Chapter 2
History

In this chapter we briefly review the history of CME observation and the scientific contributions to our understanding of these phenomena from those observations. Less emphasis has been placed on what the author considers to be secondary effects of the CME (e.g., radio bursts, solar surface activity, solar energetic particles). This is not to say that the study of these secondary effects has not made significant contributions to our understanding of the CMEs and to solar physics in general, much of which predates the discovery of the CME. In this chapter we address them only in their early historical context, and mostly before the CME was directly observed since this was the way by which CMEs were eventually identified.

2.1 Early Years of Solar and CME Observation

Early studies of the solar corona date back to antiquity: the first recording of the solar eclipse was in 1223BC [229]; and the first identification of the solar corona was probably in 968AD [73]. The first observation of a CME, however, probably didn't occur until the mid-nineteenth century when the corona was being studied in great detail for the first time. Until the coronagraph was invented in the 1930s, coronal studies were limited only to during solar eclipses when the moon temporarily blocked out the bright solar photosphere. It is therefore not surprising that CMEs, which only occur a few times day, were not observed during previous eclipses, which only last a few minutes when observed from any fixed location. The first picture of a CME is probably from the drawing reproduced in Fig. 2.1. This is a drawing of the eclipse observed on 18 July 1860 in Torreblanca (Spain). Toward the southwest (lower-right) of the image appears to be a bubble-shaped structure that is disconnected from the Sun and remaining corona. Drawings of the same eclipse by other workers also reveal an extended structure in this region of the Sun. Such a structure in the solar corona would not be observed again for 100 years, and none realized the significance of that observation at the time.

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Fig. 2.1 Drawing of the 1860 eclipse recorded by Tempel [174] and identified later by Jack Eddy. This is believed to be the first observation of a coronal mass ejection

In 1852, Edward Sabine and other workers "absolutely" connected the 11-year sunspot cycle with geomagnetic activity [183,186]. In 1859 a powerful flare erupted from a large active region on the Sun and 18 h later the most intense recorded magnetic storm in history, the Carrington Event (Carrington Storm [22]) occurred at Earth, causing telegraph systems to fail across Europe and North America (see Sect. 1). Contemporary estimates of the Dst index for the Carrington Event range from $-1{,}600$ [205] to -850 nT [191]. Associations between flares and geomagnetic storms continued in the following decades, although the relationship was not one-to-one. For example, Maunder [151] and Greaves and Newton [58,59] showed that the most intense geomagnetic storms were usually accompanied on the Sun by groups of large-area sunspots. In 1931, Chapman and Ferraro [24–26] proposed that this correlation could be explained if there was a sporadic ejection of ionized material from the Sun.

2.2 Early Ground Measurements of CME Signatures

In the decades leading to the space age, investigations of the interplanetary counterparts of solar eruptions were being investigated via the energetic particles being accelerated by them and arriving at the Earth, and via their radio signatures. Scott Forbush in 1946 noted bursts of cosmic ray intensity at the Earth that he associated with energetic particles arriving from the Sun [40]. Solar energetic particles, or SEPs were immediately associated with solar flares and with variable magnetic fields around sunspots [41]. These ground level cosmic ray enhancements, or GLEs (ground level enhancements), were later detected by neutron monitors in 1956 [154] and riometers in 1959 [175]. SEPs were described by John Wild and co-workers in 1963 to be accelerated by two stages: Flare acceleration up to $\sim$100 keV of electrons, and then a second-level acceleration process caused by an outward-moving fast magnetohydrodynamic (MHD) shock [221]. This two-stage acceleration was confirmed using in-situ observations through the 1980s and 1990s [60].

The construction of the first radiospectrograph at Penrith in New South Wales (Australia) in 1950 enabled the study of solar-related radio bursts. These were classified into three types: Type I bursts were short-lived, narrowband, and occurred during magnetic storms; Type II bursts were longer in duration, accompanied solar flares at the Sun and drifted gradually in frequency; while Type III bursts were short-lived and broadband, where the frequency of maximum intensity drifted rapidly [217]. A fourth type of burst event, designated Type IV, was identified later in 1957 by workers using an interferometer at the Nançay observatory in France [7]. They were long-duration, associated with solar flares, and often followed a Type II burst. Type V bursts, which often followed Type III, were identified in 1959 [220]. From McLean and Labrum [153]:

> The observations of Type II and Type III bursts contributed significantly to the developing subject of solar flare 'anatomy' (Wild et al. 1954b) [219]. It was found repeatedly that groups of Type III bursts occurred at the very start of flares, coincident with the arrival of X-rays as signified by the onset of sudden ionospheric disturbances. The Type II burst, if one occurred, began some minutes later. (pp. 12–13 [153])

It is from Type II radio bursts that the first height-time plots of CMEs were indirectly plotted. Figure 2.2 provides an example of such a plot from Wild et al. [218]. Type II bursts are manifestations of interplanetary shocks, and so these measurements were related to the shock rather than the CME itself. Nonetheless, these measurements did provide indicators of CME speeds in the heliosphere 20 years before their discovery in coronagraphs.

2.2.1 CME Observations in the Early Space Age

The launch of *Sputnik-1* in 1957 began the space age but CME signatures in interplanetary space were not measured until spacecraft left the Earth's magnetosphere. It was expected that interplanetary forward shocks would be observed, following a suggestion by Thomas Gold in 1955 that high-speed plasma ejected from the Sun would produce a collisionless shock in the interplanetary medium [46]. Indeed, a forward shock was directly observed in interplanetary space in 1962 by the *Mariner 2* spacecraft [192]. A further two were later reported in 1968 by Jack Gosling and

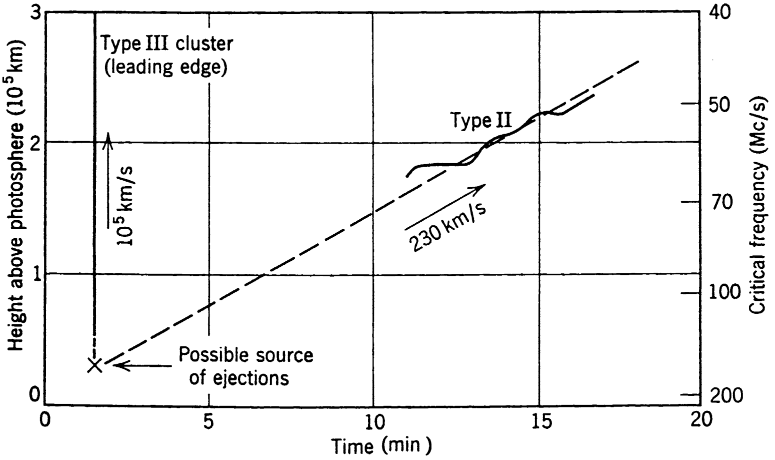

Fig. 2.2 An early example of a height-time plot, derived from Type II and Type III bursts [218]. This plot results in a speed of 230 km/s

co-workers using the *Vela 3* spacecraft pair [51]. Hundhausen et al. [106] used solar wind observations of shock disturbances to estimate that a large shock was associated with an ejection of 10^{13} kg and 10^{32} ergs from the Sun. By the year that the CME was discovered in coronagraphs (1973), several publications had emerged reporting interplanetary shock observations [34, 103, 104, 112, 113, 135, 167, 201], and many were associated with geomagnetic activity. Hence by the discovery of the CME, the theory of the formation and propagation of interplanetary shocks was firmly established, and had been confirmed with direct observation using in-situ spacecraft. They were associated with eruptions from the Sun (then mostly believed to be solar flares), and were known to cause increases in geomagnetic activity, particularly in the form of a sudden-(storm)-commencement, or S(S)C.

