Chapter 2
History

In this chapter the history of coronal mass ejection study is reviewed. The emphasis is on CME and ICME observation, and the scientific contributions made to our understanding of these phenomena from those observations. Less emphasis has been placed on what I consider to be secondary effects of the CME (e.g. radio bursts, solar surface activity, solar energetic particles). The study of these secondary effects has made significant contributions to our understanding of the CMEs and space physics in general, much of which predates the discovery of the CME. A large number of texts has been written on these phenomena, and discussing how they are all related can be confusing or even misleading in a brief review. Hence, this chapter will address these secondary phenomena only in their early historical context and mostly before the CME was directly observed. Chapter 7 addresses these secondary phenomena in more detail.

It is also important to note that significant contributions were made to our understanding of CMEs by way of modelling, work on which has continued throughout the observational history of CMEs. In this chapter, we do not consider the contributions of modelling, but rather saving these for complete chapters describing their onset and evolution (Chaps. 8 and 9).

2.1 The Early Years

The history of the observation of CMEs probably dates back to a very fortunate catch in the nineteenth century, when the solar corona was beginning to be studied in great detail for the first time. The solar corona can only be observed naturally during a solar eclipse, which only achieves totality for a few minutes, and so acquiring information on the corona proved difficult. This is most likely why early detailed descriptions are lacking, even though solar eclipses have been observed and documented for centuries (the first identification of the solar corona was probably in 968 AD [102], but observations date back to the first eclipse recording in 1223 BC [283]). Given that on average a CME occurs only a few times a day and that we only have a window of a few minutes to observe the corona during eclipse totality, one can estimate that the probability of actually observing a CME during a solar eclipse is low, even during solar maximum.

T. Howard, *Coronal Mass Ejections: An Introduction*, Astrophysics and Space Science Library 371, DOI 10.1007/978-1-4419-8789-1_2,

As with observations of the corona, the effects of space weather has its roots in antiquity as well. In 34 AD, for example, the Roman Emperor Tiberius mistook the red glow of the aurora for fires at Ostia (the port of Rome), and dispatched troops to investigate. There must have been a major geomagnetic storm for the aurora to be above Ostia, which lies at a latitude just south of 42°N. By the eleventh century the concept of magnetism was known by the Chinese and the magnet was in wide use by the Europeans by the twelfth century [192], although the magnetised Earth theory did not emerge until the turn of the seventeenth century (in Gilbert's *De Magnete*, published in 1600 [65]). Thanks to the wide use of magnets for navigation, a vast database of geomagnetic measurements was built up in the century which followed and in 1724, two workers (George Graham in London and Anders Celsius in Sweden) independently found a simultaneous deviation by a small angle in the compass needle that lasted around a day [86]. These were later named "magnetic storms" by von Humboldt in 1805.[1]

Early observations of the Sun include those of sunspots by the Chinese dating back as far as the fourth century BC, and in the west in the eighth century AD. Galileo is often (incorrectly) accredited with the discovery of sunspots (in his letters to Mark Welser in 1612) but he is the first to have observed them with a telescope [250]. The nineteenth century brought a wave of solar discoveries, including solar spectroscopy in 1817 [61], the sunspot cycle in 1843 [220], and solar flares, differential rotation and chemical composition in 1859 [30, 31, 99]. The era of photography helped here, with the first solar photograph obtained in 1845 [47].[2] Figure 2.1 shows 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. This is believed to be the first direct observation of a coronal mass ejection, although none realised what it was at the time.

In 1852, the sunspot cycle was "absolutely" connected with geomagnetic activity by Edward Sabine, based on an accumulation of data since the 1830s [216]. This relationship was confirmed by two other researchers, working independently, at around the same time [219]. Later that decade in 1859 the now famous Carrington Event (or Carrington Storm) occurred. Here a powerful flare erupted from a large active region on the Sun (recorded by Richard Carrington [30]) and 18 h later the most intense magnetic storm in recorded history occurred at Earth. As a result, telegraph systems failed across Europe and North America and aurora were observed at latitudes as low as the Caribbean. Contemporary estimates of the Dst index for the Carrington Event range from −1,600 nT [248] to −850 nT [228]. In the following years, associations between flares and geomagnetic storms continued, although the relationship was not one-to-one. For example, Maunder [184] and Greaves and Newton [87,88] showed that the great geomagnetic storms were usually

[1] For a review of geomagnetism, refer to Stern [231].

[2] An excellent summary on the history of the study of the Sun may be found at the High Altitude Observatory (HAO) webpage, at http://www.hao.ucar.edu/Public/education/spTimeline.html.

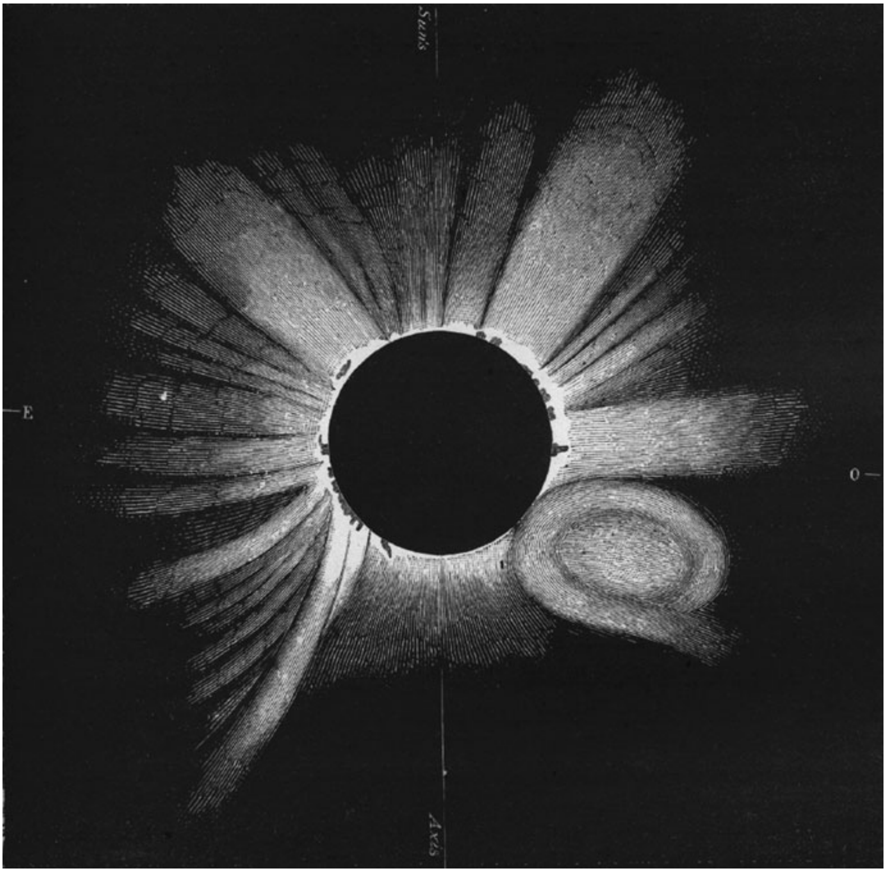

Fig. 2.1 Drawing of the 1860 eclipse recorded by Tempel [205] and identified later by Jack Eddy. This is believed to be the first observation of a coronal mass ejection

accompanied on the Sun by groups of large-area sunspots. In 1931, Chapman and Ferraro [33–35] proposed that this correlation could be explained if there was a sporadic ejection of ionised material from the Sun. In the same year, the coronagraph was invented, 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 [178].

2.2 Coronal Transients

Although the coronagraph was invented by Bernard Lyot in 1931, it was not until later that the sensitivity of the instrument was reduced to a level where faint coronal eruptions could be observed. For the most part, this required the utilisation of space-based coronagraphs, and it is Richard Tousey, using *OSO-7* coronagraph observations who is accredited with the discovery of the CME. In a review published in the Proceedings of the Fifteenth Plenary Meeting of COSPAR (*Space Research XIII*) in 1973, Tousey referred to transients in the K-corona moving with speeds of 400–1,000 km/s [244]. He described the observation of the first CME thusly:

> The prominence erupted at 1701 UT and at 1938 UT the OSO image showed a cloud just emerging from the occulter shadow… The next image frame was at 2111 UT. The extreme right edge of this frame recorded a portion of a bright cloud whose leading edge extended barely into the inner polarizing ring. In the following frame at 2123 UT the cloud had moved outward, and its recorded portion suggested a cloud of circular shape, with diameter about equal to the sun's radius, located at 35° N radially above the prominence. The next two images taken at $11\frac{1}{2}$ minute intervals, clearly show the motion of the plasma cloud through the corona. (pp. 724–725 [244])

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 [45]. By this time coronal transients had also been recognised by workers using the Mauna Loa coronagraph, with observations published the following year [64, 163]. It seems highly likely that all groups had observed manifestations of the same phenomenon.

The coronagraph on board *OSO-7* continued to observe CMEs and a total of 20 were confirmed before it re-entered the Earth's atmosphere in 1974 [120]. The previous year, in 1973 the US space station *Skylab* was launched. Around 77 transients were observed by the *Skylab* coronagraph from May 1973 to February 1974 [196], and they were immediately identified as mass ejections [81]. The first appearance of the term "coronal mass ejection" appears to be in Gosling et al. [83], although the term "mass ejection coronal transient" appears in Hildner [110]. 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 began to dominate. 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* [188] and NASA's coronagraph/polarimeter C/P [182] respectively. Among the discoveries of this next generation of space-based coronagraphs was the first Earth-directed CME by Russ Howard and co-workers. This transient was observed in November 1979 and was associated with an interplanetary shock detected near the Earth. The results were published in the *Astrophysical Journal* in 1982 [121]. 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 [138]. Figure 2.2 shows images of CMEs obtained by these early instruments.

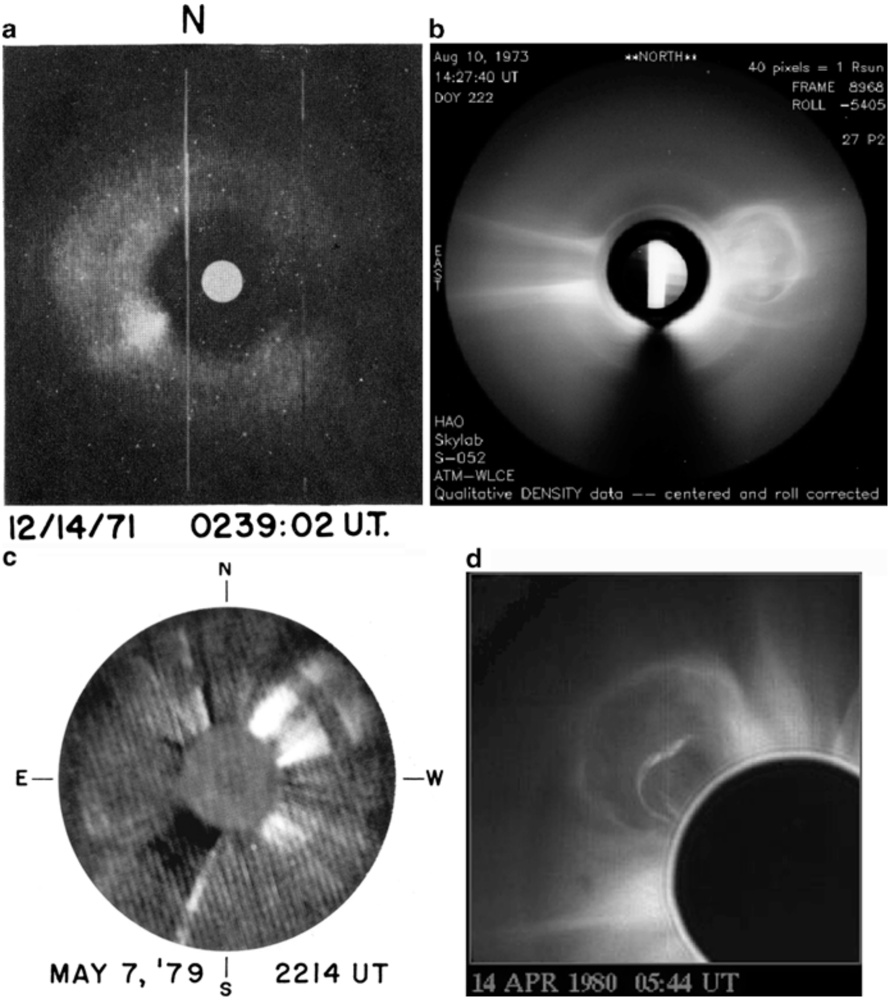

Fig. 2.2 Images of some of the early CMEs observed by space-based coronagraphs. (**a**) One of the first CMEs observed with *OSO-7* by Tousey [244]. This image was obtained on 14 December 1971 (Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission). (**b**) The coronagraph on board *Skylab* (available courtesy of the High Altitude Observatory (HAO)), obtained on 10 August 1973. Images from (**c**) *Solwind* on 7 May 1979 [151] (Reproduced with kind permission of Springer Science and Business Media), and (**d**) C/P on 14 April 1980 [230] (courtesy of HAO) follow

The combination of the two coronagraphs from *Solwind* and C/P resulted in the observation of over 2,000 CMEs, thereby enabling the detailed statistical analysis of their properties for the first time. Hundhausen et al. [137] using C/P reported that the location of the CME was more evenly distributed around the Sun than the events observed by *Skylab*, which were localised around the equator. Howard et al. [122] surveyed almost a thousand CMEs over 3 years (March 1979 to December 1981) using *Solwind* and provided extensive statistical results on structure, mass, angular span, location and kinetic energy. Both reported a "major" CME occurrence of around one per day. Similar statistical results using the complete C/P CME dataset were reported by Hundhausen et al. [136]. The fastest CME by that time was reported in this paper and determined to be 2,101 km/s. Hence, by 1995 solar physicists had a good picture of CME occurrence, structure, speed, mass and energy via an investigation of case studies as well as statistical surveys.

