# First tomographic view of coronal mass ejections

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*Much like a medical CAT (computerized axial tomography) scan, the first tomographic reconstruction of a coronal mass ejection (CME) is a breakthrough towards our better understanding of the generation and propagation of CMEs, which can produce violent 'space weather' events that can disable satellites and endanger astronauts.*

Spacecraft observations made with white light coronagraph on OSO-7 and Skylab in the early 1970s demonstrated that large quantities of material ($10^{15}$–$10^{16}$ g) are sporadically ejected from the Sun into interplanetary space[1–3]. Such transient ejections of material are known as coronal mass ejections (CMEs). They are among the most powerful eruptions in the solar system. There is a compelling body of observational evidence to believe that CMEs are launched when solar magnetic fields become strained and suddenly 'snap' to a new configuration. CMEs have very large dimensions, their angular size being about 45°. Thus they represent the disruption of closed magnetic structures along a huge part of the Sun's surface. These events propel magnetic clouds with a mass of up to $10^{17}$ g to speeds up to 2600 km/s into the heliosphere[4,5]. The nature and cause of CMEs is a fundamental, yet an unsolved problem. They are often associated with prominence eruptions and/or solar flares.

The Sun and Earth are a connected system. Electromagnetic radiation and electrically charged particles stream outward from the Sun (the solar wind), envelop the Earth, and interact with the Earth's magnetic field and terrestrial atmosphere creating an adverse environment. The main goal is to understand the changing flow of energy and matter throughout the heliosphere and planetary environments, thereby exploring the fundamental physical processes of space plasma systems. This ultimately defines the origins and societal impacts of variability in the Sun–Earth connection. There are two different types of events in the solar atmosphere that trigger disturbances in the Earth's environment. They are solar flares and CMEs. Energy released in a major solar flare is of the order of $10^{25}$ J which is comparable in strength to 20 million nuclear bombs, each blowing up with an energy of 100 megatons of TNT (one megaton of TNT is $4.2 \times 10^{22}$ ergs). A substantial fraction of this energy goes into accelerating electrons and ions to high (relativistic) speeds. These high energy particles go down towards the Sun or out in space, and they result in enhanced radio, soft X-ray, hard X-ray and gamma-ray radiation. Comparable amount of energy is released in expelling matter during a CME. The most dramatic space weather effects, however, are associated with CMEs. These eruptions (CMEs) are sometimes associated with solar flares, and sometimes not, and they now appear to be a primary cause of geomagnetic activity.

Many researchers tried to find, and discussed, differences between CMEs associated with flares and those without flares[6]. Observations from Yohkoh in X-rays and from SOHO and TRACE in ultraviolet reveal extensive arcades associated with CMEs (see Figure 2). An opening of magnetic field at the base of CME involves an extensive region on the Sun. When opening avoids any active region, no flare is seen. However, if it extends into an active

**Figure 1.** A schematic diagram of the interaction of the magnetic field of a coronal mass ejection with Earth's magnetosphere, which can produce spectacular auroral displays and knockout communication satellites. Credit: SOHO/EIT, ESA-NASA.

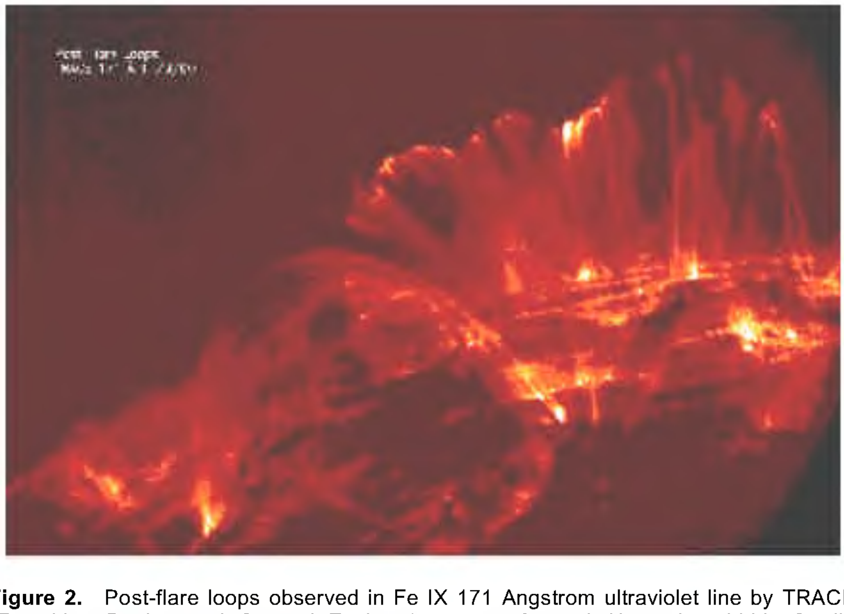

**Figure 2.** Post-flare loops observed in Fe IX 171 Angstrom ultraviolet line by TRACE (Transition Region and Coronal Explorer) spacecraft on 9 November 2000. Credit: TRACE-NASA.