The first measurements of the ionic composition of the plasma following interplanetary shocks, made in 1972, revealed a helium abundance enhancement (HAE) [81]. The association of HAEs with solar flares had already been made a few years prior [4, 134]. Following a statistical study in which 73 cases of helium abundance enhancements (HAEs) were measured, it was suggested by Borrini et al. [8, 9] that HAEs were the interplanetary signatures of CMEs. High ionization states of oxygen and iron following interplanetary shocks were detected in 1979 [5, 38]. This provided information on the thermal state of CMEs, indicating that they were typically hotter than the surrounding solar wind. Other ions and temperature measurements followed, including magnesium and neon, further suggesting the presence of filament material or dense plasma from the low corona or chromosphere [9].

2.2.2 Interplanetary Scintillation

Sometime in the 1960s (probably 1964 [77]), Tony Hewish and co-workers at Cambridge University discovered that radio signals from distant sources (of the order of 100 MHz) fluctuated as a result of variations in the interplanetary medium. They showed that this interplanetary scintillation (IPS) can monitor the density of the solar wind (for a review of early work, refer to W. A. Coles [28]. Chapter 6 of the introductory text on CMEs by the author [93] provides a review of IPS.) By the time of discovery of the CME in 1973, several papers on this detection had appeared [76, 83–85]. It was not known at the time whether the transients observed were the same ones observed in the low corona, but it was clear that these were dense structures moving through the interplanetary medium between the Sun and the Earth.

By 1978 several interplanetary transients had been detected using IPS. Houminer and Hewish [84,85] investigated density enhancements in the interplanetary medium that were at low solar latitudes and appeared to co-rotate with the Sun. Watanabe and co-workers [210, 211] reported on disturbances in the interplanetary medium which they attributed to flare shock waves. Interplanetary scintillation and proton density observed by the *Pioneer 6* and *7* spacecraft from January to April 1971 were found to be strongly correlated by Houminer and Hewish [86], and a relationship with the geomagnetic A_p index was also confirmed [86, 206–208]. Three transients were identified using IPS by Rickett [180] and these were correlated with *Pioneer 9* and *HEOS-2* at the Earth [180]. It should be noted that we use the word "transient" in a cautionary fashion here. Many of these early events were more likely the result of enhanced density regions of the Sun brought about by the merger of fast and slow solar wind streams, phenomena now known as corotating interaction regions (CIRs). Such structures corotate with the Sun but are time-stationary in structure, and so the term "transient" does not really apply. Vlasov identified two types of large-scale perturbations moving away from the Sun from 0.3 to 1.2 AU away from the Sun; those which vary over times of the order of 24 h (CMEs), and those that existed for several days (CIRs) [206].

Positive identifications of CMEs using IPS were made from 1978, when the radio telescope in the UK was upgraded. This enabled more radio sources to be monitored, thereby increasing the spatial resolution of the maps produced by IPS. This, along with coronagraph observations that were available by that time, allowed the first comparison of IPS transients with coronagraph CME images. Figure 2.3 shows an IPS map with a CME from 19 September 1980 from Tappin [195]. Each square on this figure represents a radio source and the red squares are those from which an increase in density has been identified. Later papers by Hewish and co-workers appeared that associated IPS CMEs with solar surface features, but most of those were low-latitude coronal holes [74, 75, 87, 198]. Interplanetary shock studies using IPS were studied through 1981–1985 by Woo and co-workers, who associated them with blast waves from solar flares [224–226].

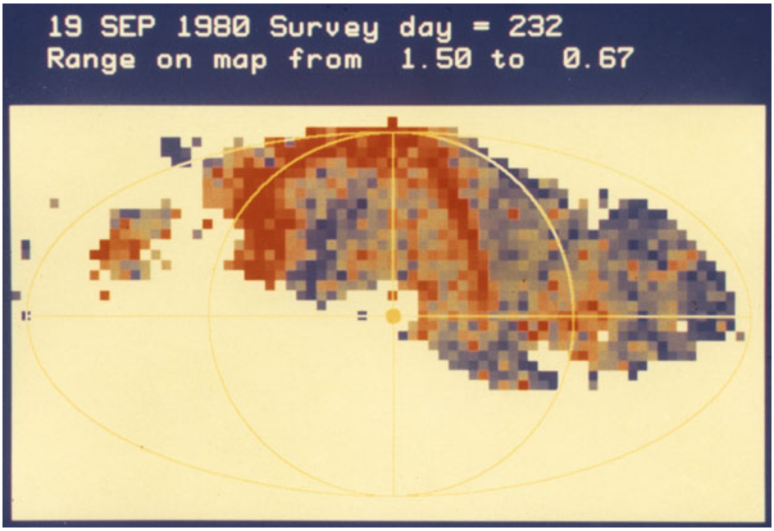

Fig. 2.3 IPS map of a CME from 19 September 1980. This is a Mollweide map with the Sun at the center and the 90° contour shown. Each *square* represents a radio source detected with the 3.6 Hectare Array and a *red square* indicates an increase in density (i.e., part of a possible CME) [195]

2.3 The Discovery of CMEs (1973)

The coronagraph was invented in 1931 by Bernard Lyot, allowing the continuous monitoring of the corona without the need to wait for a solar eclipse. This was achieved by permanently blocking the brighter light from the photosphere using a disk, known as an occulting disk [147]. It was not until decades later, however, that the sensitivity of the instrument was reduced to a level where faint coronal eruptions could be observed. This required spacecraft observation to identify them clearly, and workers then returned to ground data and identified them post-facto. The discovery of the CME is accredited to Richard Tousey, who identified transients moving with speeds of 400–1,000 km/s in the K-corona using *OSO-7* coronagraph observations. The discovery is reported in a review published in the Proceedings of the Fifteenth Plenary Meeting of COSPAR (*Space Research XIII*) in 1973 [203].

At around the same time, coronal disturbances were being monitored using the ground coronagraph at Sacramento Peak in New Mexico. These were reported by Howard DeMastus, Bill Wagner and Rich Robinson in the *Solar Physics* journal in 1973. They refer to a number of “fast green line events” or “coronal transients” observed on the solar limb from 1956 to 1972, and they attempted to associate them with other forms of solar limb activity [32]. By this time coronal transients had also been recognised by workers using the Mauna Loa coronagraph, with observations published the following year [44, 132]. It seems likely that all groups had observed manifestations of the same phenomenon.

The first direct association between interplanetary shocks and CMEs was made by Gosling et al. [53] by comparing a CME observed by the coronagraph on *Skylab* with an interplanetary shock detected by *Pioneer 9*. Other early works include Dryer [33], Burlaga et al. [15] and Michels et al. [156].

A total of 20 CMEs were observed by *OSO-7* before it re-entered the Earth's atmosphere in 1974 [89]. The US space station *Skylab* was launched in 1973, which carried a coronagraph. Around 77 transients were observed by *Skylab* from May 1973 to February 1974 [162], and they were immediately identified as mass ejections [52]. The first appearance of the term "coronal mass ejection" appears to be in Gosling et al. [54], although the term "mass ejection coronal transient" appears in Hildner [80]. Initially, workers preferred to adhere to the more conservative "coronal transient", and the coronal mass ejection term was initially reserved for a particular type of eruption observed, but over time this term was used in more general contexts. By 1990, virtually all workers were referring to all large ejecta observed with a coronagraph as a coronal mass ejection or CME.

