition of terms:

"We define a coronal mass ejection (CME) to be an observable change in coronal structure that

(1) 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." (Hundhausen et al., 1984, similar to the definition of "mass ejection events" by Munro et al., 1979).

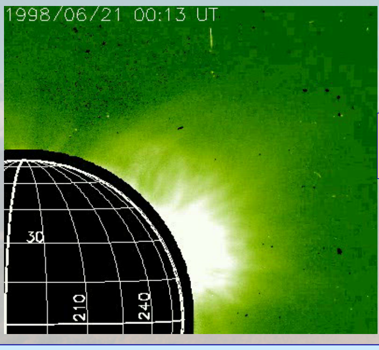
CME: coronal -------- mass ejection,
not: coronal mass -------- ejection!

This definition is very fortunate in that

- it emphasizes the observational aspect,
- it stresses the transient event character,
- it does not infer an interpretation of the "feature" and its potential origin,
- in particular, it does NOT infer any conjunction with "coronal mass", in contrast to what the term CME itself does.
- it restricts the applicability of the term to the sun's proximity.

I would prefer to call them SMEs, that avoids confusion...

CME properties vary widely



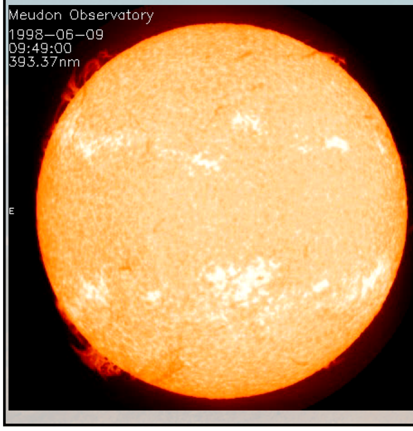
Here comes a "balloon-type" CME, observed by **LASCO-C1**, on June 21, 1998.

It also shows the characteristic 3-part structure:

bright outer loop,
dark void
bright inner kernel

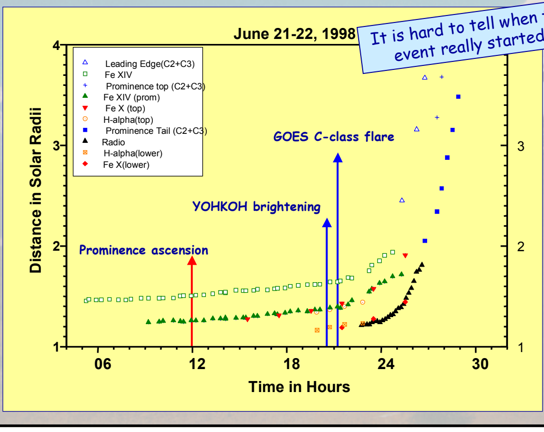
This balloon took some 30 hours to finally take off!
It was the offspring of an eruptive prominence. It ran away at about the slow wind speed, probably no shock was associated with it.

CME properties vary widely



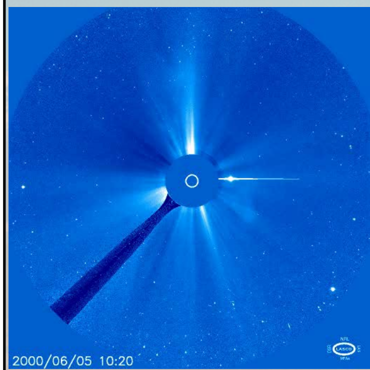
The filament had been observed in H-alpha and the K-line during its complete journey across the disk, before it finally erupted and led to the balloon type CME on June 21, 1998

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**.

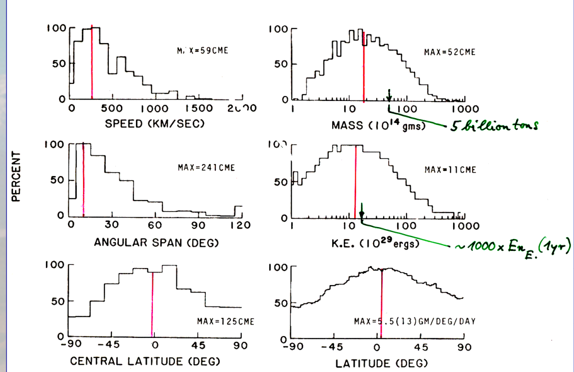
Front or backside: a new quality from SOHO

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

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.

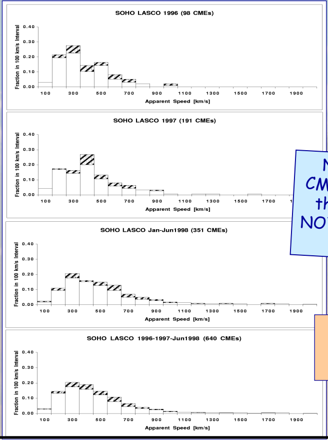
In H-alpha, similar features had been seen long ago: "Moreton-waves".
They are not the same!

