A Historical Perspective on Coronal Mass Ejections

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The concept of mass leaving the Sun was thought possible over 100 years ago from the observations of prominence material that was seen to be moving outward at speeds in excess of the escape velocity. While the direct observation was elusive, the coupling between solar activity and geomagnetic storms became quite apparent. In the 1940's the concept of corpuscular radiation from the sun was proposed and then in the 1950's used to explain the discontinuity in a comet tail. Parker's theory in 1957 predicted a continuous outflow from the sun that was then observed by in-situ spacecraft less than 10 years later. The first optical observations of a transient event showing mass moving through the solar corona in 1971 were accompanied by excitement, fascination and speculation. Two questions at that time were: What causes the CME eruption? What is their significance? These questions and others are still with us. In this paper, the coronal mass ejection is viewed in its historical context.

INDIRECT OBSERVATIONS

Coronal mass ejections are large eruptions of mass and magnetic field from the Sun. Although only discovered in the early 1970's (Tousey, 1971, MacQueen, 1974), the effects of CMEs have been seen indirectly at Earth for many thousands of years. The impact of a CME on the Earth can generate an aurora. Such aurorae were reported in ancient literature in both eastern and western cultures, including the Old Testament, Greek and Chinese literature, and must have been a source of awe, fright and indeed wonderment. They have also been an inspiration for paintings and woodcuts for centuries. While common at northern latitudes such as here in Turku, they would have been quite rare in the most of the regions contributing to this literature. Figure 1 is a composite of a variety of auroral pictures.

The next major milestone was the discovery that the Earth had a magnetic field. The earliest indication of the existence of a geomagnetic field is from the Chinese in the 11th Century. They recognized that certain stones, "lodestones", had a strange property in that they could attract other substances.

Further, an iron needle stroked with such a stone would always point in the north-south direction when freely suspended. The concept of the compass spread to Europe and was used by Christopher Columbus in his voyage across the Atlantic in 1492.

Figure 1. Composite of Auroral Images

In 1600, William Gilbert published a treatise on the magnetic properties of the Earth, "De Magnete". By postulating the Earth's magnetic field, he was able to explain the behavior of the compass to always point along the same direction.

Then in 1722, George Graham noticed that the compass needle would suddenly change its direction of pointing by a small angle and would remain that way for up to several days. About 20 years later, Anders Celsius and his student Olaf Peter Hiorter discovered the diurnal variation of the Earth's magnetic field fluctuations and that the occurrence of the aurora were correlated to magnetic field deflections.

As a result of these discoveries, Baron Alexander van Humbolt in 1836 called for a worldwide network of magnetometers to be established to record global magnetic fluctuations. In the 1840s van Humbolt called such disturbances "magnetic storms" and associated such periods with the occurrence of the aurora. In 1852, Sir Edward Sabine showed that geomagnetic variations are a world-wide phenomenon.

SOLAR ACTIVITY CYCLE

In 1609 Galileo Galilei modified a design for a telescope to produce one of excellent quality that could see the moons of Jupiter, the phases of Venus and the surface of the moon, a capability that was not matched for several years. But he also turned it to the Sun and charted the location and numbers of sunspots, which had been done with the naked eye by the ancient Chinese. The use of the telescope for looking at the heavens marked the beginning of a new era of astronomy. The interest in tracking sunspots continued for a few more years, but then they virtually disappeared between 1645 and 1715, during what is now known as the Maunder minimum.

Sunspot tracking resumed in earnest, after Heinrich Schwabe, an amateur astronomer in Dessau Germany, reported in 1843 on his observations of a cycle in the number of sunspots. He measured the number of sunspots over a period of 17 years beginning in 1826. His paper was noticed by the Swiss astronomer, Rudolf Wolf (1851), who in 1847 then began recording sunspots, and computing the Zurich sunspot number, still in use today.

In 1852 Sabine showed that global magnetic fluctuations synchronized with the sunspot cycle. This relationship is shown in Figure 2, which demonstrates the excellent correspondence of the periodicity of the Zurich sunspot number with geomagnetic activity.

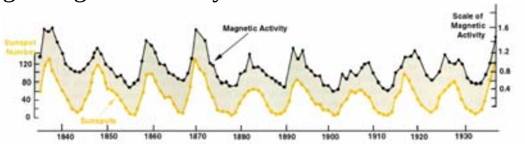

Figure 2. Comparison of Magnetic Activity and Sunspot Number

In the late 1800's and early 1900s, E. Walter Maunder was studying the relationship of solar phenomena to geomagnetic storms. In 1892 and more fully in 1904, he stated that the rare, large geomagnetic storms are associated with large sunspots near the center of the visible disk, but that for smaller sunspot groups the association broke down. Later in 1904, he found that many geomagnetic storms occur at 27-day intervals. H. W. Newton (1943) found an association between large solar flares and geomagnetic storms. He studied 37 large flares and found that a storm followed 27 of the largest ones within 2 days of the flare as long as the flare was within 45º of the central meridian.