Observations of CMEs continued into the 1980s with the launch of the US Department of Defense Test Program satellite *P78-1* in February 1979, and of NASA's *Solar Maximum Mission* (*SMM*) in February 1980. On board each, amongst an assortment of other solar instruments, was the Naval Research Laboratory's coronagraph *Solwind* [155], and NASA's coronagraph/polarimeter C/P [148]. Among the discoveries of this next generation of space-based coronagraphs was the first Earth-directed CME by Russ Howard and co-workers in [90]. The term "halo CME" arises from this publication. The "classic" three-part CME structure shown in Fig. 1.1 was also first identified by the *SMM* C/P in this era [111]. Figure 2.4 shows images of CMEs obtained by these early instruments.

This second generation of spacecraft coronagraph collectively observed over 2,000 CMEs, thereby enabling the detailed statistical analysis of their properties for the first time. Such studies include those by Hundhausen et al. [107], who reported that the location of the CME was more evenly distributed around the Sun than those observed by *Skylab* (which were localized around the equator), and Howard et al. [91] and Hundhausen et al. [108], who surveyed almost a thousand CMEs over 3 years and provided extensive statistical results on structure, mass, angular span, location and kinetic energy. Hence, by 1995 solar physicists had a good picture of CME occurrence, structure, speed, mass and energy via a detailed investigation of single events as well as statistical surveys.

2.3.1 Magnetic Clouds

In Sect. 1.4, we discussed the internal core of the CME as comprising a flux rope that is often measured near 1 AU as a highly structured magnetic spiral. This signature was first identified in 1981, when Len Burlaga and co-workers identified a smoothly rotating magnetic field vector following an interplanetary shock for a single CME

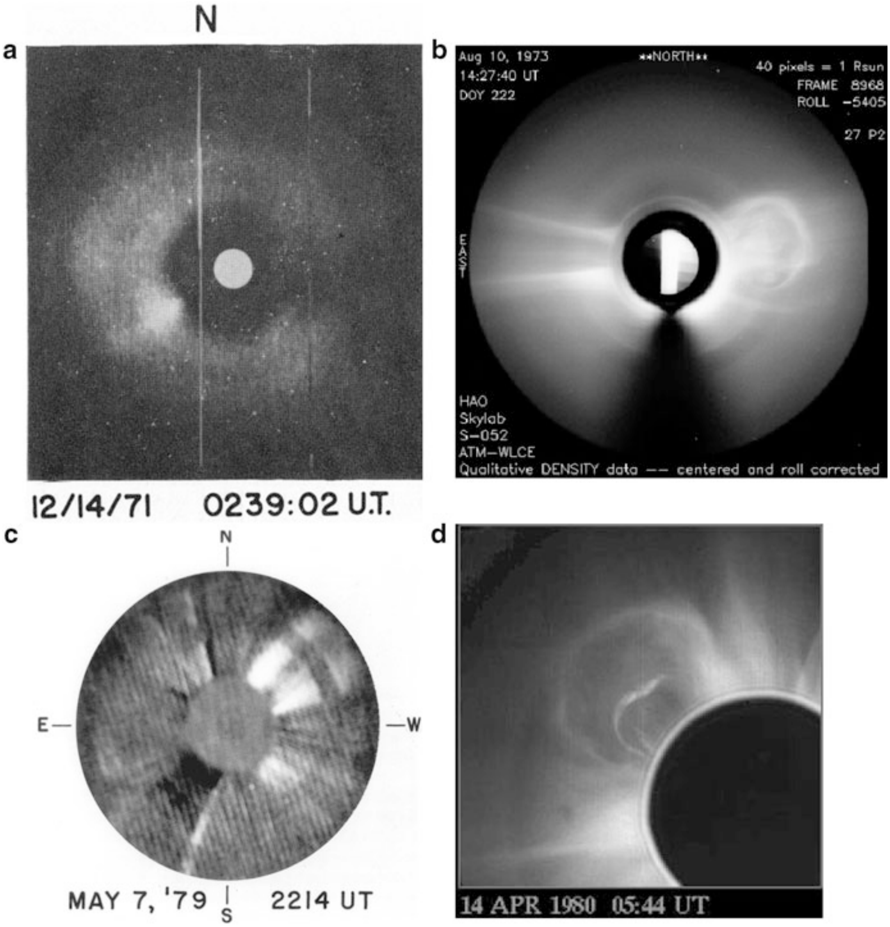

Fig. 2.4 Images of some of the early CMEs observed by space-based coronagraphs. (**a**) One of the first CMEs observed with *OSO-7* by Tousey [203]. This image was obtained on 14 December 1971 (Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission). (**b**) The coronagraph on board *Skylab* (available courtesy of the High Altitude Observatory (HAO)), obtained on 10 August 1973. Images from (**c**) *Solwind* on 7 May 1979 [121] (Reproduced with kind permission of Springer Science and Business Media), and (**d**) C/P on 14 April 1980 [193] (courtesy of HAO) follow

observed with five separate spacecraft (*Voyager 1* and *2*, *Helios 1* and *2* and *IMP-8*) [14]. They called it a "magnetic cloud" following a term used in theoretical studies starting from the 1950s [159]. Figure 2.5 shows their diagram of this event, including the structure that later became synonymous with CMEs observed in-situ: a shock, followed by a sheath, followed by the magnetic cloud (see Sect. 1.5). An accompanying paper [130], which presented a study of 45 magnetic clouds, made their connection with CMEs. These papers established the combination of

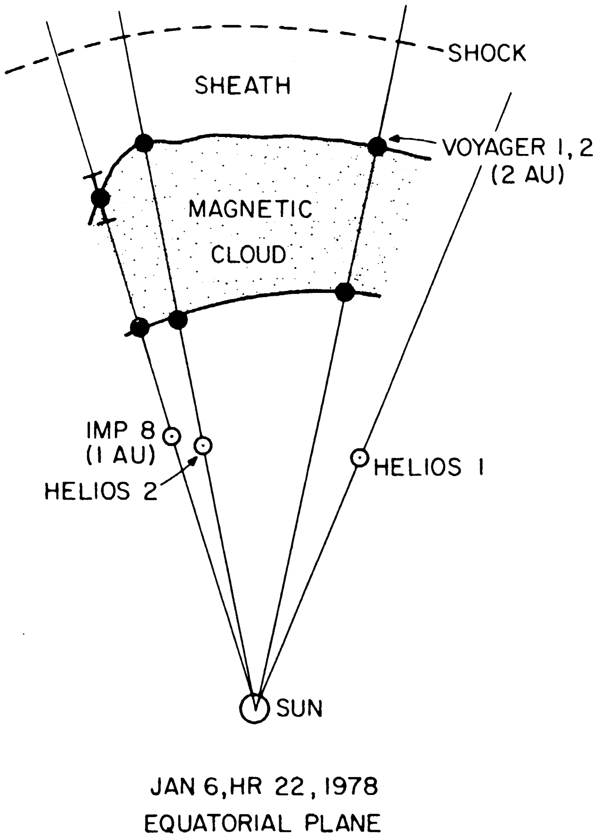

Fig. 2.5 Sketch of the geometry of the magnetic cloud observed by Burlaga et al. [14] from spacecraft observations on 6 January 1978 (their Fig. 5). The *dots* show where the observed boundaries of the cloud would be at 22:00UT on that day, assuming they moved at constant speed

characteristics of magnetic clouds that are still used today: low temperatures, high magnetic field strength, and a smoothly rotating magnetic field vector. By 1990, it was accepted that magnetic clouds were probably manifestations of coronal mass ejections [13, 223], that they were regarded as a strong source of increased geomagnetic activity [227], and that they were often drivers of interplanetary shocks [130]. It was also known that only a subset of in-situ CMEs (30–50 %) showed a clear magnetic cloud signature [20, 48]. Other CMEs were identified by other signatures in the solar wind, such as the presence of an interplanetary shock, expansion signatures in the speed and density profiles, energetic particle and temperature decreases, and chemical composition signatures such as HAEs.