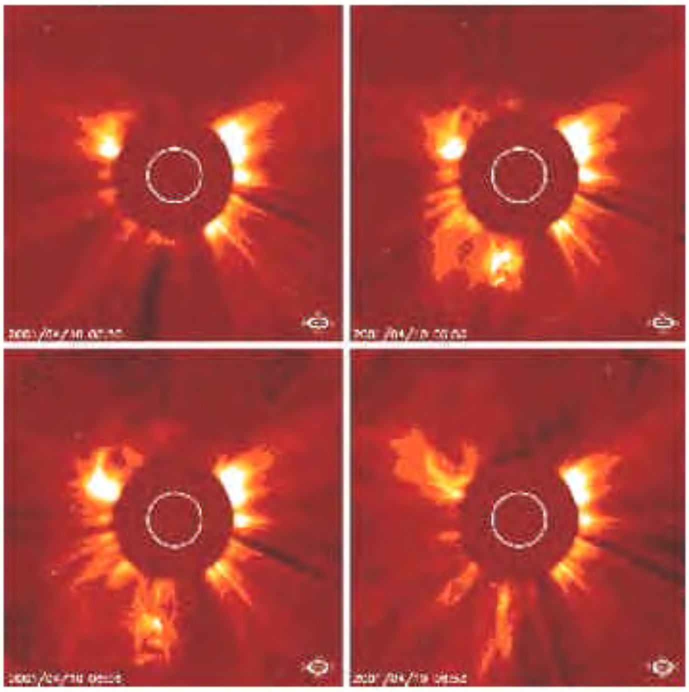

**Figure 3.** CME blast seen by LASCO C2 – An image sequence over 90 min of a large coronal mass ejection 10 April 2001 associated with an X2.3 flare. A CME blasts a billion tons of particles travelling millions of kilometers an hour into space. This CME impacted Earth about 36 h later and caused a severe geomagnetic storm. Credit: LACSCO/SOHO, ESA-NASA.

region, the subsequent closing field lines are seen as post-flare loops of an eruptive flare.

CMEs have been studied primarily from observations using ground-based and space-borne coronagraphs. Observation and interpretation of these events have continuously been carried out with the LASCO (Large Angle and Spectrometric Coronagraph) instrument on the SOHO[7] (Solar and Heliospheric Observatory) spacecraft since its launch on 2 December 1995. SOHO is located at the L1 Lagrangian point (the point 1.5 million kilometers away from us at which gravitational pull of the Earth balances that of the Sun). LASCO provides CME images of excellent quality (Figure 3), and reveals a variety of complex and diverse forms. The major limitation of CME observations to date has been a lack of three-dimensional structure and trajectory measurements. Speed and direction measurements would allow more accurate prediction of CME impacts, which would allow better planning of protective measures, such as attitude adjustment and astronaut shielding. In addition, three-dimensional measurements would yield insight into CME generation and permit additional tests of CME dynamical models.

To fully understand the origin of these powerful blasts and the process that launches them from the Sun, we need to see the structure of CMEs in three dimensions. Three dimensional (3D) view of a CME is critical for a complete understanding of CMEs to better predict its arrival times and impact angles at the Earth. Moran and Davila[8] have analysed two-dimensional images obtained from LASCO instrument on the SOHO spacecraft in a new way to yield 3D images. Their technique is able to reveal the complex and distorted magnetic fields that travel with the CME cloud and sometimes interact with Earth's own magnetic field, pouring tremendous amounts of energy into the space near Earth. These magnetic fields are invisible. Since the CME gas is electrified, it spirals around the magnetic fields, and traces out their shapes. Therefore, a 3D view of the CME plasma gives valuable information on the structure and behaviour of the magnetic fields that power the CME. The new analysis technique for SOHO data determines the three-dimensional structure of a CME by taking a sequence of three images from the LASCO through various polarizers, at different angles.