2.3 Interplanetary Coronal Mass Ejections (ICMEs)

Long before the discovery of the CME, investigations of the interplanetary counterparts of solar eruptions were being investigated, in studies pre-dating the space age. Here, interplanetary shocks were being studied via particles that were accelerated by them, and via their radio signatures. Solar energetic particles, or SEPs as they are now known, were first observed by Scott Forbush in 1946 when he noted bursts of cosmic ray intensity at the Earth [59]. They were immediately associated with solar flares and with variable magnetic fields around sunspots [60]. Such ground level enhancements, or GLEs, were later detected by neutron monitors in 1956 [187] and with riometers in 1959 [206]. Although always associated with flares, solar energetic particles (SEPs) were described by John Wild and co-workers in 1963 to be accelerated by two stages: Flare acceleration of electrons up to $\sim$100 keV, and acceleration caused by an outward-moving fast magnetohydrodynamic shock. The second phase appeared to be necessary for substantial acceleration of protons and higher-energy electrons [271]. This two-stage acceleration was confirmed using in-situ observations through the 1980s and 1990s [68].

The study of radio bursts arose from observations with the first radiospectrograph at Penrith in New South Wales (Australia) in 1950. The observed radio bursts were classified into three "Types": Type I bursts were short-lived, narrowband bursts occurring during storm periods, Type II bursts were longer in duration, accompanied solar flares and drifted gradually in frequency, while Type III bursts were short-lived broadband bursts where the frequency of maximum intensity drifted rapidly [267]. Later in 1957, using an interferometer at the Nançay observatory in France, a fourth type of burst event, designated Type IV, was discovered [14]. Type IV bursts were long-duration, associated with solar flares, and often followed a Type II burst. Finally, a new burst which often followed Type III was identified in 1959 and classified as a Type V [270]. According to McLean and Labrum [186]:

> The observations of Type II and Type III bursts contributed significantly to the developing subject of solar flare 'anatomy' [269]. 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 [186])

The first height-time plots of CMEs (or rather, their shocks) were plotted indirectly using analysis of Type II bursts. Figure 2.3 provides an example of such a plot

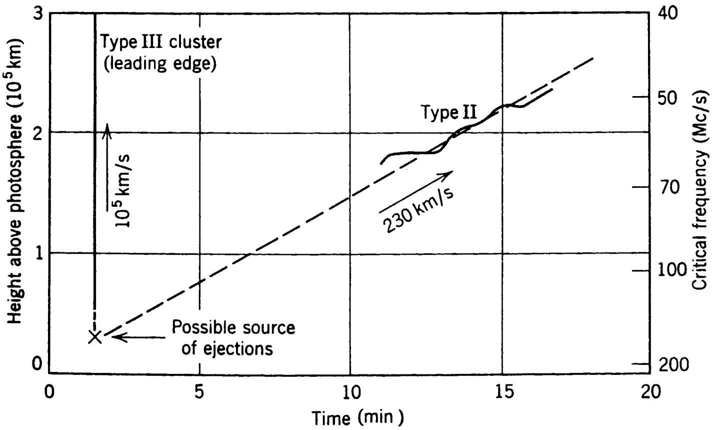

Fig. 2.3 An early example of a height-time plot, derived from Type II and Type III bursts [268]. This plot results in a Type II speed of 230 km/s

from Wild et al. [268]. While it was not entirely understood at the time what was being observed, relatively precise measurements of the kinematic evolution of solar eruptions were being made well before the discovery of the CME, and even before the space age.

2.3.1 In-Situ Observations

Into the space age, and still before the detection of CMEs by coronagraphs, interplanetary shocks were being observed by in-situ spacecraft as they were impacted by, and passed through these shocks in space. It was suggested by Thomas Gold (1955) that high-speed plasma ejected from the Sun would produce a collisionless shock in the interplanetary medium [70]. So, while the shock is not the ICME itself, it is a convenient associated signature. Interplanetary shocks were first directly observed in 1962 by the *Mariner 2* spacecraft [229] and a further two were reported in 1968 by Jack Gosling and co-workers using the *Vela 3* spacecraft pair [78]. Hundhausen et al. [135] 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 1973, several publications had emerged reporting interplanetary shock observations, many of which were connected with geomagnetic activity [50,132,133,139,140,166,199,242]. 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 direct association between interplanetary shocks and CMEs was made by Gosling et al. [82] by comparing a CME observed by the coronagraph on *Skylab* with an interplanetary shock detected by *Pioneer 9* [82]. Other early works include Dryer [48], Burlaga et al. [21] and Michels et al. [189]. The term "ICME" appears to have been coined by Xuepu Zhao in a paper presented at the Solar-Terrestrial Predictions Workshop in Ottawa in 1991, and a paper published in the *Journal of Geophysical Research* in 1992 [282]. It was brought into mainstream use following the publication of a review by Murray Dryer [49].

The next question that was addressed with the usage of in-situ data was the elemental/ionic composition and thermal behaviour of ICMEs. The first observations of the composition of the plasma behind interplanetary shocks revealed a helium abundance enhancement, and pre-dates the discovery of the CME [111]. The association of such enhancements with solar flares was made even earlier, dating back to the late 1960s [9, 165]. Following a statistical study in which 73 cases of helium abundance enhancements (HAEs) were measured, it was suggested by Borrini et al. [15, 16] that HAEs were the interplanetary signatures of CMEs. In 1979, high ionisation states of oxygen and iron were detected following interplanetary shocks [8, 56]. This also provided information on the thermal state of ICMEs, indicating that they were hotter than the surrounding solar wind. It is now believed that the cooler, singly charged helium ions may be associated with filament material known to be associated with CMEs [27, 79, 138, 221]. 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 [16]. Detailed measurements of ion composition, however, would need to await the next generation of in-situ explorers in the 1990s.

2.3.1.1 Magnetic Clouds

The quest for the identification of a magnetic structure within the ICME was fulfilled in 1981, when Len Burlaga and co-workers identified a smoothly rotating magnetic field vector following an interplanetary shock for an ICME observed with five spacecraft (*Voyager 1* and *2*, *Helios 1* and *2* and *IMP-8*) [25]. They called it a "magnetic cloud" citing early theoretical work dating back to the 1950s [193]. Figure 2.4 shows their sketch of this event, including the structure that later became synonymous with ICMEs: a shock, followed by a sheath, followed by the magnetic cloud.[3] While this paper did not make the connection with solar transients, an accompanying paper [161] did. This paper presented a statistical survey of 45 magnetic clouds, and directly associated many of them with CMEs. It is this paper that first identified the combination of characteristics of magnetic clouds that are still

[3] This is not to be confused with the classic three part CME structure observed in coronagraphs, where the shock and sheath are not involved. Relative to that structure the shock and sheath will form ahead of the leading structure (flux rope).

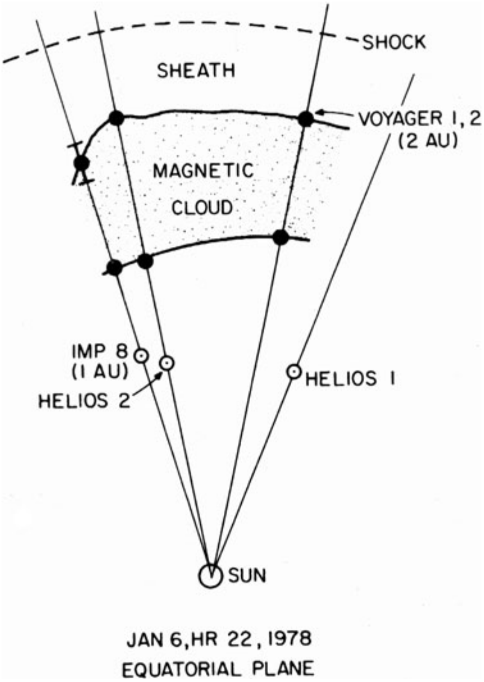

Fig. 2.4 Sketch of the geometry of the magnetic cloud observed by Burlaga et al. [25] from spacecraft observations on 6 January 1978 (their Fig. 5). The dots show where the observed boundaries of the cloud would be at 2200 UT on that day, assuming they moved at constant speed [25]

used today: low temperatures, high magnetic field strength, and a smoothly rotating magnetic field vector. Magnetic clouds also have a long duration, typically about 10–48 h with an average of around 27 h [170].

By 1990, it was accepted that magnetic clouds were probably manifestations of coronal mass ejections [20, 273] and/or filaments [274], that they were regarded as a strong source of increased geomagnetic activity [281] and that they were often drivers of interplanetary shocks [161]. It was also known that only a subset of in-situ ICMEs (30–50%) showed a clear magnetic cloud signature [29, 74]. The rest 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 the same year that Chapman & Ferraro made their suggestion of the ionised material ejection as possibly being responsible for geomagnetic storms, Hale [89] suggested that this material came from large solar flares [89]. Dellinger [44] associated flares with the geomagnetic disturbance known as a sudden ionospheric disturbance (or SID), and Newton [197, 198] found a statistical correlation between large flares and magnetic storms. Later in 1950, Chapman [32], 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. Quoting Kahler [156]:

> Thus, we see that by about 1960 there appeared little reason to doubt that all three solar-terrestrial disturbances — large geomagnetic storms, SIDs and SEP events — were directly caused by the flare itself. (p. 115 [156])

This idea continued into the space era. For example, when interplanetary shocks were first observed by spacecraft in the 1960s, they were assumed to be caused by solar flares, even though effective associations were made with only mixed success [78, 132, 133, 229]. So, when the CME was discovered in the 1970s, it was naturally assumed by many that the CME was also the result of a shock wave from the solar flare. This assumption persisted despite early revelations that CMEs and geomagnetic storms were often not associated with flares [45, 81, 155, 180], and that the energy required to launch the mass ejection was much greater than that of the flare itself [180, 263].

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 expressing doubts about their association with flares. In 1972, Hundhausen expressed concerns about this association [132, 133], and workers using the early CME results from the *Skylab* coronagraph noted the inconsistency between CME and flare occurrence [81]. Joselyn and McIntosh [155] expressed surprise at the small percentage of flare-related geomagnetic storms, and proceeded to question the validity of previous work that found a large percentage of such storms. Sime et al. [223] 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 loop top moved outward through the corona. Further evidence, 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) were presented by Sime and Hundhausen [224]. At the same time, Simnett and Harrison [97, 226, 227] found that the flare associated with the CME was confined to a loop at only one footpoint of the CME, while Harrison and co-workers [94, 96, 98] back-projected CMEs to determine their onset time, and found that none of them were coincident with a solar flare onset. They found that typically the flare onset occurred some time later than that of the CME. Figure 2.5 shows two diagrams produced by Harrison [92] demonstrating the relationship between the CME and its associated flare.

By 1992, evidence of a CME-centred concept had been accumulated from virtually every area of space physics research. In his excellent review in the *Annual Reviews of Astronomy and Astrophysics*, Steve Kahler 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 [156])

The review presented evidence from CME and flare observations themselves, to metric radio bursts, interplanetary shocks and magnetic fields, solar-energetic

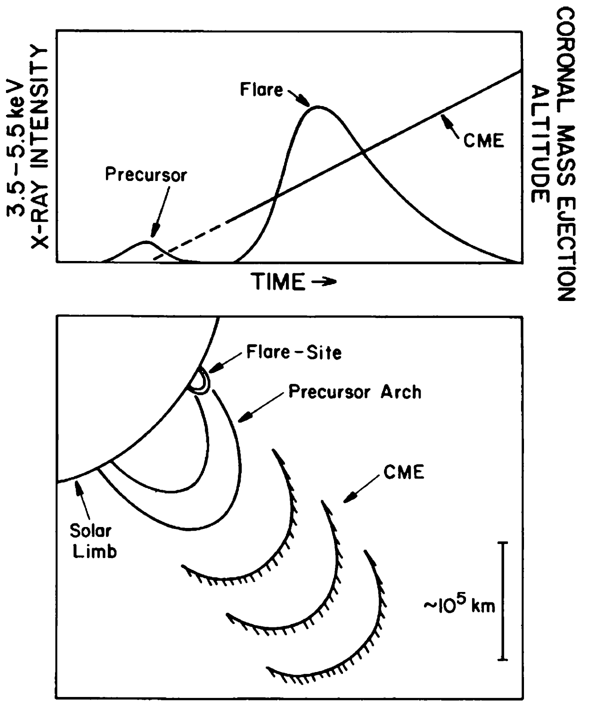

Fig. 2.5 Diagram representing the relationship between the CME and its associated flare (originally from Harrison [92] (his Fig. 6), and reproduced in Hundhausen [134] and Gosling [75]). Reproduced here with permission © ESO. The *top panel* shows the temporal relationship, showing the flare onset time 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

particles and their geomagnetic consequences. Kahler demonstrated that it is the CME, not the flare, which played the central role in major heliospheric and geomagnetic phenomena [156].