2.4 The Solar Flare Myth

In 1931, the same year that Chapman and Ferraro made their suggestion of the ionized material ejection as possibly being responsible for geomagnetic storms, Hale [62] suggested that this material came from large solar flares. Dellinger [35] associated flares with geomagnetic disturbances, while Newton [163, 164] found a statistical correlation between large flares and magnetic storms. Later in 1950, Chapman [23], who had not mentioned flares in his and Ferraro's initial suggestion of the cause of magnetic storms, then cited flares as the likely cause. Given the accumulation of evidence over the decades it is not unreasonable to conclude that solar flares were responsible for interplanetary and geomagnetic disturbances. Hence, when interplanetary shocks were first observed by spacecraft in the 1960s, they were assumed to be caused by solar flares, even though shock associations with flares were not always established [51, 103, 104, 192].

When the CME was finally discovered in the 1970s, it was also naturally assumed by many to be a shock wave from a solar flare. This assumption persisted despite early revelations that CMEs and geomagnetic storms were often not associated with flares [32, 52, 126, 148], and that the energy required to launch the mass ejection was much greater than that of the flare itself [148, 213].

While it was known that interplanetary shock waves were the likely cause of most geomagnetic sudden storm commencements, by the early 1970s some workers were already having doubts about their association with flares. Hundhausen expressed concerns in 1972 [103, 104], and workers using the early CME results from *Skylab* noted the inconsistency between CME and flare occurrence [52]. Joselyn and McIntosh [126] expressed surprise at the small percentage of flare-related geomagnetic storms, and Sime et al. [188] questioned the validity of describing a CME as a shock front with the observation that the flanks of the CME did not move laterally as the CME loop top moved outward. Further evidence was accumulated through the 1980s, including the movement of surrounding plasma ahead of the CME (implying that the CME cannot be a shock because the shock should be the leading feature) [187], the location of the flare as being at only one footpoint of the CME [66, 189, 190], and a lacking in coincidence in the timing between flare and CME onset [67–69]. Figure 2.6 shows two diagrams produced by Harrison in [64] demonstrating the relationship between the CME and its associated flare.

By 1992 the culmination of evidence from virtually every area of space physics research presented a strong case for a CME-centered, rather than flare-centered paradigm. In his excellent review in the *Annual Reviews of Astronomy and Astrophysics*, Steve Kahler [127] addressed the questions of

> [H]ow did we form such a fundamentally incorrect view of the effects of flares after so much observational and theoretical work... [and] what is the... evidence to support a primary role for CMEs? (p. 114 [127]),

by presenting evidence from CME and flare observations, metric radio bursts, interplanetary shocks and magnetic fields, solar-energetic particles and their geomagnetic consequences.

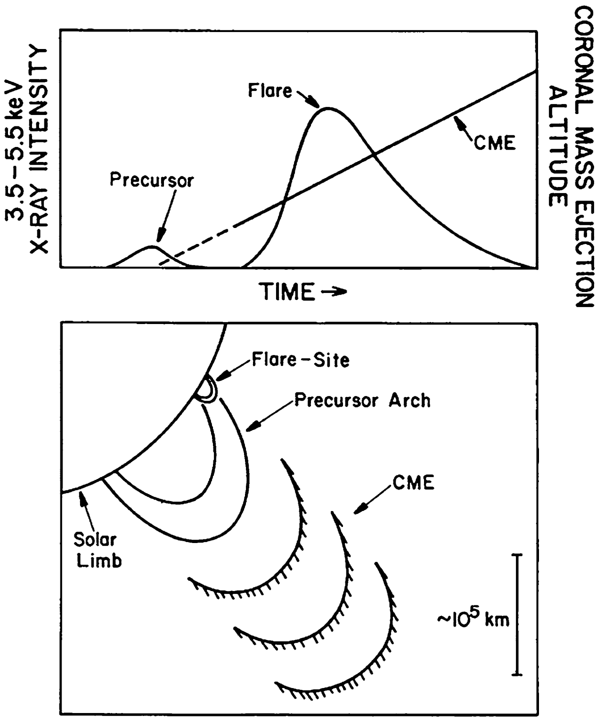

Fig. 2.6 Diagram representing the relationship between the CME and its associated flare (originally from Harrison [64] (his Fig. 6), and reproduced in Hundhausen [105] and Gosling [49]). Reproduced here with permission © ESO. The *top panel* shows the temporal relationship, showing the flare onset time occurring later than that of the CME, while the *bottom panel* shows the structural relationship, with the flare associated with one footpoint of the CME

Despite the solidity of evidence, most of the solar physics community continued to advocate the flare as the primary source of major space weather events. A review by Hudson in 1987 listed 42 great discoveries in solar physics and did not even mention CMEs [101], while a Lockheed Martin X-ray flare poster distributed at the AGU Fall Meeting in 1992 explicitly cited flares as the source for major geomagnetic storms. Finally, following a presentation of a soon-to-be traveling AGU exhibit addressing the Sun-Earth connection but not mentioning CMEs, Jack Gosling decided to write his now famous paper "The Solar Flare Myth", which was published in the *Journal of Geophysical Research* in late 1993 [49]. This paper confirmed that the source of interplanetary shocks and of most geomagnetic storms was the CME and not the flare, and that the relationship between the flare and CME was secondary (at best). He proposed a so called "modern paradigm" describing the relationship between flares, CMEs and geomagnetic activity.

The Solar Flare Myth paper caused outrage among the solar physics (particularly the flare) community and the debate intensified. A special session of the AGU

Meeting in Baltimore in May 1995 entitled 'Is "The Solar Flare Myth" Really a Myth?' was convened (a session to which Gosling himself was not invited). A challenge paper by Švestka [194] referred to Gosling's conclusions as "faulty and dangerous" and the response by Gosling and Hundhausen (p. 57) accused Švestka and others of attempting to re-classify the definition of a solar flare. A further response by Harrison [65] referred to the attempted reclassification to encompass virtually all eruptions from the Sun as "very misleading". Other challenges (e.g., Hudson et al. [102] and Pudovkin [172]) and responses were issued throughout 1995 and it seemed likely that this debate would remain unresolved for years to come.

Towards the end of 1995, however, the intensity of the Solar Flare Myth debate suddenly appeared to die away. Not coincidentally, the *SOHO* spacecraft was launched in December 1995 (Sect. 2.5.2). Perhaps the clarity of CME data from LASCO proved more conclusive, or perhaps the community was distracted by the quality of the data delivered by *SOHO*, but when the dust settled it appeared that the CME community had prevailed. The final settling of the debate probably occurred at a meeting on CMEs in Bozeman Montana in 1996 where a large number of those from the flare camp were present. Loren Acton, a main player in solar flares, was instrumental in getting the solar community to take notice. It is generally accepted today that CMEs, and consequently large transient solar wind disturbances and geomagnetic storms, are not caused by solar flares.

2.5 The 1990s

Only one spacecraft relevant to CME study (*SMM*) was launched in the 1980s, and had that been launched only 2 months earlier it would have been a 1970s launch. So while many of the spacecraft launched in the 1970s continued to function well into the 1980s (and some into the 1990s and later), after *SMM* no new missions of significance to CME study were launched throughout the 1980s decade. Furthermore, once *SMM* re-entered Earth's atmosphere in 1989, no continuous surveillance of the outer corona occurred until 1996. The next significant solar mission, *Ulysses*, was launched in 1990 although it was originally scheduled for launch in 1986.