Properties of CMEs, 1979 to 1981



Statistical analysis of about 1000 CMEs observed by **SOLWIND**

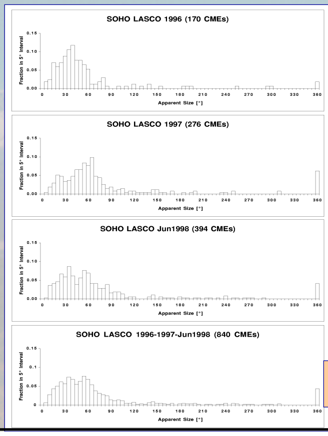
Properties of CMEs, 1996 to 1998



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**

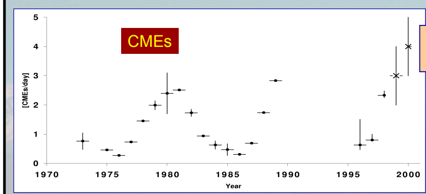
Properties of CMEs, 1996 to 1998



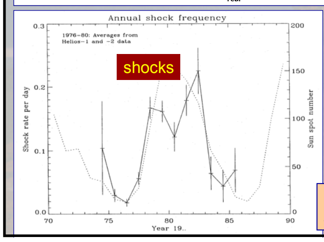
- The average width of all LASCO-CMEs is about 50⁰.
- If non-limb events were sorted out, the scatter would be less.
- Very few limb CMES with widths of up to 180⁰ occur. These are the real fast and dangerous „biggies".
- The average angular size did not change much with rising solar activity..

Apparent angular size of 840 CMEs

CMEs and shock rates during 2 solar cycles



The daily rate of all CMEs



The daily rate of shocks seen by an *in-situ* observer

- There is a clear maximum of CME and shock occurrence at maximum acticivty.
- 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 α_{sh} of a shock front. It is

$$\cos \alpha_{sh}/2 = 1 - S/(2 \pi R^2)$$

with S as the shock font 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

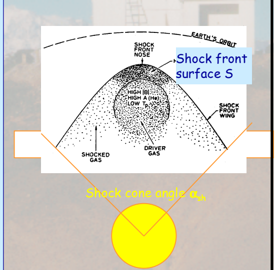
$$\alpha_{sh} = 75^0$$

Result: The average cone angle α_{sh} of shock fronts amounts to about 75⁰.

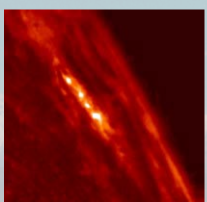
Compare that to the average cone angle of CMEs which is only 50⁰. In other words:

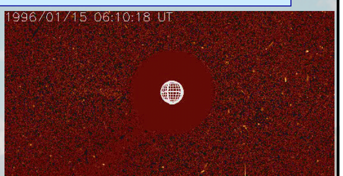
Shock fronts extend much further than the ejecta!

Q.e.d.

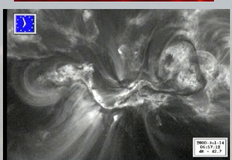


The relationship between flares and CMEs





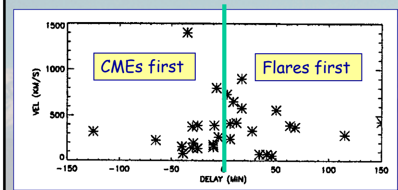
The CME of Jan 15, 1996, as seen by LASCO-**C3** on **SOHO**



The „Bastille" flare, on July 14, 2000

- 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.

CME-flare relation, a hen-and-egg situation?



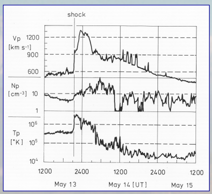
Time separation between flares and correlated CMEs

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.

The flares vs CMEs controversy,
problematic for space weather predictions

Since Skylab/Helios times we learned to look for CMEs/shocks/ejecta rather than for flares as has been common for the past 130 years.



Results from correlations between CMEs and interplanetary shocks:

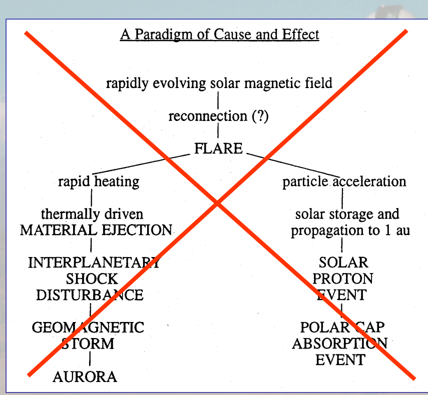
- an observer within the angular span of a fast >400 km/s) CME has a 100% chance to be hit by a fast shock wave,
- every shock (except at CIRs) can be traced back to a fast CME.

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

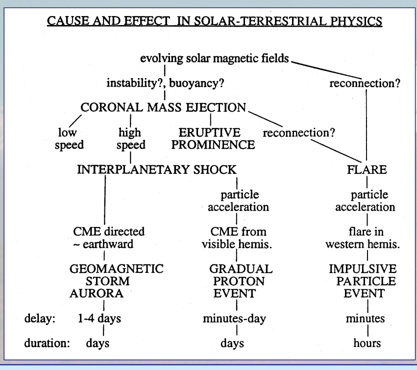
Note: no such statement applies to flares!