Despite the solidity of evidence, most of the solar physics community continued to advocate the flare as the primary source of space weather. A review by Hudson in 1987 listed 42 great discoveries in solar physics and did not even mention CMEs [129], 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 travelling 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 [75]. This paper reviewed and consolidated previous work with the express intention of removing the operation of the flare from "centre stage", at which it was still firmly placed in the eyes of much of the solar-terrestrial community. He confirmed that the source of interplanetary shocks and of most geomagnetic storms was the CME and not the flare, and that the

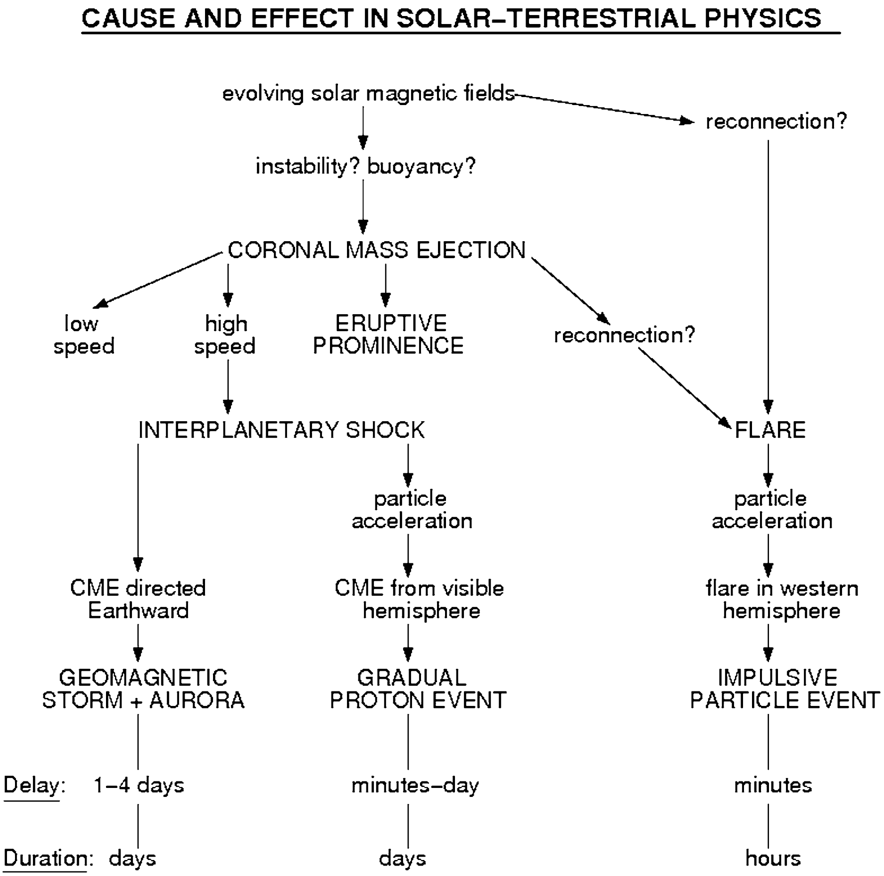

Fig. 2.6 The Gosling "modern paradigm" of cause and effect in solar-terrestrial physics. The events labeled in all caps refer to observational phenomena while lowercase letters indicate physical processes or descriptive characteristics. Reproduced from Gosling [75]

relationship between the flare and CME was secondary at best. He proposed a so called "modern paradigm", shown in Fig. 2.6 (his Fig. 16), describing the relationship between flares, CMEs and geomagnetic activity. Note that two possibilities are suggested for the occurrence of the flare. Either they are connected as secondary to a common physical process (labeled as simply "evolving solar magnetic fields"), or they are a secondary process to that of the CME launch.

This publication 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 [234] 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 [93] referred to the attempted reclassification to encompass virtually all eruptions from the Sun as "very misleading". Other challenges (e.g. Hudson et al. [131] and Pudovkin [203]) 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. Perhaps the clarity of CME data from LASCO proved more conclusive, or perhaps the community was in awe at the quality of the data delivered by *SOHO*, but when the dust settled it appeared that the CME community had prevailed.[4] While the CME and flare "camps" remain largely divided in the solar physics community, it is generally accepted today that CMEs, and consequently large transient solar wind disturbances and geomagnetic storms, are not caused by solar flares. The Gosling paradigm remains the commonly accepted "big picture" of the relationship between CMEs, flares and geomagnetic activity, although it is worth noting that despite this almost unanimous acceptance the remnants of the flare confusion remain. To this day prominent solar physicists still carelessly refer to a flare associated with a CME as its "source". This is often intended to imply the source region of the CME as projected onto the solar surface, but even this association is likely to be inaccurate. Using flares to assist in CME identification is a fundamentally flawed process for two main reasons. Firstly, as often as not the CME is not associated with a significant flare, and secondly, at best, the flare is located at a single footpoint of large CMEs only.

2.5 Interplanetary Scintillation

Also before the detection of CMEs by coronagraphs, the possibility for ICME detection was being investigated from a completely different direction. Sometime in the 1960s (probably 1964 [106]), Tony Hewish and co-workers at Cambridge University discovered that radio signals from distant sources vary as a result of variations in the interplanetary medium This is known as interplanetary scintillation (IPS) and the distortions were observed at radio sources around the metre wavelength level (frequencies around 100 MHz). Using IPS one can monitor the solar wind.[5] and so can monitor density perturbations in the medium. Hence one could track ICME density using IPS. By the discovery of the CME in 1973 several papers on this detection had appeared [107, 114–116]. 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.

[4] The settling of the debate may have occurred at a meeting on CMEs in Bozeman Montana in 1996 where a large number of those from the flare camp were present. According to Jack Gosling (private communication (2009)), Loren Acton, a main player in solar flares, was instrumental in getting the solar community to take notice.

[5] For a review of early work, refer to W. A. Coles in *Space Science Reviews* [37].

By 1978 a number of interplanetary transients had been detected using the IPS technique. Houminer and Hewish [116] and Houminer [115] 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 [258, 260] 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–April 1971 were found to be strongly correlated by Houminer and Hewish [117], and a relationship with the geomagnetic A_p index was also confirmed [117]. Three transients were identified using IPS by Rickett [211] and these were correlated with *Pioneer 9* and *HEOS 2* at the Earth [211]. A further relationship between the A_p index and scintillation parameters was found by Vlasov et al. [252] and later confirmed using data later than 1978 [253, 254]. The work was performed using four separate ground-based radio arrays, two early arrays at Lords Bridge near Cambridge (the $4\frac{1}{2}$ Acre Array [46][6]) and Pushchino near Moscow (BSA Large-Phased Array [251]), and two later ones in San Diego County [4] and Toyokawa [259].

It should be noted that many of the events mentioned above were more likely the result of enhanced density regions of the Sun brought about by the merger of fast and slow streams, phenomena now known as corotating interaction regions (CIRs). Vlasov et al. (1981) 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 (ICMEs), and those that existed for several days (CIRs) [252].

Despite these efforts it remained unclear whether some of the transients observed using IPS were related to the CMEs being observed in the coronagraphs. The CME review paper by MacQueen [180] includes the comment that:

> Radio scintillation measurements have, for the most part, proved to be a disappointment [at associating IPS interplanetary transients with coronagraph mass transients], due principally to the limited temporal and angular coverage brought about by the paucity of suitable radio sources, and also as a result of the low [signal-to-noise ratio] present in the observations of a single event. (p. 618 [180])

It would require an improvement of the IPS technique along with a large statistical database of CMEs produced by the next generation of coronagraphs in order for a firm connection between the two phenomena to be made.

2.5.1 Connecting CME and ICME Images Using IPS Observations

In 1978, the $4\frac{1}{2}$ Acre IPS radio array was upgraded. The collecting area was doubled to create the 3.6 Hectare Array, and the receivers were upgraded. This enabled more radio sources to be monitored, thereby increasing the spatial resolution of the maps

[6] The $4\frac{1}{2}$ Acre Array was the telescope used by Hewish and co-workers to identify the first pulsar, a discovery for which he received the Nobel Prize in Physics in 1974.

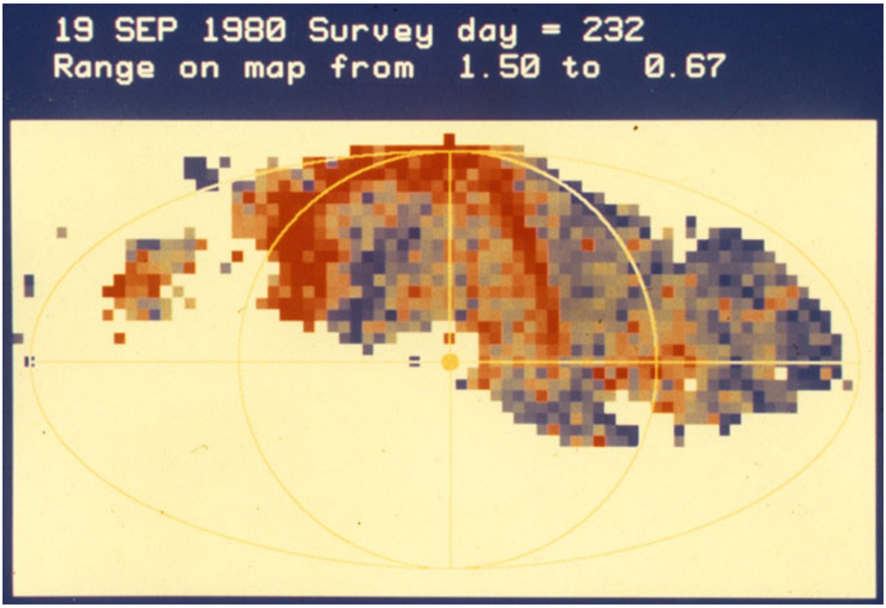

Fig. 2.7 IPS map of an ICME from 19 September 1980. This is a Mollweide projection with the Sun at the centre and the 90° contour shown. Each *square* represents a radio source detected with the 3.6 Hectare Array and a *red square* indicates an increase in density (i.e. part of a possible ICME) [237]

produced by IPS. This, along with the coronagraph dataset provided by *Solwind* and C/P allowed the first comparison of IPS transients with coronagraph CME images. Thus, for the first time ICMEs observed by IPS (the first effective ICME images) were connected with coronagraph CMEs. Figure 2.7 shows an IPS map with a CME from 19 September 1980 from Tappin [237]. Each square on this figure represents a radio source and the red squares are those from which an increase in density has been identified.

In his PhD research work, James Tappin [237] analysed results from a survey of IPS observations from February 1980 to March 1981 using the 3.6 Hectare Array. He identified nine transients with a likely association between CME and IPS transients, three of which were also associated with disappearing filaments. Other papers by Hewish and co-workers later emerged connecting IPS ICMEs with a solar surface feature, but most of these were associated with a low latitude coronal holes [104, 105, 118, 240]. Also through 1981–1985, Woo and co-workers reported on using IPS to study interplanetary shocks, which they connected with blast waves from solar flares [276–278]. It appears that apart from the work of Tappin, a direct association between coronagraph CMEs and IPS ICMEs was not made again until the end of the 1980s (e.g. [222]), or at least not in the literature. Into the 1990s, however, the association was made more readily [144, 275].

2.5.2 White Light ICME Images

Also of vital importance in the connection of CMEs and ICMEs was the first white light heliospheric imager, launched in the mid-1970s on board the *Helios* spacecraft. 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 ~0.3 AU, aphelion ~1.0 AU).

Each contained a white light imager as the zodiacal light experiment [169], 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 centred at 15°, 30° and 90° below the spacecraft equatorial plane, and the first two cameras scanned at 5.6° to 22.5° longitude width, depending on the required angular resolution. Figure 2.8 provides a projected view of the scans of the first two *Helios 2* cameras, from Jackson et al. [151]. While this was not the primary science objective of the instrument, they could be used to obtain partial images of ICMEs in white light for the first time: They would be observed as they passed through the field of view of each camera (note the arc labeled CME in Fig. 2.8).