2.5.1 The Next Generation of In-Situ Probes: Ulysses, Wind *and* ACE

Ulysses, launched in 1990, carried an assortment of magnetic field, energetic particle and other experiments, and was placed into a near polar orbit around the Sun. It achieved this by a gravitational assist around the planet Jupiter, and it needed to pass closer to the planet than any previous artificial object to do so. Given its unique orbit, the contributions to solar and interplanetary exploration made by *Ulysses* were mainly of observations of the polar regions of the Sun. Using *Ulysses*, Gosling [50] showed that CMEs can occur in the fast solar wind and several studies were made of CMEs at distances out to 5 AU [19,55,184,228]. Later, CMEs observed with *Ulysses* were compared with transients observed with IPS [124, 125] and with heliospheric white light images when they became available [196]. Charge state distributions of CMEs were investigated by Henke et al. [71, 72], who found that the charge state ratios of heavy solar wind ions (C^{6+}/C^{5+}, O^{7+}/O^{6+}, Si^{10+}/Si^{9+}, Fe^{12+}/Fe^{11+}) were related to the structure of the internal magnetic field.

In February 2008, *Ulysses* lost its secondary X-band transmitter which, among other things, enabled the regulation of temperature of the spacecraft. As it was on its way out away from the Sun, operators predicted 6 weeks before it froze to a point beyond operation. Despite this, the spacecraft continued to function for a further 18 months, and was finally turned off on 30 June 2009.

The next two solar/interplanetary in-situ spacecraft (*Wind*, launched November 1994 and *ACE*, launched August 1997) contained sophisticated instrumentation and have since been used as scientific and monitoring probes. The instruments on board *Wind* and *ACE* were mostly improved or modified versions of those already tested on previous missions. Likewise, the orbits from each spacecraft are not unlike those that had been seen before. The L1 location of *ACE* had been occupied by *ISEE-3* 20 years previously, and *Wind* was certainly not the first spacecraft to assume a high-Earth orbit passing into the upstream solar wind region beyond the magnetosphere.

Wind and *ACE* provided a continuous datastream of CME properties that remain continuous to this day. Their enhanced instrumentation also provided more in-depth studies of phenomena in the interplanetary medium. This, coupled with the next generation of imaging instruments (discussed in the following sections), allowed for the first time a reliable long-term continuous monitoring of solar, interplanetary and magnetospheric activity. This greatly enhanced our space weather forecasting. *ACE* remains the most crucial early-detection system for space weather, as it is always in the Sunward direction of the Earth. Unfortunately, it does not provide much of an early warning, as when a CME reaches *ACE* at L1 it is usually only around an hour away from arriving at Earth.

Statistical studies of CMEs using *Wind* and *ACE* include those by Cane and Richardson [21, 177], Lynch et al. [145, 146] and Howard and Tappin [94]. Iron charge distribution of CMEs were investigated by *ACE* by Gloeckler et al. [45] and Lepri et al. [141], who found typical charges of 9+ to 11+, but charges greater than 16+ were also identified . As with earlier studies, the higher charge states were attributed to hot plasma originating low in the solar corona or from initial heating during the launch of the CME. Later work includes the investigation of solar wind heating by CME-driven shocks and the relationship between composition and solar surface parameters [133, 176].

As mentioned previously, it was already known by 1990 that only a small fraction of CMEs were observed to contain magnetic clouds. However, by that year a global picture of the structure of a magnetic cloud had been formed ([17], see Fig. 2.7). Consequently, empirical modeling of magnetic clouds using in-situ data were based

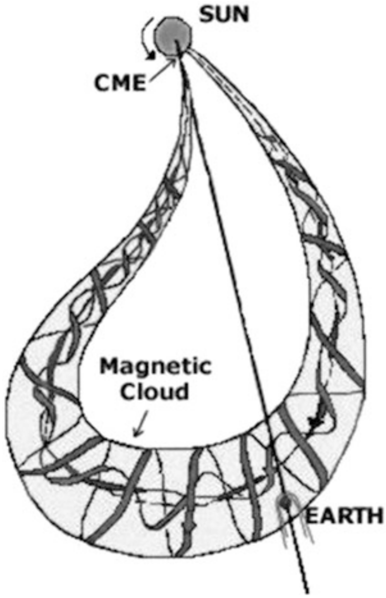

Fig. 2.7 Sketch of a global view of a magnetic cloud through the ecliptic plane, including the effects of solar rotation [150]

on this global picture. A model developed by Burlaga [12] and refined by Lepping et al. [139] using *ISEE-3* and *IMP-8* set the scene for magnetic cloud reconstruction techniques for when the next generation of in-situ data became available. Several different methods for such reconstruction followed; Riley et al. [181] provides a review of some of these models.

Since the launch of *Ulysses* in 1990, several hundred publications have appeared dealing with magnetic clouds with *Ulysses*, *Wind* and *ACE*. Studies have involved comparing them with CMEs [21, 177], solar surface structures [29, 137] and solar flares [173], geoeffectiveness [37, 61], magnetic reconnection [56, 57] and even internal whistler wave propagation [160]. The general picture of magnetic clouds remains as was defined from their discovery, but they are now an integral and essential part of CME study.

2.5.2 The SOHO *Era*

The *Solar and Heliospheric Observatory* (*SOHO*), launched in December 1995, was part of the European Space Agency's (ESA) "cornerstone" of its long-term "Horizon 2000" science program, and it was truly a cornerstone of solar physics research. First and foremost was the quality and variety of the data provided by its 12 instruments

Table 2.1 The 12 *SOHO* instruments in order of field of view. The instruments are identified first by their acronym then their full names, their field of view (if applicable), primary purpose and a reference to the instrument paper is also provided. Each of these papers were published in a special edition of the *Solar Physics* journal in 1995

Acron.	Name	Field of view	Primary purpose	Ref.
SWAN	Solar Wind Anisotropies	Whole-sky	Lyman alpha radiation detector	[6]
LASCO	Large Angle Spectroscopic Coronagraph	1.1–30 $R_\odot$	White light and EUV coronagraph	[10]
EIT	Extreme-Ultraviolet Imaging Telescope	Full solar disk	Multiwavelength EUV imager	[31]
MDI	Michelson Doppler Imager	Full solar disk	Solar oscillations and magnetic field investigation	[185]
UVCS	UltraViolet Coronagraph Spectrometer	$\sim 40 \times 60'$	UV spectroscopy and visible polarimetry studies	[131]
CDS	Coronal Diagnostic Spectrometer	$\sim 240 \times 240''$	EUV imaging spectrometer	[70]
SUMER	Solar Ultraviolet Measurements of Emitted Radiation	Thin slits	EUV analysis	[222]
CELIAS	Charge, Element, and Isotope Analysis System	N/A	Solar wind and particle detector	[88]
COSTEP	Comprehensive Suprathermal and Energetic Particle Analyzer	N/A	Energetic particle detector	[161]
ERNE	Energetic and Relativistic Nuclei and Electron Experiment	N/A	Energetic particle detector	[202]
GOLF	Global Oscillations at Low Frequencies	N/A	Helioseismology observer	[43]
VIRGO	Variability of the Solar Irradience and Gravity Oscillations	N/A	Helioseismology and radiometry	[42]

(summarised in Table 2.1). While many of these types of instruments had been used in the past, on *SOHO* they were of higher quality, and were all available on board a single spacecraft.

With regard to CME study, the EUV imager EIT and spectrometer CDS provided invaluable information on solar eruptions associated with CMEs, but the major contributors to CME research were of course the coronagraphs. LASCO originally consisted of three coronagraphs, C1 with a field of view (FOV) of 1.1–3.0 $R_\odot$, C2

(FOV 1.5–6.0 $R_\odot$) and C3 (FOV 3.7–30 $R_\odot$). C2 and C3 are white light imagers, while C1 observed at variable EUV wavelengths.