SOLAR PLASMA EMISSION

The idea of corpuscular radiation being expelled from the Sun became advanced in the early 1930s. Chapman & Ferraro (1930) proposed that the Sun ejected a neutral plasma associated with eruptive solar prominences. The direct evidence for corpuscular emission from the Sun came from an analysis of the orientation of comet tails (Biermann, 1951). The orientation was consistent with a wind blowing continuously away from the Sun.

Eclipse observations have been carried out for thousands of years. During the eclipse of 1860 over Spain the drawing in Fig. 3 was made by G. Tempel. Eddy (1974) showed that those observers to the east of Tempel's location did not record any structures other than streamers, but those in the approximate location of Tempel drew similar structures. While such drawings were probably greeted with derision, we now know that it could have been a coronal mass ejection.

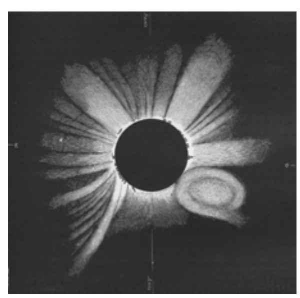

Figure 3. 1860 Eclipse Drawing Showing a Possible CME

Prominence eruptions from the limb of the Sun were commonly observed. It wasn't clear if the material escaped the solar atmosphere, especially since prominence material was seen to drain back. A significant observation of outward motion far from the Sun was observed at 80 MHz by the Culgoora radioheliograph (Riddle, 1970) and is shown in Figure 4. It was a moving type IV radio burst, which is emission from a dense plasma cloud.

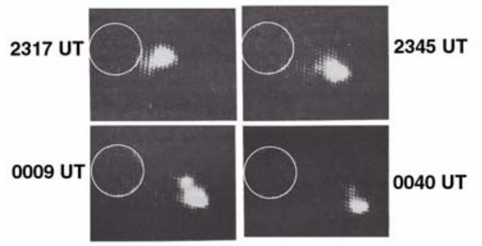

Figure 4. 80 MHz Radio Observation of an Expulsion of a Dense Plasma Cloud from the Sun on 1 Mar 1969

CORONAL MASS EJECTIONS

The advent of the space age saw the development of externally occulted white light coronagraphs. During the 1960s, balloon and rocket coronagraphs were observing the outer corona. Then in Sept. 1971, the first orbiting coronagraph was launched on OSO-7. Table 1 gives a chronology of the spaceborne coronagraphs, dates of operation, some characteristics, primary results and weaknesses.

Table 1. Spaceborne Coronagraphs

NASA Orbiting Solar Observatory 7 (1971-1973)
3.0 - 10 Rs; SEC Vidicon detector (3 arc min resolution)
First discovery of coronal transient (CME) 14 Dec 1971
Weakness - 4 full images per day (~30 CMEs observed)
NASA Skylab (1973-1974)
2.0 - 6 solar radii; Film detector (5" resolution)
~100 CMEs observed, established importance (and beauty); statistics; associations
Weakness: limited film capacity, 3 short duration missions
USAF P78-1 (Solwind) 1979-1985)
Same characteristics as OSO-7
CME Statistics, solar cycle dependence, relation to shocks, first halo event
German Helios mission presented in-situ measurements of solar wind in quadrature to Sun-Earth line and had a zodiacal light photometer that provided the first detection of a CME in the inner heliosphere
Weakness: limited spatial resolution, field of view
NASA Solar Maximum Mission (SMM) (1980, 1984-1989)
1.6 - 6 solar radii
5 cm SEC Vidicon detector, (30 arc second resolution)
CME statistics, 3-part structure to CMEs
Weakness: quadrant field of view, cadence
ESA Solar and Heliospheric Observatory - SOHO (1995-)
EIT /LASCO provide wide field of view &dynamic range
EIT: UV Disk Imager, (2.5 arc sec pixels)
C1: 1.1-3 solar radii (5.6 arc sec pixels)
C2: 2.-7 solar radii (12 arc sec pixels)
C3: 4-32 solar radii (60 arc sec pixels)
CCD Imagers (1024 x 1024)
Initiation of CME, Helical flux rope model, shocks and CMEs, geomagnetic effects
Weakness: Cadence, single viewpoint

The first CME observed optically is shown in Fig 5. On 13-14 Dec 1971, a bright streamer in the southeast participated in the "coronal transient" that traveled outward at over 1000 km/s (Tousey, 1973).