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

The "old" paradigm: the "solar flare myth"

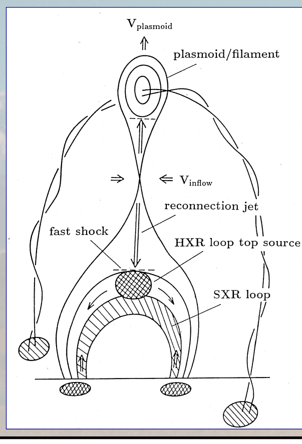


The modern paradigm



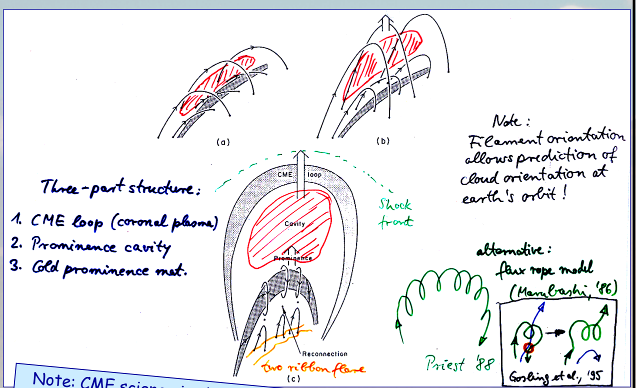
However, the very big events have everything: flares, radio bursts, CMEs, shock waves, energetic particles, etc, within a few minutes. Causes and effects? Remain to be disentangled...

Models, sketches, ideas on CME onset...



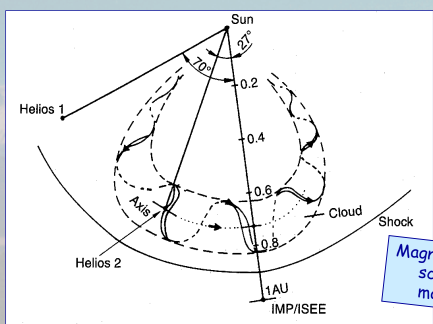
There are several scenarios being sketched. In order to decide which one applies, we need precisely timed multi-wavelength (interdisciplinary?) observations!

Models, sketches, ideas on CME onset...



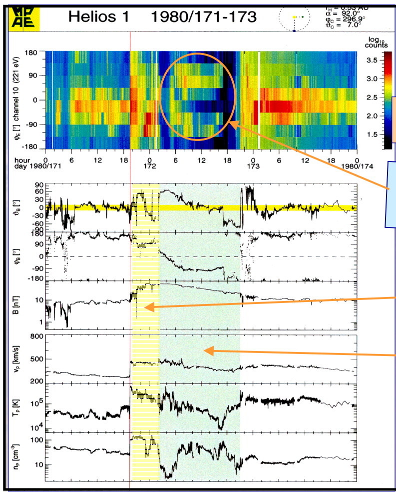
Note: CME science is also a field for creative artists...

Ejected plasma clouds in space



Sketch showing the possible large-scale geometry of the MC observed by Helios 2 and IMP/ISEE in April 1979 (see Fig. 10) based on results of the MVA of the magnetic field data. Helios 1 did observe the shock, but not the MC. *Arrows* denote the orientation of the magnetic field lines at the cloud's outer boundaries and on its axis

Magnetic clouds imply large-scale rotations of the magnetic field vector



Ejected plasma clouds in space

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

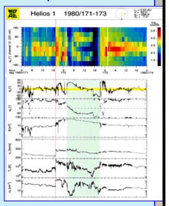
This cloud contains "bidirectional electrons", evidence for magnetic cut-off

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!

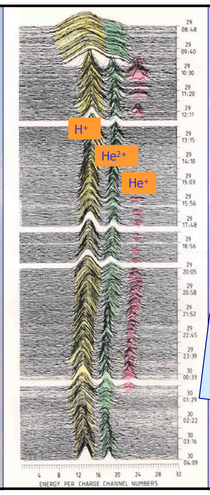
Ejected plasma clouds in space

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,
- counterstreaming of suprathermal electrons (BDEs),
- 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.



Ejected plasma clouds in space

Discovery of singly ionized Helium ions in the driver gas following an interplanetary shock wave by **Helios 1** in January 1977: remnants of cold prominence material.

There was only one more such event in July 1977. The next one occurred not earlier than in January 1997, following the halo event on Jan. 6th.

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!

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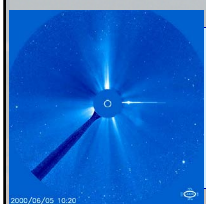
Lectures at the „Escuela Mexicana de Astrofísica 2002"
July 31 to Augst 7, 2002
by Rainer Schwenn, MPAe Lindau



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