For $2\frac{1}{2}$ years *SOHO* returned images of unprecedented detail on the Sun, including CMEs. The sensitivity of LASCO led to halo (Earth directed) CMEs being easily detected for the first time, and a large statistical database of CME observations had begun. Then on 25 June 1998, the spacecraft suddenly went into an uncontrolable spin and was lost for around a month. It was located on 23 July by a radio telescope and was dead in space, but careful analysis of its spin and trajectory enabled a prediction for when solar panels would be pointing at the Sun, providing power to the spacecraft. The first signal was received on 3 August and it was fully recovered by 16 September. Some ingenious engineering and scientific analysis went into the recovery of *SOHO*, including a study of the images of the Sun as they moved in and out of the field of view. The incident was later attributed to a sequence of operational errors leading to both gyroscopes being left off [204]. This is the only critical malfunction to occur in *SOHO* during its 17 year lifetime, and only the LASCO C1 camera was lost during the anomaly. Since January 2003 its data transmission capabilities have been limited following a malfunction in the pointing system of its high-gain antenna, which is now unable to move. Since the launch of *SDO* in February 2010, some of *SOHO*'s instruments have been turned off as they were deemed redundant (Sect. 5.1). No suitable replacement for LASCO has yet to be launched, and so its C2 and C3 coronagraphs remain operational and are central to the space weather forecasting effort.

The actual number of publications using LASCO is virtually impossible to identify, but it easily numbers in the thousands and probably tens of thousands. Along with the detailed study of CMEs, LASCO has assisted in research from solar wind origination to space weather to comet discovery. Two popular CME catalogs have appeared, managed by NRL (http://lasco-www.nrl.navy.mil/cmelist.html) and Goddard (http://cdaw.gsfc.nasa.gov/CME_list/). From 1996 to the end of 2011, the latter provided details on just under 18,000 CMEs observed with LASCO C2 and C3.

2.6 Heliospheric Imaging

Ten years ago, a new class of instrument was launched and a new era of CME observation was born. The heliospheric imager bridges the gap between coronagraph measurements near the Sun and in-situ measurements near the Earth by continually observing CMEs throughout their transit through the inner heliosphere. They function similarly to a coronagraph, in that they observe white light that has been Thomson scattered off free electrons in the heliosphere. The first of these, the Solar Mass Ejection Imager (SMEI), was launched in 2003 and was capable of observing the entire sky beyond around 20° from the Sun. A second instrument, simply called the Heliospheric Imager (HI) was launched on board *STEREO* in 2006.

2.6.1 *The* Helios *Zodiacal Light Cameras*

The heliospheric imager concept was proven by an instrument carried by the *Helios* spacecraft, launched much earlier in the mid-1970s. There were two spacecraft launched as part of this mission, *Helios 1* was launched in December 1974 and *Helios 2* was launched in January 1976. The missions ended in 1982 and 1976 respectively, although both spacecraft continued to deliver data until the mid-1980s. To this day they remain in their highly eccentric orbit about the Sun (perihelion $\sim$0.3 AU, aphelion $\sim$1.0 AU).

Each *Helios* spacecraft contained a white light imager as their zodiacal light experiment [138], which consisted of three photometers (white light cameras) oriented such that large strips at constant ecliptic latitude could be scanned as the spacecraft spun. The cameras were centered at 15°, 30° and 90° below the spacecraft equatorial plane, and the first two cameras scanned at 5.6°–22.5° longitude width, depending on the required angular resolution (see, for example, [121]). While it was not the primary science objective of the zodiacal light instrument, they did confirm that transients in the inner heliosphere could be detected in white light. Richter et al. [179] noted high-latitude "plasma clouds" and measured speeds for a number of them of around 300 km/s. They even associated one event with a CME observed by *Solwind* on 5 June 1979. This CME had a measured speed of 500 km/s and the *Helios* plasma cloud, observed on 6 June 1979, had a speed of 260–330 km/s, and therefore had decelerated en-route. Jackson and co-workers attempted to produce low-resolution images of these density changes [114, 116, 119, 121]. The technique was developed further through the 1990s [79, 117] and eventually *Helios* white light data were compared with IPS observations [78]. Other contemporary work compared *Helios* transients with coronagraph CMEs and interplanetary shocks [115, 120, 212, 214], and by the end of the *Helios* era the association between coronagraph CMEs and white light and IPS CMEs had been firmly established.

2.6.2 *SMEI*

The Solar Mass Ejection Imager, SMEI [36, 122], was launched on the Air Force Space Test Program *Coriolis* spacecraft. SMEI consisted of three scanning cameras that built up an image of the sky throughout its 102 min polar orbit about the Earth. It observed the sky starting from around 20° elongation, or around 0.35 AU (75 $R_\odot$). While parts of the images were often contaminated by aurora and particle noise from the passage of the spacecraft through various regions of the magnetosphere (i.e., the polar caps and South Atlantic Anomaly), SMEI allowed for the first time direct measurement of complete CMEs at large distances from the Sun in white light. As with coronagraphs, the images were heavily projected, but unlike coronagraphs the problems posed by projection were mitigated with the application of geometry [96, 98, 197]. Hence, SMEI enabled the three-dimensional reconstruction of CMEs at large distances from the Sun. Figure 2.8 shows a SMEI image, shown as an all-sky Hammer-Aitoff projection.

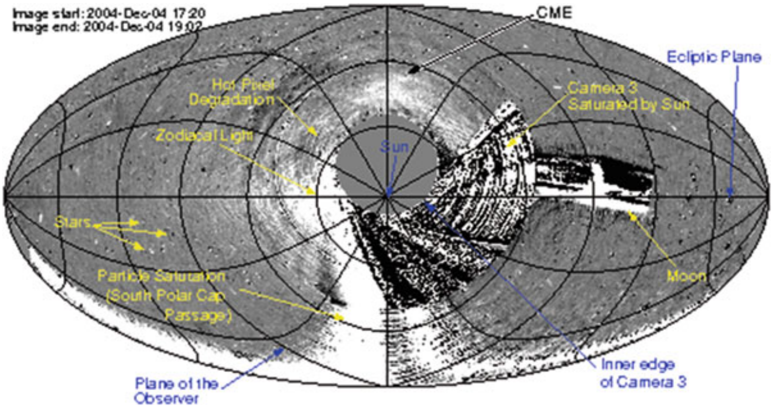

Fig. 2.8 A Hammer-Aitoff projection of a whole-sky SMEI image (it is probably more appropriate to think of it as a map) of a CME observed on 4 December 2004 around 18:00UT [200]. A number of features are labeled. Those labeled in *blue* indicate regions due to the projection, and those labeled in *yellow* are sources of interference. A CME appears in this map heading to the north (upwards), which is labeled

Early work with SMEI involved mostly height-time comparisons with coronagraph CMEs, interplanetary shocks and geomagnetic storms [99, 196, 199, 215] but some three-dimensional work was attempted from the start. For example, Jackson and co-workers extended their *Helios* and IPS reconstruction work to include SMEI data [123] and the author and co-workers have performed more simplified reconstruction techniques based on leading edge measurements of SMEI CMEs [99, 100]. Later, we developed more sophisticated 3-D reconstructions using the theory of Thomson scattering and the geometry of the CME [96, 98, 197]. Figure 2.9 shows some of these 3-D reconstructions of CMEs made using SMEI data.

SMEI was de-activated in September 2011, but work with its dataset continues.