The usage of *Helios* to detect ICMEs was first demonstrated by Richter et al. [210]. They noted high-latitude "plasma clouds" and measured speeds for a number of them at 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. Thus they noted that if this was the same event then it had experienced a deceleration en-route. Jackson and co-workers took the observations further, and attempted to

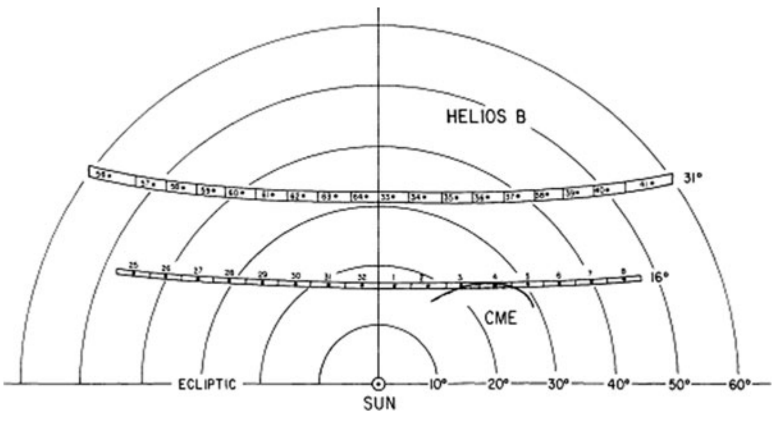

Fig. 2.8 Projection of the field of view of *Helios 2* with a CME leading edge included. This is from a study on the 7 May 1979 CME [151]. The strips shown are from the 15° and 30° photometers from *Helios 2*, with a longitudinal width of 5.6° (Reproduced with kind permission of Springer Science and Business Media)

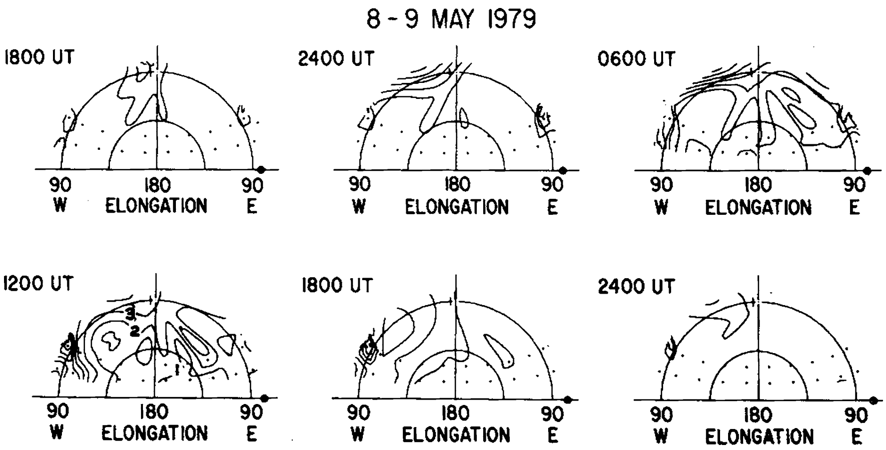

Fig. 2.9 Early attempts at ICME 3-D production for the event on 8–9 May 1979 CME [150]

produce low-resolution images of the density changes. Early works using this technique were published in 1985, 1988 and 1989 [141, 143, 150, 151] and Fig. 2.9 show the results from one of these early production attempts. The technique was developed further through the 1990s [109, 147] and eventually *Helios* white light data were used with IPS data [108]. This is now termed tomography [143] and is still in use for ICMEs mostly by the University of California, San Diego (CASS) today. Other contemporary work compared *Helios* transients with coronagraph CMEs and interplanetary shocks [142, 149, 265, 266], and by the end of the *Helios* era the association between coronagraph CMEs and white light and IPS ICMEs had been firmly established.

Although the early attempts at 3-D construction by *Helios* have been questioned by some, the zodiacal light experiment was a success as a proof of concept for a white light heliospheric imager. Without the success of this instrument, it is likely that the next generation of heliospheric imagers would not have been constructed, even though it took 20 years for the next one to emerge.

2.5.3 Contribution to the Solar Flare Myth Debate

As should be obvious, interplanetary imaging of ICMEs using white light imagers and IPS were contemporary with the Solar Flare Myth debate. So those working in IPS and with *Helios* made their contribution. Early IPS work attempted to connect interplanetary transients with flares [258] and Tappin tried to make this connection with little success [237, 240]. Studies which did make the flare connection include those by Woo and colleagues [276–278]. Hence, by 1985 the connection between IPS ICMEs and solar flares remained ambiguous.

From the white light ICME side, although the majority of the *Helios* photometer workers were in the solar flare “camp”, studies attempting to link the white light

ICMEs were also met with mixed success. Richter et al. [210] in their first results paper tried, but failed to associate solar flares with their observed transients [210], yet others successfully made the connection [235]. Most of the studies, however, wisely focused mostly on the CME connection, and spent less time on the flares.

The latter half of the 1980s saw a series of studies accumulating evidence of a lack of flare association with IPS ICMEs. In a survey of 96 interplanetary transients using IPS, Hewish and Bravo, writing in *Solar Physics* in 1986, found that many events had no association with flares or even disappearing filaments [105]. Houminer and Hewish [118] showed that the large geomagnetic disturbance in August 1972 was not associated with a flare, and presented a case in favour of a coronal hole source. In the same year Hewish, in an article in *New Scientist* stated:

> The widely held textbook theory is that solar flares are responsible... [T]he energy launches blast waves upwards into the solar atmosphere, producing an interplanetary shock wave that could ultimately reach the Earth and produce magnetic storms. This has been the generally accepted theory for the past 50 years, but our new method of mapping interplanetary weather with a radio telescope does not agree with it. (p. 48 [103])

Note that here Hewish refers to "interplanetary weather", which has now been replaced with the more catchy term "space weather". While Hewish and colleagues clearly rejected the notion that magnetic storms were caused by solar flares, they mostly believed that coronal holes were the source of ICMEs and of major space weather at the Earth. Today it is generally accepted that major magnetic storms are probably caused by erupting closed magnetic field structures (CMEs), which do create the occasional coronal hole (see coronal dimming in Sect. 7.2.6). It is also quite clear that recurrent geomagnetic activity is caused by corotating fast streams from equatorial coronal holes or the equatorial extension to polar coronal holes, but the storms caused by these are generally (but not always) not particularly large.

2.6 The 1990s: The Next Generation of Imaging and In-Situ Spacecraft

A list of the spacecraft making significant contributions to our understanding of CMEs is provided in Chap. 3. Section 3.3 reveals that only one such spacecraft was launched in the 1980s (*SMM*), and had that been launched only 2 months earlier it would have been a 1970s launch. 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.[7]

[7] The low corona did continue to be observed by ground coronagraphs throughout, solar flare activity was monitored by the *GOES* spacecraft, and brief studies of the outer corona were provided by the SPARTAN-201 flights with the Shuttle in 1993, 1994, 1995 and 1998.

So, after such a productive decade of space-based solar observatories, why was there such a sudden and prolonged slump? There are two reasons. Firstly, the solar community was largely focused on solar flares, not CMEs. The second reason, I'm convinced, lies in the changes in priority for NASA launches during the 1980s. My understanding is that following the success of the Shuttle (first launched in April 1981), an edict was issued requiring scientific (particularly NASA-funded) spacecraft to be launched via the Shuttle. Unfortunately, launches fell behind in schedule from the very beginning, and thus did the launch of many missions. *Ulysses*, for example, was scheduled to be launched on board *Challenger* in its very next flight following STS-51L on 31 January 1986. History remembers the tragic events of that morning, and the loss of the spacecraft with all hands. The grounding of the Shuttle fleet following the *Challenger* disaster created further delays, and *Ulysses* was finally launched on board *Discovery* in October 1990. It seems likely that NASA had changed its priorities for launches by then, for the next generation of solar and interplanetary medium space observatories would not be launched from the Shuttle.[8]

2.6.1 In-Situ Probes: Ulysses, WIND and ACE

As mentioned in the previous section, the launch of *Ulysses* was delayed considerably through the 1980s and was launched in 1990. On board was an assortment of magnetic field, energetic particle and other experiments (Sect. 3.4) but what was unique about *Ulysses* was its orbit. This spacecraft was charged with the exceptionally difficult task of leaving the ecliptic plane and achieving 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. *Ulysses* passed within six Jovian radii in February 1992, and provided unprecedented information about the planet's magnetosphere in the process. It then moved into its (almost) polar orbit about the Sun, where it has performed over three complete orbits to date. Figure 2.10 shows the third orbit of *Ulysses* from ∼2002–2008.

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. It was already known that the polar regions lay on open magnetic field lines and at the surface were polar coronal holes, long known to be the source of fast-flowing solar wind. *Ulysses* found, for example, that there were two solar wind types, with fast solar wind emanating from the polar regions and slow solar wind at lower latitudes, and no intermediate speed solar wind in-between [185, 255]. Other discoveries include the behaviour of the solar dipole, which seemed to act more like two monopole fields due to the distortion by the solar wind [7], and the blockage of cosmic rays into the polar regions by high levels of Alfvén waves [113]. It was also found that polar magnetic fields were connected with the equatorial regions, if one moved far enough away from the Sun [58, 214].

[8] With the exception of a number of brief flights with the SPARTAN-201 coronagraph.

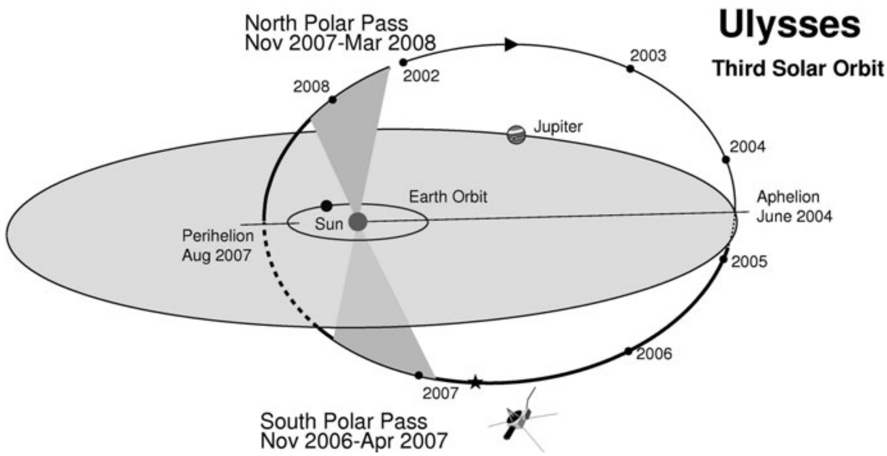

Fig. 2.10 Diagram of the third orbit of *Ulysses* (available courtesy of NASA)

Ulysses also contributed to our understanding of the nature of ICMEs. Gosling (1994) showed that CMEs can occur in the fast solar wind [77] and characteristics of ICMEs at distances from the Sun out to 5 AU were observed in large numbers [26, 80, 217, 282]. Later, ICMEs in *Ulysses* were compared with transients observed with IPS [153, 154] and with heliospheric white light images when they became available [238]. Charge state distributions of ICMEs were investigated using *Ulysses* data by Henke et al. (1998, 2001), 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 [100, 101].

In February 2008, *Ulysses* lost its secondary X-band transmitter which, among other things, allowed 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, just 4 months shy of its 19th anniversary from launch.

The next two solar/interplanetary in-situ spacecraft (*WIND*, launched November 1994 and *ACE*, launched August 1997: refer to Sect. 3.4) contained sophisticated instrumentation and have since been used as scientific and monitoring probes. The instruments on board the *WIND* and *ACE* spacecraft were mostly improved or modified versions of those already tested on previous missions. Many of the instruments on board *ACE*, for example, are actually flight spares from *Ulysses* and *WIND*,[9] and *ACE*/SEPICA is an upgraded version of the *ISEE-3* solar wind particle analyser. Likewise, the orbits from each spacecraft are not unlike those that had been

[9] EPAM is the flight spare for *Ulysses*/HI-SCALE, SWEPAM is the flight spare for *Ulysses*/ SWOOPS, SWICS is the flight spare for *Ulysses*/SWICS, and MAG is the flight spare from *WIND*/MFI.

seen before. The L1 location of *ACE* had been previously occupied by *ISEE-3*, and *WIND* was certainly not the first spacecraft to assume a high-Earth orbit that passed into the upstream solar wind region beyond the magnetosphere (the *Vela* spacecraft were in such orbits in the early 1960s (Sect. 3.1)), although its orbit did take on a slightly unique posture.

So, along with detailed observations of the solar wind and ICMEs, these spacecraft provided a continuous datastream of interplanetary medium and ICME 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 continuous monitoring of solar, interplanetary and magnetospheric activity simultaneously from the perspective of instruments in long-term stable orbits. This greatly enhanced the space weather forecasting product that is still in use. *ACE* remains the most crucial early-detection system for space weather, as it is always in the sunward direction of the Earth and is capable of monitoring both ICME ram pressure and (crucially) magnetic field orientation. *WIND* provides a similar monitoring capacity as well, but its new orbit does not place it Sunward of the Earth very often, and it is too close to the Earth to provide sufficiently advanced forecasting. Also, *WIND* data are not available in real time.