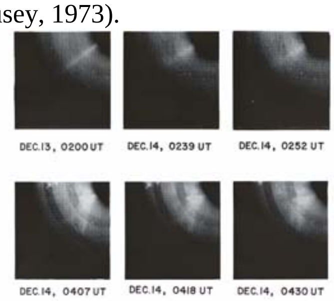

Fig 5. CME Observed on 13-14 Dec 1971

The OSO-7 and Skylab coronagraphs operated with some overlap between 1971 and 1974. The major discoveries from these instruments include:

- Discovery of mass expulsions escaping gravity – no material seen to fall back (Tousey, 1973; MacQueen et al., 1974)
- Relation to EPL: If a prominence reached 0.3R above the limb it always resulted in an eruption (Munro et al 1979)
- A good relation to solar activity cycle was established (Hildner, 1976)
- Kinematic properties identified (speed, size, mass) (MacQueen, 1980)
- Morphology: planar loops were in vogue
  - Attempt to use polarization to indicate depth (Crifo et al, 1983)
  - Orientation of loop-like CME to the orientation of filament
    - Supported planar CME(Trottet & MacQueen, 1980)
    - Supported shell CME (Webb, 1988)
- Flare associated (Rust et al., 1980)
- Modeled by MHD flare pulse (Wu & Han, 1974)

During the next decade two coronagraphs again were flying, one on the USAF Space Test Program P78-1 satellite and one on the NASA Solar Maximum Mission satellite. Both of these lasted much longer than the previous missions. The prototypical CME was observed on 18 Aug

1980 (Fig 6). In this event the three-part CME (Illing & Hundhausen, 1985) was identified in which the front is followed by a cavity of reduced density and a bright core. The bright core is likely to be prominence material. This became the prototypical CME structure.

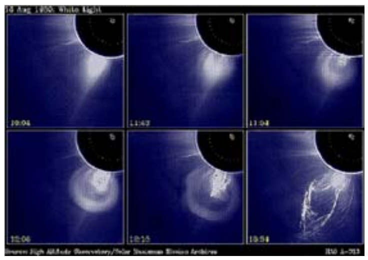

Fig 6. 3-Part CME on 18 Aug 1980

Another significant observation was the discovery of the “halo” CME on 27 Nov 1979 (Howard et al., 1982). Fig 7 shows in difference images a circular band of emission surrounding the occulting disk moves outward. It was followed by a geomagnetic storm a few days later.

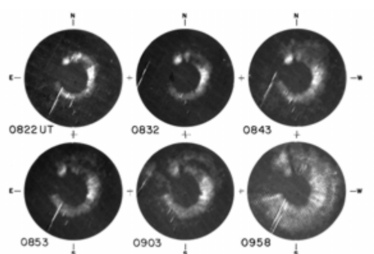

Fig 7. Halo CME on 27 Nov 1979

These instruments observed many CMEs over 9 years. Other significant results from the 1980’s instruments included:

- •Streamer blowout (Howard et al., 1985, Illing & Hundhausen, 1986)
- •Disconnection events (Illing & Hundhausen, 1983)
- •Associations with IP shocks, LDE X-ray, radio Type IIs, energetic particle emissions (Sheeley et al, 1985, 1983, 1984; Kahler, 1985)
- •Prominence associated events accelerate in low corona (with Mauna Loa K-coronameter) (MacQueen and Fisher, 1983)
- •Indirect evidence for acceleration in upper corona (Woo et al, 1985)
- •Association with SSN (Howard et al., 1985, 1986)
- •Rates as high as 3 per day (Howard et al., 1985)
- •Kinematics well established (speed, span, mass, energy) (Howard et al, 1985, Hundhausen et al., 1993)

The third decade has observations from the SOHO mission, launched in 1995. This has been the best mission for CME studies because of the increased resolution, dynamic range and cadence over previous missions, but also because of a large array of ground-based instruments. There are many results and they are still coming. I only list a few here.

- •More CME observations than all previous missions (Yashiro et al, 2004)
- •Acceleration profile (Howard et al., 1997), flux rope (Chen et al., 1997), interacting CMEs (Gopalswamy et al., 2001)
- •Established Halo CMEs source of geomagnetic storms (Gosling, 1993, Brueckner et al. 1998)
- •Higher Occurrence Rates (St. Cyr et al., 2000, Gopalswamy, 2004)

FUTURE

The next mission with a coronagraph will the NASA STEREO mission to be launched in 2006. The mission objective is to understand the 3D nature of CMEs, their initiation and propagation. A drawback of previous missions is that the observations of the optically thin Thomson scattering give little information on the distribution along the line of sight. Thus the internal structure of CMEs is uncertain.

STEREO will send two identically instrumented spacecraft into a heliocentric orbit, one leading Earth and one trailing. The instrument complement consists of optical and radio remote sensors as well as *in-situ* measurements of energetic particles and solar wind composition. Modeling must be used to determine the 3D structure and to couple the remote sensing to the *in-situ* observations. The spacecraft will drift away from Earth at an average rate of about 22º/year resulting in varying science objectives. At the end of the two-year nominal mission the spacecraft will be 90º from each other. In this orientation the coronagraphs from one spacecraft will observe the solar corona above the EUV disk observed by the other spacecraft.

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