2.7 *STEREO*

In 2006 the *STEREO* spacecraft [129] assumed an orbit and carried a suite of instruments never before seen on a solar mission. The purpose of *STEREO* was to provide multiple in-situ measurements and images of the Sun from different viewpoints from the traditional Sun-Earth line, and so each were placed in an orbit similar to that of the Earth about the Sun. The difference was that one spacecraft would orbit slightly faster than the Earth with the other slightly slower, resulting in leading and lagging spacecraft in the ecliptic plane. Figure 2.10 shows the location of each spacecraft at various times during the mission. The angular separation between the spacecraft and the Sun-Earth line grows by around 22.5° per year.

Along with providing continuous in-situ measurements of interplanetary transients, allowing a study of the longitudinal structure of CMEs [97, 100, 158], the *STEREO* imagers allow both the continuous monitoring of CMEs throughout their entire journey to 1 AU (including within 20° elongation that was missed by SMEI), and also a three-dimensional image of solar structures much in the same way as depth is perceived using our two eyes. Figure 5.4 shows combined views of the *STEREO* imaging suite, which is called SECCHI [92]. As the spacecraft separated further, three-dimensional reconstructions became possible with different instruments, first with the EUV low corona structures [3, 142], then the coronagraphs [95, 157, 158], and finally the heliospheric imagers [97].

The *STEREO* spacecraft continue to move apart and are functioning to date, even though they are now well on the far side of the Sun relative to the Earth. Eventually they will pass each other on the far side of the Sun and return from the opposite direction.

2.8 The Continuing Role of Past Missions

It is helpful to remind the reader that many of the missions launched in earlier years continue to function and play a role in our understanding of space and CMEs to this day. The *Voyagers*, for example, continue to monitor the outer regions of the heliosphere [30]. By the year 2000, they were over 58 AU from the Sun and were still capable of observing CMEs even there. At those distances, CMEs tend to merge with other dense regions (such as corotating interaction regions or other CMEs), the combination of which are called merged interaction regions (MIRs [16]). Richardson et al. [178] studied a single event from the Sun to the *Wind* spacecraft at 1 AU to *Ulysses* at 5 AU then to *Voyager 2* at 58 AU. Similar studies include the “Bastille Day” CME by Burlaga et al. [18] and a series of events the following year [209]. A review of Voyager observations of MIRs involving CIRs can be found in Lazarus et al. [136].

Along with the *Voyager* observations, new publications continue to emerge from ongoing missions dating from the 1970s, such as *IMP-8* [47, 140]. Also, analyses of data from spacecraft no longer operating continue to yield new scientific results, such as those from *Helios* [47, 118, 144], *ISEE-3* [39, 182], *Solwind* [27, 128] and *SMM* [11, 149].

2.9 Other Missions

We have focused in this chapter on those missions that were used to observe CMEs directly, but other missions have been launched in the meantime that provided insight into the onset and evolution of CMEs. The instruments on board these missions did not observe CMEs directly, but did observe CME-related phenomena,

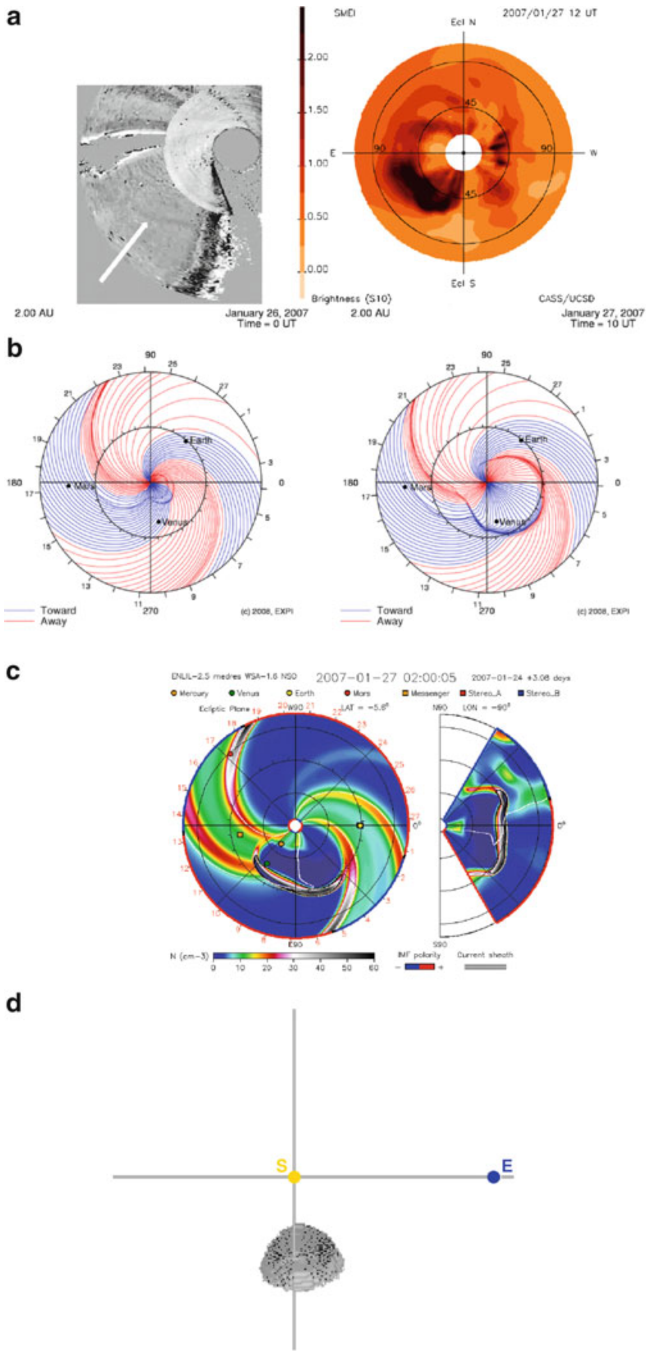

Fig. 2.9 Results from three-dimensional reconstruction efforts of CMEs that were used throughout the SMEI mission. These are for the CME observed in late January 2007 and panels **(a)**–**(c)** are from Webb et al. [216]. (**a**) SMEI "fisheye" image (*left*) and fisheye tomographic reconstruction

such as flares, filaments, and the response of the Earth's magnetosphere to their impact. More details on these missions are provided in Chaps. 2 and 3 of the author's introductory text on CMEs [93], but a list of many of these missions is provided in Table 2.2. We do not include the *GOES* spacecraft in this table, but a complete listing can be found in the Wikipedia entry for *GOES* (http://en.wikipedia.org/wiki/List_of_GOES_satellites). NOAA provides a website of the status of *GOES* (http://www.oso.noaa.gov/goestatus/) and a summary of the Space Environment Monitor (SEM) can be found at http://ngdc.noaa.gov/stp/satellite/goes/index/html.

2.10 Summary

To summarize, CMEs have been detected using a large variety of instruments and techniques. Directly:

1. Using white light coronagraphs that detect the light that is Thomson scattered from the electrons in the CME,
2. Directly measuring properties of the CME as it passes by in-situ spacecraft,
3. Measuring the changes in longwave radio signals from distant sources as the CME passes between them and the Earth (IPS);

and indirectly, through investigation of the secondary effects of CME launch and propagation:

1. Solar flares, observed in visible light, EUV, X-ray,
2. Erupting prominences/disappearing filaments, observed in visible light and EUV,
3. Other solar surface eruptions, such as post-eruptive arcades and coronal dimming,
4. Solar energetic particles accelerated by the shock in the interplanetary medium from the CME,
5. Type II and Type IV radio bursts, driven by the CME shock.