Statistical studies of ICMEs using *WIND* and *ACE* include Cane and Richardson [28, 208], Lynch et al. [176, 177] and Howard and Tappin [124]. The main scientific contributions provided by these spacecraft seem to be advances in our understanding of the composition of ICMEs, and of magnetic clouds. Iron charge distribution of ICMEs were investigated by *ACE* by Gloeckler et al. [67] and Lepri et al. [173] who found typical charges of 9+–11+, but charges greater than 16+ were also identified [67, 173]. 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 ICME-driven shocks [164], and the relationship between composition and solar surface parameters [164, 207].

As mentioned in Sect. 2.3.1.1, it was already known by 1990 that only a small fraction of ICMEs were observed to contain the recognised magnetic cloud structure. However, by that year a global picture of the structure of a magnetic cloud had already been formed [22]. This picture, shown in Fig. 2.11 is described at 1 AU by Lepping [170]:

> [M]agnetic clouds at 1 AU are approximately force-free structures. The magnetic cloud's geometry is that of a nested set of helical magnetic field (**B**) lines confined to a flux tube, which is curved on a scale of about 1 AU (or maybe a little smaller at its nose) ... when considered globally... When examined locally, the structure is approximately cylindrically symmetric, and the pitch angle of the helical field lines increases with increasing distance from the axis of the cloud, such that the field is aligned with the axis of symmetry at the position of the axis and perpendicular to it on the cloud's boundary, in most cases. (pp. 80–81 [170])

Consequently, empirical modelling of magnetic clouds using in-situ data were based on this global picture. A model developed by Burlaga [19] and refined by

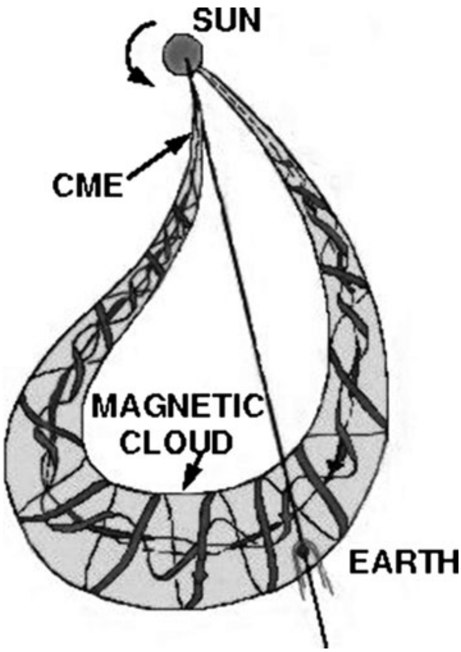

Fig. 2.11 Sketch of a global view of a magnetic cloud through the ecliptic plane, with solar rotation taken into account [183]

Lepping et al. [171] using *ISEE-3* and *IMP-8* (and described further in Sect. 7.3.2) 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, and Riley et al. [212] provides a review of the more popular models.

Another important discovery using *ACE* data is magnetic reconnection within ICMEs, including magnetic clouds. Briefly, magnetic reconnection is the process where field lines from different magnetic regimes are connected, which violates the frozen-in field condition of magnetohydrodynamics (MHD). This enables the transfer of energetic particles across magnetic regimes, and the release of large amounts of stored energy in magnetised plasma environments. We discuss this in further detail with regard to the Earth's magnetic field in Sect. 10.3. The theory of reconnection as applying to solar flares dates back to the electromagnetic "neutral point" idea of Giovanelli [66], which was developed for MHD by Dungey and others through the 1950s [51, 52, 200, 236] and established by Petschek [201]. The exact role of reconnection in CME launch and evolution remains to this day unknown (we discuss some theories surrounding this role in Chap. 8), and although some evidence for reconnection has been observed in coronagraph CME data [225], it had not been directly observed by in-situ spacecraft until recently. Observations by Gosling and co-workers using *ACE* identified this signature [84, 85] and by the end of 2005 over 40 reconnection events had been observed by *ACE* with a large fraction within ICMEs [76].

Since the launch of *WIND* in 1994 several hundred publications have appeared dealing with magnetic clouds with *Ulysses*, *WIND* and *ACE*. Studies have involved comparing them with CMEs [28, 208], solar surface structures [40, 168] and solar flares [204], geoeffectiveness [55, 159], magnetic reconnection [84, 85] and even internal whistler wave propagation [194]. The general picture of magnetic clouds remains as was defined from their discovery, but they are now an integral and essential part of ICME study.

2.6.2 Imaging Observatories: Yohkoh, TRACE

The next generation of imaging observatories began with the launch of the Japanese spacecraft *Yohkoh* in August 1991 (Sect. 3.4). The spacecraft was abundant with imagers, including soft and hard x-ray, and x-ray and gamma-ray spectrometers. The most popularly used instrument appears to be the Soft X-ray Telescope (SXT [246]), which provided whole-disk images of the Sun in soft x-rays. New features associated with CMEs were observed with this instrument, including the "sigmoid" of active regions [1, 215] (Sect. 7.2.8) and a renewed inspiration to study coronal dimming [73, 232] (Sect. 7.2.6). Of great significance was the overlap in observing between *Yohkoh* and *SOHO*, which does not have an x-ray imager on board. Studies comparing CMEs with *Yohkoh*/SXT include Webb [261], Hudson et al. [130] and Sterling et al. [233].

Another milestone in solar coronal observations was provided by the *Transition Region And Coronal Explorer* (*TRACE*) spacecraft. This is a dedicated NASA Small Explorer (SMEX) mission providing high-resolution, multiwavelength EUV images of a selected region of the Sun [90]. Because of its limited field-of-view, it is a campaign-based instrument, meaning that researchers apply for observing time on the instrument to study a region of interest on the Sun. *TRACE* provided views of the corona in unprecedented detail, along with some spectacular movies of eruptions in the low corona. It has allowed an investigation of the structure of flux ropes and loops in the low corona, along with the nature of the helicity (twist) of magnetic structures during an eruption [3, 6]. Thus it has also assisted in model development of CME eruptions. CME work involving *TRACE* includes Zhang and Wang [280], Goff et al. [69], and Qiu et al. [204].

Yohkoh observed the Sun for 10 years (almost an entire solar cycle) until it ceased operations in December 2001. *TRACE* completed its final observing sequence in June 2010 after just over 12 years in operation.

2.6.3 The Solar and Heliospheric Observatory (SOHO)

There are many reasons why the cornerstone of solar observing to this day is the *Solar and Heliospheric Observatory* (*SOHO*), and not just because it was identified by the European Space Agency (ESA) as part of the "cornerstone" of its long-term

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	[11]
LASCO	Large Angle Spectroscopic Coronagraph	1.1–30 $R_\odot$	White light and EUV coronagraph	[17]
EIT	Extreme-ultraviolet Imaging Telescope	Full solar disk	Multiwavelength EUV imager.	[43]
MDI	Michelson Doppler Imager	Full solar disk	Solar oscillations and magnetic field investigation	[218]
UVCS	UltraViolet Coronagraph Spectrometer	$\sim 40 \times 60'$	UV spectroscopy and visible polarimetry studies	[162]
CDS	Coronal Diagnostic Spectrometer	$\sim 240 \times 240''$	EUV imaging spectrometer	[95]
SUMER	Solar Ultraviolet Measurements of Emitted Radiation	Thin slits	EUV analysis	[272]
CELIAS	Charge, Element, and Isotope Analysis System	N/A	Solar wind and particle detector	[119]
COSTEP	Comprehensive Suprathermal and Energetic Particle Analyzer	N/A	Energetic particle detector	[195]
ERNE	Energetic and Relativistic Nuclei and Electron experiment	N/A	Energetic particle detector	[243]
GOLF	Global Oscillations at Low Frequencies	N/A	Helioseismology observer	[63]
VIRGO	Variability of the Solar Irradience and Gravity Oscillations	N/A	Helioseismology and radiometry	[62]

"Horizon 2000" science program. First and foremost was the quality and variety of the data provided by its 12 instruments (summarised in Table 2.1). While many of these types of instruments had been used in the past, on *SOHO* they were of higher resolution and 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 to be 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 uncontrollable 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 [245] but it was actually caused by a combination of blunders. It is very rare for a spacecraft to be recovered once such a malfunction has occurred. This is the only critical malfunction to occur in *SOHO* during its 15 years lifetime, although 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 *SDO* launch some of *SOHO*'s instruments have become redundant and so have been turned off. Most recently MDI in April 2011.

Almost all of the instruments on board *SOHO* returned to operation unscathed during the 1998 incident, with the exception of the LASCO/C1 camera. Nobody knows for certain what happened to C1, but it generally believed that one of the glass plates of the Fabry-Perot was misaligned when the instrument froze (in the early stages of the spin, the side of the spacecraft on which LASCO was located was pointing away from the Sun). Thus, C1 was disabled before most workers had really figured out how to work with it.[10] Unlike C2 and C3 which were mandated to continuously observe the Sun (following a decision by the late Guenther Brueckner, original Principal Investigator of LASCO), C1 remained essentially a campaign instrument, so joint studies with the other coronagraphs were often difficult. Hence, relatively few scientific investigations of CMEs have been performed using C1. Some examples include Plunkett et al. [202], Cook et al. [38], and Mierla et al. [191].

The other two instruments, C2 and C3 have gone on to great heights. 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. While many of the parameters CMEs documented had been measured with previous instruments (kinematics, mass, energy), LASCO provided them with a sensitivity not before seen, and has now for the first time provided a continuous dataset of observations for more than an entire solar cycle. 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 2008, the latter provided details on just under 14,000 CMEs observed with LASCO C2 and C3. Milestones achieved by these instruments include:

1. The largest database of CMEs, by an order of magnitude.
2. The first statistical database of CME properties over an entire solar cycle.

[10] I like to joke that LASCO should now be called LACO, as the spectroscopic capabilities of the instrument were lost when C1 ceased to operate.

3. Unprecedented statistical details on CME properties [279].
4. The first large database of halo CMEs and their relationship with space weather and interplanetary shocks [124].
5. The first attempts at 3-D reconstruction of CMEs [123].
6. Studies of the onset region of CMEs, including evidence of magnetic reconnection [225].

Although some of the instruments on board *SOHO* have been eclipsed by their successors (e.g. *SDO*), LASCO remains crucial to the solar mission despite its succession by newer space coronagraphs. It is probably the main reason for why the *SOHO* mission remains active – had it not been for the unique dataset provided by LASCO, the spacecraft would likely have been retired in 2008.

2.6.3.1 Information Exchange

Another reason for the success of *SOHO* is the manner with which its information was disseminated to the scientific and general community. The importance of the internet, or specifically the World Wide Web regarding information exchange cannot be overstated. For previous space missions, data were available either via specific publications (such as the King NSSDC Interplanetary Medium Data Book [39, 160] or from scientific publications), or via personal request to those responsible for collecting and maintaining the data (i.e. those who owned the dataset). The latter particularly applied to early coronagraph data. Hence, scientific information related to the Sun and CMEs was typically only available to the scientific elite, and public exposure was extremely limited. The World Wide Web became widely used around the time of the launch of *SOHO*,[11] which enabled NASA to introduce its open-data policy. Hence through the Web, data from *SOHO* were universally available, thereby increasing its popularity, accessibility and public exposure. Scientists and the general public alike can to this day access *SOHO* data in whichever form is preferred, from the high-quality "FITS" files to complete images constructed by the *SOHO* analysis teams. NASA now encourages an open data policy on many of its scientific missions, and it is now the accepted standard for the generations of solar and space missions (and not only the NASA ones) that have followed. Table 2.2 provides a selection of popular websites at which space science data are accessible to the general public. There are many others and the list continues to grow.

UFOs? Or Misuse of Data?

Provision of scientific data to the general public has proven to be an outstanding success in terms of exposure, scrutiny and public participation in scientific work. For example, the University of California, Berkeley's SETI@Home project, launched in

[11] The World Wide Web Consortium (WC3), for example, was founded in September 1994 [152].

Table 2.2 A selection of popular websites at which space science data are available. These range from the general to the specific, such as those managed by a single spacecraft team

Name	Manged by	URL
General		
National Space Science Data Center	NASA/GSFC	http://nssdc.gsfc.nasa.gov/space/
Coordinated Data Analysis Workshop (CDAW)	NASA/GSFC	http://cdaw.gsfc.nasa.gov/
Solar-Geophysical Data	NOAA	http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp
Solar Data Analysis Center	NASA/GSFC	http://umbra.nascom.nasa.gov/sdac.html
Community Coordinated Modeling Center	NASA/GSFC	http://ccmc.gsfc.nasa.gov/models/index.php
Solar Data	NOAA	ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/
Specific		
SOHO Data	NASA/GSFC	http://sohowww.nascom.nasa.gov/data/data.html
STEREO Science Center	NASA/GSFC	http://stereo-ssc.nascom.nasa.gov/data/
ACE Science Center	Caltech	http://www.srl.caltech.edu/ACE/ASC/
WIND MFI Page	NASA/GSFC	http://lepmfi.gsfc.nasa.gov/
Yohkoh SXT Data	MSU	http://www.lmsal.com/SXT/data.html

1999 [2], has taken public participation to a new level, by analysing data using the processing power of home computers. Comet hunters have used the *SOHO*/LASCO coronagraphs to identify hundreds of new comets, assisting LASCO in becoming the instrument with the greatest number of comet discoveries (a review on the comet work can be found in Biesecker et al. [12] and a "Sungrazing Comet" website has been established by NRL which can be found at http://sungrazer.nrl.navy.mil/index.php). Accessibility has also improved public awareness and interest in space science and has encouraged new generations of scientists (myself included) to join the community.