The Sun emits unpolarized light. When it is scattered off electrons in the CME plasma, it takes up some polarization. This means that the electric fields of some of the scattered light are forced to oscillate in certain directions, whereas the electric field in the light emitted by the Sun is free to oscillate in all directions. The light from CME structures closer to the plane of the sky which refers to the plane centered on the Sun and perpendicular to the Earth–Sun line (as seen on the LASCO images) had to be more polarized than light from structures farther from that plane. Thus, by computing the ratio of polarized to unpolarized light for each CME structure, one can measure its distance from the plane. This provides the missing 3D view to the LASCO images (Figure 4). With this technique, it has been confirmed that the structure of CMEs directed towards Earth is an expanding arcade of loops, rather than a bubble or rope-like structure. This technique is not new, and has been in use to study relatively static solar structures during eclipses. However, it is applied to fast-moving CMEs for the first time. This method will complement data from the upcoming NASA's Solar Terrestrial Relations Observatory (STEREO) mission, scheduled for launch in February 2006. STEREO will use two widely separated spacecrafts to construct 3D views of CMEs

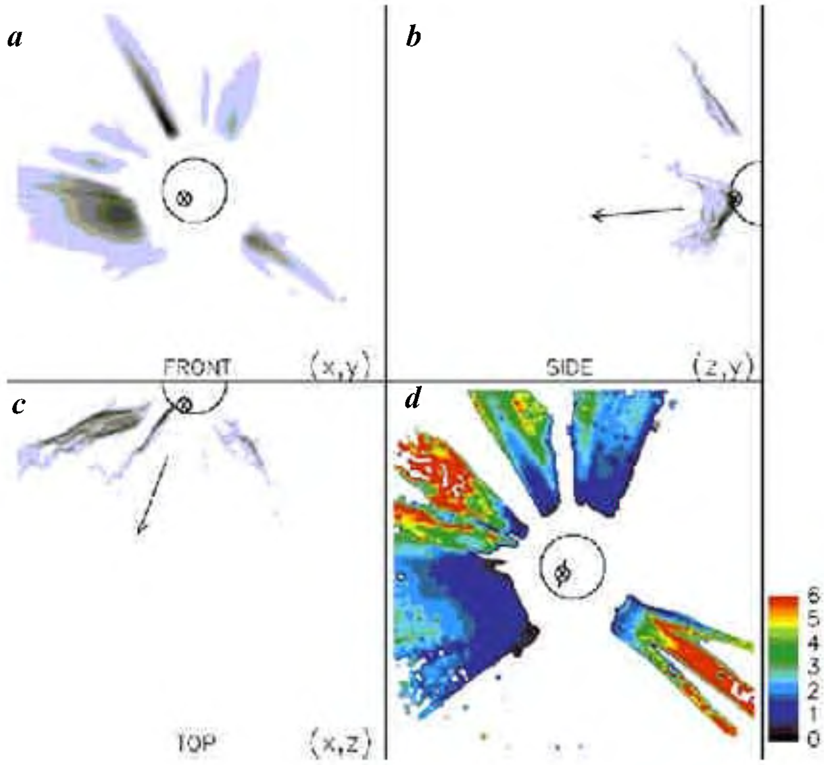


**Figure 4.** A CME heading almost directly towards Earth, observed by LASCO C2. The size of the Sun is indicated by a circle, and the x-marked circle on the Sun shows the origin of the CME. ***a***, Shows the total intensity (darker means more intensity) as imaged directly by LASCO. Only the narrow lower end of the 'lightbulb' shape is visible – the widest portion has expanded beyond the field of view, whereas the front part and the core are too dim to be seen or hidden behind the occulter. ***d***, A topographic map of the material shown in ***a***. The distance from the plane of the Sun to the material is colour coded – the scale in units of solar radii is shown on the side. ***b*** and ***c*** show the intensity as it would have appeared to an observer positioned to the side of the Sun or directly above it, respectively. Credit: T. G. Moran and J. M. Davila, LASCO/SOHO, ESA-NASA.

by combining images from different vantage points of the twin spacecrafts.

The polarization technique, STEREO imaging, and spectroscopic technique provide different ways of viewing CME structure and greatly enhance the capability of forecasting 'space weather', and unraveling the physical processes that drive CMEs.

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