Figure 2.11 shows a timeline of the significant events that have led to an enhancement of our understanding of CMEs. The passage from ground-based to space-based observations is indicated, but the importance of the work leading up to the space age cannot be overstated. It seems clear that even by the time of the

Fig. 2.9 (continued) (*right*) at 12:00UT on 27 January. (**b**) HAFv2 (Sect. 3.2.2.2) solar wind disturbance reconstruction at 0UT on 26 Jan (*left*) and 10:00UT on 27 Jan (*right*), looking down onto the ecliptic plane and showing the orientation and polarity of interplanetary magnetic field lines. (**c**) ENLIL (Sect. 3.2.2.3) MHD solar wind injection reconstruction on 02:00UT on 27 Jan, showing the density of the solar wind and looking down onto the ecliptic plane (*left*) and along the north-south meridian (*right*). (**d**) TH model reconstruction on 27 Jan 2007, looking down onto the ecliptic plane. In panels (**b**)–(**d**) the location of the Sun and Earth are shown, and all four models show considerable agreement

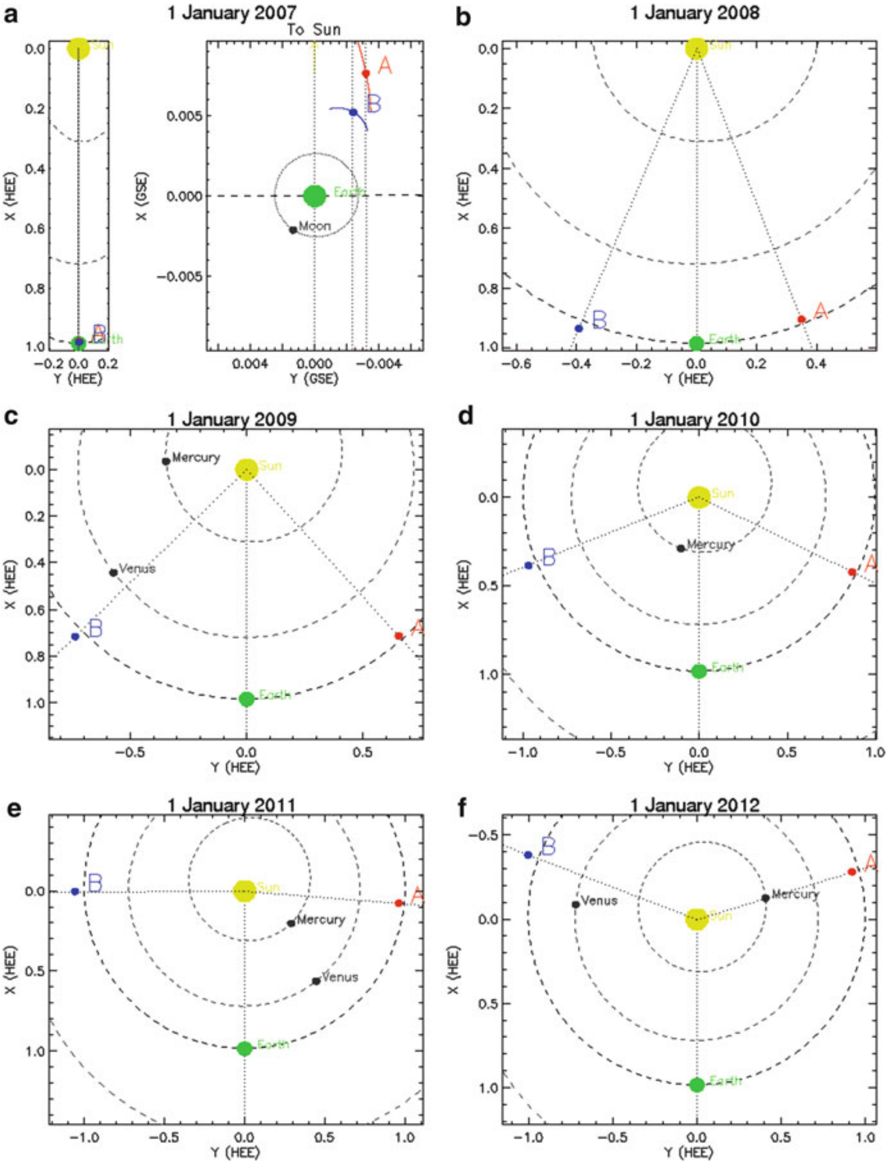

Fig. 2.10 The location of the *STEREO* spacecraft on 1 January of (**a**) 2007, (**b**) 2008, (**c**) 2009, (**d**) 2010, (**e**) 2011, (**f**) 2012 (from the STEREO website). The coloured circles indicate the following: *Yellow* = Sun, *green* = Earth, *red* = *STEREO-A*, *blue* = *STEREO-B*. The angular separation between the spacecraft and the Sun-Earth line grows by around 22.5° per day (Images provided courtesy of the "Where is STEREO?" tool (NASA/GSFC))

Table 2.2 Other missions that have not detected CMEs directly, but provided observations of CME-related phenomena, thereby providing insight into the nature of CMEs.

Name	Launch date	End date	Instrument	Ref.
IMP-8	26 October 1973	October 2001	In-situ suite	[170]
Voyager 1	5 September 1977	Continues to operate	Imagers, in-situ suite	[2]
Voyager 2	20 August 1977	Continues to operate	Imagers, in-situ suite	[2]
ISEE-3	12 August 1978	Became *ICE* in 1982	X-ray and gamma-ray spectrometers, in-situ suite	[168, 169]
Yohkoh	31 August 1991	14 December 2001	X-ray imagers, gamma-ray spectrometers	[152, 165, 166]
TRACE	1 April 1998	21 June 2010	UV and EUV imagers	[63, 109]
RHESSI	5 February 2002	Continues to operate	X-ray imager, spectrometer	[82, 143]
Hinode	22 September 2006	Continues to operate	Imaging suite	[1, 110]
SDO	11 February 2011	Continues to operate	Imaging suite	[171]

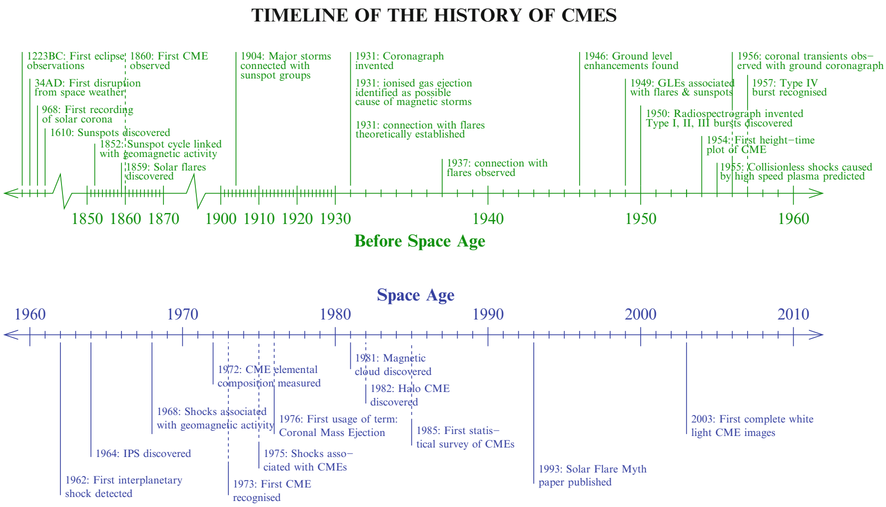

Fig. 2.11 Timeline of the significant events that have led to an enhancement of our understanding of CMEs. It has been divided into before and during the space age (*green* and *blue* respectively)

emergence of the first spacecraft around 1960, our understanding of interplanetary transients and the interplanetary medium had a firm foundation.

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