The downside to an open data policy is the increased risk of misuse or misinterpretation. For example, there are no shortage of conspiracy theories surrounding data from Mars and the other planets. Regarding solar instruments, my personal favourite (probably because I was working in the UK Midlands at the time) involves the "UFO superhighway" supposedly passing through the field of view of some of the solar imagers. It was cited by UFO hunters as the most conclusive evidence of UFOs yet obtained. Here's the story:

In January 2003, the British Newspaper *The Daily Mail* reported that *SOHO* was beaming back:

> hundreds of images of UFOs travelling along a kind of super-highway. [249]

They were provided with one such image by the owner of an electronics company in Manchester, who stated that the images were provided to him by a Spanish businessman using a large dish to directly collect *SOHO* data.

The objects observed were claimed to be on-edge flying saucers that were only a few hundred miles from *SOHO* itself, and that they failed to navigate a straight course, indicating a form of intelligence. Other newspapers reported the claims, including the *Perth Sunday Times* and *The Evening News of Scotland* and they were due for presentation at the National Space Centre in Leicester.

Unfortunately (and not surprisingly), these claims turned out to be untrue. Suspicions were immediately raised when the claimants did not release the original images, but only the digitally enhanced ones. It was also noted that the "UFOs" were always seen edge-on. NASA responded later that month with a "How to Make Your Own UFO" page, which can be found on the *SOHO* website at http://sohowww.nascom.nasa.gov/hotshots/2003_01_17/. They showed that bright objects, such as planets and (in that case) cosmic ray hits saturate the cameras on *SOHO*, resulting in a "bleeding" of the intensity of the object to the left and right of the instrument's CCD. These can be isolated and heavily processed using any number of graphics-editing software packages, to produce the "UFO" image. Figure 2.12 shows how this can be achieved.

Finally, the success of *SOHO* can also be attributed to the publicity, or "PR machine" behind the mission. Along with the open-data policy, the "PR" team was responsible for public outreach programs, classes for students including an online "Ask Dr. SOHO" email exchange, a screen saver, a cutout module of the spacecraft, and even souvenirs ranging from cards with moving images to small satchels of sunscreen with an image of the Sun as observed in EUV. The *SOHO* team appears to have been the first solar research team to seriously attempt to reach the general public in this way, and its success has set a precedent for the missions that followed.

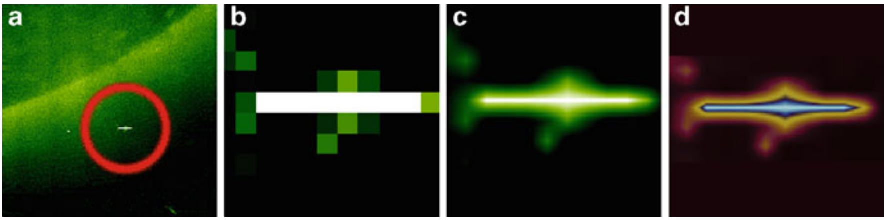

Fig. 2.12 How to make a UFO using *SOHO* images. (**a**) The original: a section of a *SOHO*/EIT image. The circle highlights a cosmic ray hit. (**b**) Step 1: Cut-out the region of interest and enlarge, this image shows the cosmic ray pixels highlighted on the image to the left, with a little different colour scaling. (**c**) Step 2: Interpolate the enlarged image (using any one of many methods) instead of simply re-sampling it. (**d**) Step 3: Change and "touch up" the colour table, and we have what may look like a nice UFO with a glow and exhaust fumes! (Courtesy of the NASA *SOHO* team)

2.7 The 2000s: Continuous Monitoring of CMEs, ICMEs and Space Weather

We now move towards the present day, and the contributions from missions launched since 2000. There are five missions of relevance in this decade, all of them containing imagers and one with in-situ instruments as well. Regarding their contribution to our understanding of CMEs, three of these missions are in a similar league with *Yohkoh* and *TRACE*, that is they provided detailed information on solar surface characteristics, but nothing beyond the low corona in the Sun. These are reviewed briefly and further details may be found in Sect. 3.5. The other two have contributed greatly to our understanding of CMEs and particularly ICMEs, and are discussed in greater detail.

2.7.1 Low Corona and Solar Observers: RHESSI and Hinode

The first of the twenty-first century dedicated solar observatories was the *High Energy Solar Spectroscopic Imager* (*HESSI*), launched in February 2002 and renamed *RHESSI* in honour of Reuven Ramaty who passed away in 2001 [112]. *RHESSI* is a hard and soft x-ray imager, and in such capacity cannot observe CMEs directly. However the solar surface phenomena associated with CMEs have been studied in great detail. Among the achievements of these instruments are microflare heating of the solar corona [10] and polarization measurements of solar gamma-ray flares [13], and while little work has been done with CMEs, some work includes flare/CME energy comparison [53] and CME-associated coronal waves [256].

In September 2006, the Japanese spacecraft *Hinode* was launched. As with *RHESSI*, the purpose of *Hinode* is to investigate the solar surface, not CMEs. On board are x-ray and visible light imagers (SXT [71] and SOT [247]) and an EUV spectrometer (EIS [41]). CME work with *Hinode* to date has been mainly for comparison purposes, to investigate the solar response to CME launches. Such work includes Harra et al. [91], Webb [262] and MacIntosh [179].

It is also important to note that although not dedicated solar observatories, *GOES* spacecraft also carry soft x-ray instruments for monitoring the Sun. They have been doing so since 1974 as part of the Sun Environment Monitor (SEM). *GOES-12* (launched in 2001) was the first to include an x-ray imager. The *GOES* instruments are used for cataloging x-ray flares – the A, B, C, M and X classes describe x-ray flux as observed by *GOES*.

2.7.2 2003: SMEI – The First Complete White Light ICME Images

In the same month in 2003 that the news of UFOs in the *SOHO* images were being addressed, the USAF/NRL spacecraft *Coriolis* was launched. On board was a polarimetric microwave radiometer designed for space-based monitoring of ocean wind speed and direction, called WINDSAT. Also on board was an almost full-sky camera payload, designed to monitor interplanetary transients in white light. The instrument, called the Solar Mass Ejection Imager or SMEI [54, 145] was the first instrument since *Helios* (20 years prior) to observe the outer corona/interplanetary medium in white light and the first instrument to provide complete white light images of ICMEs.

SMEI consists of three scanning cameras which build up an image of the sky throughout its 102 polar orbit about the Earth. It observes the sky starting from around 20° elongation, or around 0.35 AU (75 $R_\odot$). While parts of the images are 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 has allowed for the first time direct measurement of complete ICMEs through white light. As with coronagraph images, the images are heavily projected, but unlike coronagraphs the projection effects may be reduced with the application of some sophisticated geometry (refer to Sect. 5.3). Hence, SMEI allows three-dimensional reconstructions of ICMEs.

Early work with SMEI involved mostly height-time comparisons with coronagraph CMEs, interplanetary shocks and geomagnetic storms [128, 238, 239, 264] but some three-dimensional work has been attempted from the start. For example, Jackson and co-workers have extended his tomographic reconstruction work (which originally used *Helios* and later IPS work) to include SMEI data [146] and myself and co-workers have performed more simplified reconstruction techniques based on leading edge measurements of SMEI ICMEs [123, 128]. Figure 2.13 shows results from one such event.

The most recent work with SMEI involves the utilisation of the projection effects in order to accurately reconstruct the three-dimensional structure and trajectory of ICMEs. The theory behind this reconstruction is discussed in Chap. 5, but briefly it involves applying the physics of CME appearance and geometry relative to an observer in order to reconstruct the ICME itself. This work is still in its infancy but discussion of the development and utility of this technique has appeared in a series of three papers by myself and James Tappin in *Space Science Reviews* [126, 127, 241].

2.7.3 2006: STEREO – A New Approach to Solar Observation

The successes of SMEI and *Helios* contributed to the launch of a white light heliospheric imager on board the next solar observatory. The *STEREO* spacecraft [158], launched a month after the launch of *Hinode* in 2006, assumed an orbit and 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

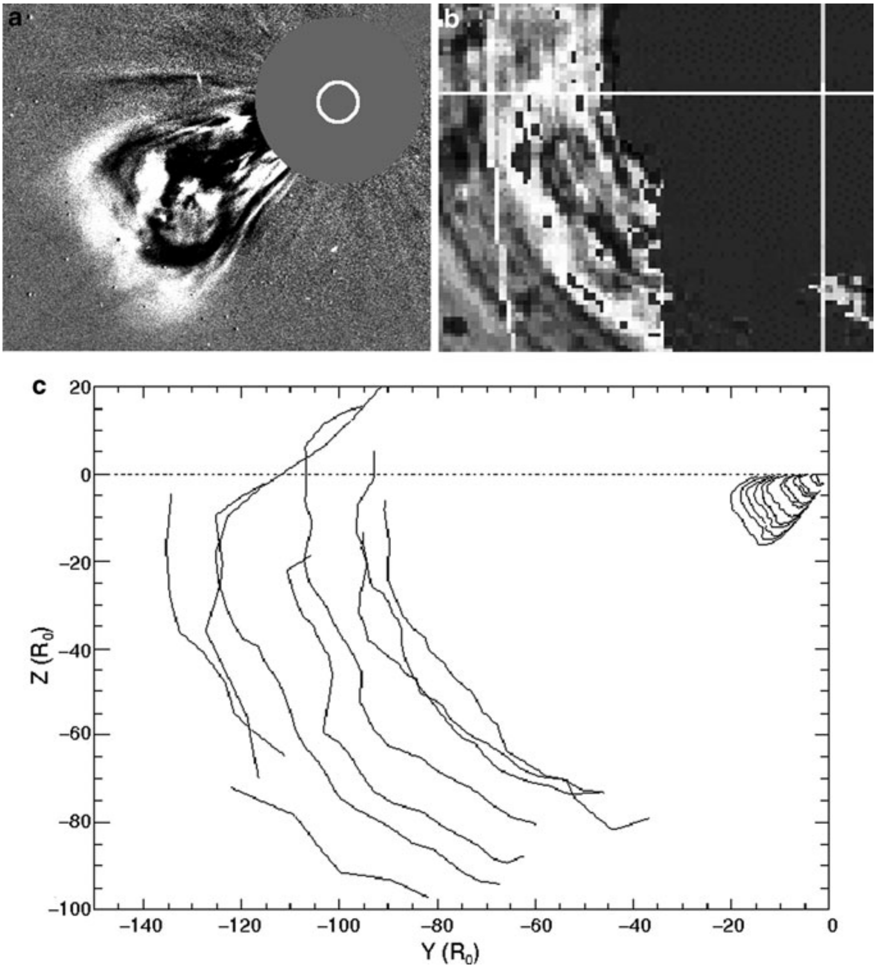

Fig. 2.13 Images of a CME observed by LASCO and SMEI in February 2004. (**a**) LASCO/C3 image obtained on 2004/02/15 at 08:18 UT. The *white circle* represents the solar surface and the *grey disk* is the occulter. (**b**) SMEI image obtained on 2004/02/16 at 07:01 UT. The horizontal and vertical lines cross at the location of the Sun. (**c**) Three-dimensional reconstruction of the leading edge of the CME combining the entire sequence of leading edge measurements from LASCO and SMEI. Because this event was very close to the sky plane, there is no Sun–Earth component for this event [123]

in leading and lagging spacecraft in the ecliptic plane. Figure 2.14 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 ICMEs [123, 127], the *STEREO* imagers allow a three-dimensional image of solar structures much in the same way as depth is perceived using our two eyes. As the spacecraft become

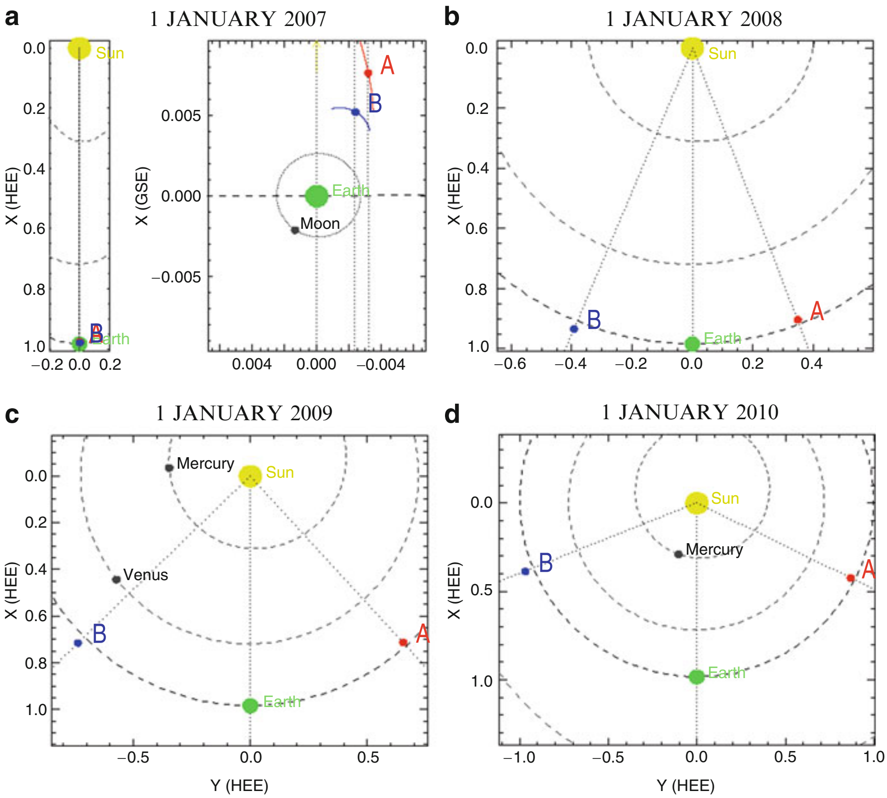

Fig. 2.14 The location of the *STEREO* spacecraft on 1 January of (**a**) 2007, (**b**) 2008, (**c**) 2009, (**d**) 2010 (from the STEREO website). The *coloured circles* indicate the following: Yellow = Sun, green = Earth, red = *STEREO-A*, blue = *STEREO-B*. The angular separation between the spacecraft and the Sun–Earth line grows by around 22.5° per day (Images provided courtesy of the "Where is STEREO" tool (NASA/GSFC))

separated further, three-dimensional reconstructions became possible with different instruments, first with the EUV low corona structures [5, 174], then the coronagraphs [125, 190], and finally the heliospheric imagers [127]. The results from one such reconstruction are shown in Fig. 2.15.

The *STEREO* spacecraft continue to move apart and are functioning to date. 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

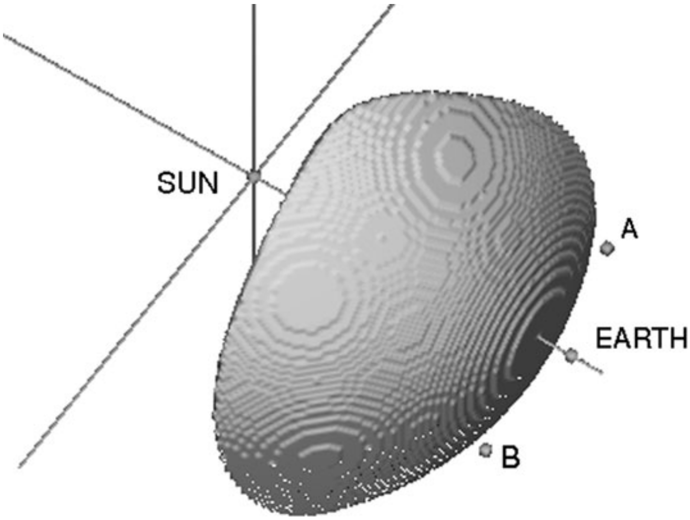

Fig. 2.15 Three-dimensional reconstruction of the leading edge of an ICME observed by SMEI and both *STEREO* in November 2007. The *grey surface* represents the leading edge of the ICME, and A and B are the locations of *STEREO-A* and *-B* at the time of the event. The location of the Earth and Sun are also indicated [127]

heliosphere, and they are reaching the edges of the heliosphere [42]. By the year 2000, they were over 58 AU from the Sun and were still capable of observing ICMEs even there. At those distances, ICMEs tend to merge with other dense regions (such as corotating interaction regions or other ICMEs), the combination of which are called merged interaction regions (MIRs [23], see Sect. 9.7). Richardson et al. [209] 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. [24] and a series of events the following year [257]. A review of Voyager observations of MIRs involving CIRs can be found in Lazarus et al. [167].

Along with the *Voyager* observations, new publications continue to emerge from ongoing missions dating from the 70s, such as *IMP-8* [72, 172]. Also, analysis of data from spacecraft no longer operating continue to yield new scientific results, such as those from *Helios* [72, 148, 175], *ISEE-3* [57, 213], *Solwind* [36, 157] and *SMM* [18, 181].

2.9 Summary

To summarise, 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 free electrons in the CME,

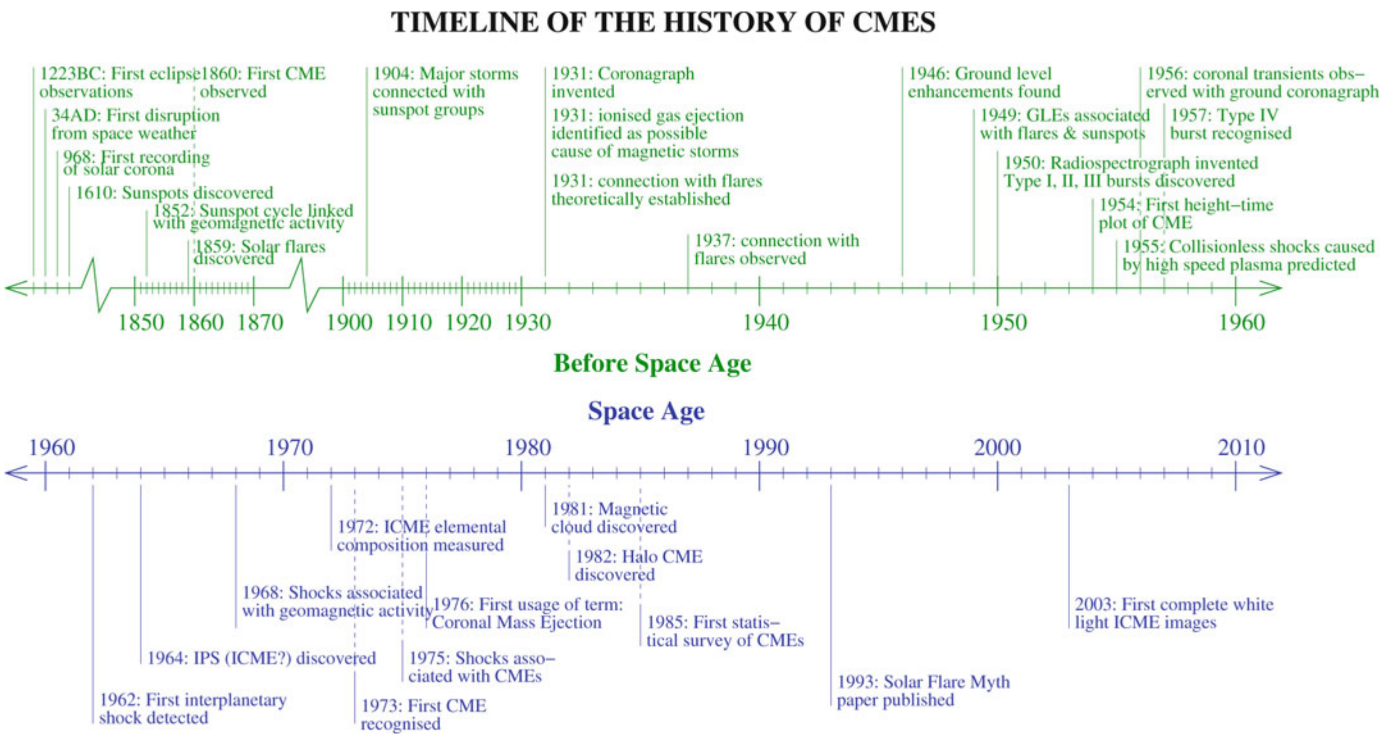

Fig. 2.16 Timeline of the significant events that have led to an enhancement of our understanding of CMEs. It has been divided into before and during the space age (green and blue respectively)

2. Directly measuring properties of the ICME as it passes by in-situ spacecraft,
3. Measuring the changes in longwave radio signals from distant sources as the ICME passes between them and the Earth (IPS),

And 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 2.16 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 emergence of the first spacecraft around 1960, our understanding of interplanetary transients and the interplanetary medium had a firm foundation.

2.9.1 The Future

As this is a history chapter, I will only briefly mention those missions planned for the future. Further details on the current plans for these missions can be found in Sect. 3.6.

On 11 February 2010, a new solar observatory which many regard as the next generation of *SOHO* was launched. The *Solar Dynamics Observatory* (*SDO*) is an geosynchronous orbit and contains a suite of instruments for solar observation, including white light, UV and EUV imagers. Other planned missions for the 2010–2020 decade include NASA's Solar Sentinels and Solar Probe, NASA/ESA's Solar Orbiter and JAXA's Solar-C all tentatively planned for launch in 2018.

References

1. Acton, L., Tsuneta, S., Ogawara, Y., Bentley, R., Bruner, M., Canfield, R., Culhane, L., Doschek, G., Hiei, E., Hirayama, T.: Science **258**, 618–625 (1992).
2. Anderson, D.P., Cobb, J., Korpela, E., Lebofsky, M., Werthimer, D.: Comm. ACM **45**, 56–61 (2002).
3. Antiochos, S.K.: Astrophys. J. **502**, L181 (1998).
4. Armstrong, J.A., Coles, W.A.: J. Geophys. Res. **77**, 4602–4610 (1972).
5. Aschwanden, M.J., Wülser, J.-P., Nitta, N.V., Lemen, J.R.: Astrophys. J. **679**, 827–842 (2008).
6. Aulanier, G., DeLuca, E.E., Antiochos, S.K., McMullen, R.A., Golub, L.: Astrophys. J. **540**, 1126–1142 (2000).

7. Balogh, A., Smith, E.J., Tsurutani, B.T., Southwood, D.J., Forsyth, R.J., Horbury, T.S., Science **268**, 1007–1010 (1995).
8. Bame, S.J., Asbridge, J.R., Feldman, W.C., Fenimore, E.E., Gosling, J.T.: Solar Phys. **62**, 179–201 (1979).
9. Bame, S.J., Asbridge, J.R., Hundhausen, A.J., Strong, I.B.: J. Geophys. Res. **73**, 5761–5767 (1968).
10. Benz, A.O., Grigis, P.C.: Solar Phys. **210**, 431–444 (2002).
11. Bertaux, J.L., Kyrölä, E., Quémerais, E., Pellinen, R., Lallement, R., Schmidt, W., Berthé, M., Dimarellis, E., Goutail, J.P., Taulemesse, C., Bernard, C., Leppelmeier, G., Summanen, T., Hannula, H., Huomo, H., Kehlä, V., Korpela, S., Leppälä, K., Strömmer, E., Torsti, J., Viherkanto, K., Hochedez, J.F., Chretiennot, G., Peyroux, R., Holzer, T.: Solar Phys. **162**, 403–439 (1995).
12. Biesecker, D., Lamy, P., St. Cyr, O.C., Llebaria, A., Howard, R.: Icarus **157**, 323–348 (2002).
13. Boggs, S.E., Coburn, W., Kalemci, E.: Astrophys. J. **638**, 1129–1139 (2002).
14. Boischot, A.: C. R. Acad. Sci. **244**, 1326 (1957).
15. Borrini, G., Gosling, J.T., Bame, S.J., Feldman, W.C.: J. Geophys. Res. **87**, 7370–7378 (1982).
16. Borrini, G., Gosling, J.T., Bame, S.J., Feldman, W.C.: Solar Phys. **83**, 367–378 (1983).
17. Brueckner, G.E., Howard, R.A., Koomen, M.J., Korendyke, C.M., Michels, D.J., Moses, J.D., Socker, D.G., Dere, K.P., Lamy, P.L., Llebaria, A., Bout, M.V., Schwenn, R., Simnett, G.M., Bedford, D.K., Eyles, C.J.: Solar Phys. **162**, 357–402 (1995).
18. Burkepile, J.T., Hundhausen, A.J., Stanger, A.L., St. Cyr, O.C., Seiden, J.A.: J. Geophys. Res. **109**, doi:10.1029/2003JA010149 (2004).
19. Burlaga, L.F.: J. Geophys. Res. **93**, 7217–7224 (1988).
20. Burlaga, L.F., Behannon, K.W.: Solar Phys. **81**, 181–192 (1982).
21. Burlaga, L.F., Klein, L., Sheeley, N.R., Jr., Michels, D.J., Howard, R.A., Koomen, M.J., Schwenn, R., Rosenbauer, H.: Geophys. Res. Lett. **9**, L1317–L1320 (1982).
22. Burlaga, L.F., Lepping, R.P., Jones, J.A.: In Russell, C.T., Priest, E.R., Lee, L.C. (eds.) Geophys. Monog. Ser. **58**, p.373, AGU, Washington DC (1990).
23. Burlaga, L.F., McDonald, F.B., Goldstein, M.L., Lazarus, A.J.: J. Geophys. Res. **90**, 12127–12039 (1985).
24. Burlaga, L.F., Ness, N.F., Richardson, J.D., Lepping, R.P.: Solar Phys. **204**, 399–411 (2001).
25. Burlaga, L., Sittler, E., Mariani, F., Schwenn, R.: J. Geophys. Res. **86**, 6673–6684 (1981).
26. Burton, M.E., Smith, E.J., Goldstein, B.E., Balogh, A., Forsyth, R.J., Bame, S.J.: Geophys. Res. Lett **19**, L1287–L1289 (1992).
27. Cane, H.V., Kahler, S.W., Sheeley, N.R., Jr.: J. Geophys. Res. **91**, 13321–13329 (1986).
28. Cane, H.V., Richardson, I.G.: J. Geophys. Res. **108**, doi:10.1029/2002JA009817 (2003).
29. Cane, H.V., Richardson, I.G., St. Cyr., O.C.: J. Geophys. Res. **102**, 7075–7086 (1997).
30. Carrington, R.C.: Mon. Not. R. Astron. Soc. **20**, 13–15 (1860).
31. Carrington, R.C.: Observations of Spots on the Sun, Williams and Norgate, London (1863).
32. Chapman, S.: J. Geophys. Res. **55**, 361 (1950).
33. Chapman, S., Ferraro, V.C.A.: Terr. Mag. Atmos. Electr. **36**, 77–97 (1931a).
34. Chapman, S., Ferraro, V.C.A.: Terr. Mag. Atmos. Electr. **36**, 171–186 (1931b).
35. Chapman, S., Ferraro, V.C.A.: Terr. Mag. Atmos. Electr. **37**, 147–156 (1932).
36. Cliver, E.W., Ling, A.G.: Astrophys. J. **556**, 432–437 (2001).
37. Coles, W.A.: Space Sci. Rev. **21**, 411–425 (1978).
38. Cook, J.W., Socker, D.G., Korendyke, C.M., Howard, R.A., Brueckner, G.E., Karovska, M., Wood, B.E.: Adv. Space Res. **25**, 1883–1886 (2000).
39. Couzens, D.A., King, J.H.: Interplanetary Medium Data Book – Supplement 3A, 1977–1985, NSSDC (1986).
40. Crooker, N.U.: J. Atmos. Solar Terr. Phys. **62**, 1071–1085 (2000).
41. Culhane, J.L., Harra, L.K., James, A.M., Al-Janabi, K., Bradley, L.J., Chaudry, R.A., Rees, K., Tandy, J.A., Thomas, P., Whillock, M.C.R., Winter, B., Doschek, G.A., Korendyke, C.M., Brown, C.M., Myers, S., Mariska, J., Seely, J., Lang, J., Kent, B.J., Shaughnessy, B.M., Young, P.R., Simnett, G.M., Castelli, C.M., Mahmoud, S., Mapson-Menard, H., Probyn, B.J., Thomas, R.J., Davila, J., Dere, K., Windt, D., Shea, J., Hagood, R., Moye, R., Hara, H., Watanabe, T., Matsuzaki, K., Kosugi, T., Hansteen, V., Wikstol, Ø.: Solar Phys. **243**, 19–61 (2007).

42. Decker, R.B., Krimigis, S.M., Roelof, E.C., Hill, M.E., Armstrong, T.P., Gloeckler, G., Hamilton, D.C., Lanzerotti, L.J.: Science **309**, 2020–2024 (2005).
43. Delaboudiniére, J.-P., Artzner, G.E., Brunaud, J., Gabriel, A.H., Hochedez, J.F., Millier, F., Song, X.Y., Au, B., Dere, K.P., Howard, R.A., Kreplin, R., Michels, D.J., Moses, J.D., Defise, J.M., Jamar, C., Rochus, P., Chauvineau, J.P., Marioge, J.P., Catura, R.C., Lemen, J.R., Shing, L., Stern, R.A., Gurman, J.B., Neupert, W.M., Maucherat, A., Clette, F., Cugnon, P., van Dessel, E.L.: Solar Phys. **162**, 291–312 (1995).
44. Delinger, J.H.: Terr. Mag. Atmos. Electr. **42**, 49–53 (1937).
45. Demastus, H.L., Wagner, W.J., Robinson, R.D.: Solar Phys. **100**, 449–459 (1973).
46. Dennison, P.A., Hewish, A.: Nature **213**, 343–346 (1967).
47. De Vaucouleurs, G.: Astronomical Photography, New York: MacMillan (1961).
48. Dryer, M.: Space Sci. Rev. **33**, 233–275 (1982).
49. Dryer, M.: Space Sci. Rev. **67**, 363–419 (1994).
50. Dryer, M., Smith, Z.K., Endrud, G.H., Wolfe, J.H.: Cosmic Electrodyn. **3**, 184–207 (1972).
51. Dungey, J.W.: Phil. Mag. **44**, 725 (1953).
52. Dungey, J.W.: In Lehnert, B (ed.), Proc IAU Symp. **6**, 135 (1958).
53. Emslie, A.G., Kucharek, H., Dennis, B.R., Gopalswamy, N., Holman, G.D., Share, G.H., Vourlidas, A., Forbes, T.G., Gallagher, P.T., Mason, G.M., Metcalfe, T.R., Mewaldt, R.A., Murphy, R.J., Schwartz, R.A., Zurbuchen, T.H.: J. Geophys. Res. **109**, doi:10.1029/2004JA010571 (2004).
54. Eyles, C.J., Simnett, G.M., Cooke, M.P., Jackson, B.V., Buffington, A., Hick, P.P., Waltham, N.R., King, J.M., Anderson, P.A., Holladay, P.E.: Solar Phys. **217**, 319–347 (2003).
55. Farrugia, C.J., Scudder, J.D., Freeman, M.P., Janoo, L., Lu, G., Quinn, J.M., Arnoldy, R.L., Torbert, R.B., Burlaga, L.F., Ogilvie, K.W., Lepping, R.P., Lazarus, A.J., Steinberg, J.T., Gratton, F.T., Rostoker, G.: J. Geophys. Res. **103**, 17261–17278 (1998).
56. Fenimore, E.E.: Astrophys. J. **235**, 245–257 (1980).
57. Feroci, M., Hurley, K., Duncan, R.C., Thompson, C.: Astrophys. J. **549**, 1021–1038 (2001).
58. Fisk, L.A.: J. Geophys. Res. **101**, 15547–15554 (1996).
59. Forbush, S.E.: Phys. Rev. **70**, 771–772 (1946).
60. Forbush, S.E., Gill, P.S., Vallarta, M.S.: Rev. Mod. Phys. **21**, 44–48 (1949).
61. Fraunhofer, J.: Denkschriften der koeniglichen Academie der Wissenschaften zu München **5**, 193–226 (1817).
62. Fröhlich, C., Romero, J., Roth, H., Wehrli, C, Andersen, B.N., Appourchaux, T., Domingo, V., Telljohann, U., Berthomieu, G., Delache, P., Provost, J., Toutain, T., Crommelynck, D.A., Chevalier, A., Fichot, A., Däppen, W., Gough, D., Hoeksema, T., Jiménez, A., Gómez, M.F., Herreros, J.M., Cortés, T.R., Jones, A.R., Pap, J.M., Willson, R.C.: Solar Phys. **162**, 101–128 (1995).
63. Gabriel, A.H., Grec, G., Charra, J., Robillot, J.-M., Roca Cortés, T., Turck-Chiéze, S., Bocchia, R., Boumier, P., Cantin, M., Cespédes, E., Cougrand, B., Crétolle, J., Damé, L., Decaudin, M., Delache, P., Denis, N., Duc, R., Dzitko, H., Fossat, E., Fourmond, J.-J., García, R.A., Gough, D., Grivel, C., Herreros, J.M., Lagardére, H., Moalic, J.-P., Pallé, P.L., Pétrou, N., Sanchez, M., Ulrich, R., van der Raay, H.B.: Solar Phys. **162**, 61–99 (1995).
64. Gergely, T.E., Kundu, M.R.: Solar Phys. **34**, 433–446 (1974).
65. Gilbert, W.: De Magnete, Peter Short, London (1600).
66. Giovanelli, R.G.: Mon. Not. R. Astron. Soc. **107**, 338 (1947).
67. Gloeckler, G., Fisk, L.A., Hefti, S., Schwadron, N.A., Zurbuchen, T.H., Ipavich, F.M., Geiss, J., Bochsler, P., Wimmer-Schweingruber, R.F.: Geophys. Res. Lett. **26**, L157–L160 (1999).
68. Gloeckler, G., Geiss, J., Roelof, E.C., Fisk, L.A., Ipavich, F.M., Ogilvie, K.W., Lanzerotti, L.J., von Steiger, R., Wilken, B.: J. Geophys. Res. **99**, 17637–17643 (1994).
69. Goff, C.P., van Driel-Gesztelyi, L., Harra, L.K., Matthews, S.A., Mandrini, C.H.: Astron. Astrophys. **434**, 761–771 (2005).
70. Gold, T.: In van de Hulst, J.C., Burgers, J.M. (eds.), Gas Dynamics of Cosmic Clouds, p.103, North-Holland, New York (1955).

71. Golub, L., Deluca, E., Austin, G., Bookbinder, J., Caldwell, D., Cheimets, P., Cirtain, J., Cosmo, M., Reid, P., Sette, A., Weber, M., Sakao, T., Kano, R., Shibasaki, K., Hara, H., Tsuneta, S., Kumagai, K., Tamura, T., Shimojo, M., McCracken, J., Carpenter, J., Haight, H., Siler, R., Wright, E., Tucker, J., Rutledge, H., Barbera, M., Peres, G., Varisco, S.: Solar Phys. **243**, 63–86 (2007).
72. González-Esparza, A.: Space Sci. Rev. **97**, 197–200 (2001).
73. Gopalswamy, N., Hanaoka, Y.: Astrophys. J. **498**, L179–L182 (1998).
74. Gosling, J.T.: In Russell, C.T., Priest, E.R., Lee, L.C. (eds.) Geophys. Monog. Ser. **58**, p.343, AGU, Washington DC (1990).
75. Gosling, J.T.: J. Geophys. Res. **98**, 18937–18949 (1993).
76. Gosling, J.T.: Proc. Solar Wind 11 – SOHO 16, Whistler, Canada (2005).
77. Gosling, J.T.: Coronal Mass Ejections in the solar wind at high solar latitudes: an overview, Presented at the Third SOHO Workshop, Estes Park, CO (1994).
78. Gosling, J.T., Asbridge, J.R., Bames, S.J., Hundhausen, A.J., Strong, I.B.: J. Geophys. Res. **73**, 43–50 (1968).
79. Gosling, J.T., Asbridge, J.R., Bame, S.J., Feldman, W.C., Zwickl, R.D.: J. Geophys. Res. **85**, 3431–3434 (1980).
80. Gosling, J.T., Bame, S.J., McComas, D.J., Phillips, J.L., Scime, E.E., Pizzo, V.J., Goldstein, B.E., Balogh, A.: Geophys. Res. Lett. **21**, L237–L240 (1994).
81. Gosling, J.T., Hildner, E., MacQueen, R.M., Munro, R.H., Poland, A.I., Ross, C.L.: J. Geophys Res. **79**, 4581–4587 (1974).
82. Gosling, J.T., Hildner, E., MacQueen, R.M., Munro, R.H., Poland, A.I., Ross, C.L.: Solar Phys. **40**, 439–448 (1975).
83. Gosling, J.T., Hildner, E., MacQueen, R.M., Munro, R.H., Poland, A.I., Ross, C.L.: Solar Phys. **48**, 389–397 (1976).
84. Gosling, J.T., Skoug, R.M., McComas, D.J., Smith, C.W.: J. Geophys. Res. **110**, A01107, doi:10.1029/20043A010809 (2005a).
85. Gosling, J.T., Skoug, R.M., McComas, D.J., Smith, C.W.: Geophys. Res. Lett. **32**, L05105, doi:10.1029/2005GL022406 (2005b).
86. Graham, G.: Phil. Trans. R. Soc. Lond. **383**, 96–107 (1724).
87. Greaves, W.M.H, Newton, H.W.: Mon. Not. R. Astron. Soc. **88**, 556–567 (1928a).
88. Greaves, W.M.H, Newton, H.W.: Mon. Not. R. Astron. Soc. **89**, 84–92 (1928b).
89. Hale, G.E.: Astrophys. J. **73**, 379–412 (1931).
90. Handy, B.N., Acton, L.W., Kankelborg, C.C., Wolfson, C.J., Akin, D.J., Bruner, M.E., Caravalho, R., Catura, R.C., Chevalier, R., Duncan, D.W., Edwards, C.G., Feinstein, C.N., Freeland, S.L., Friedlander, F.M., Hoffmann, C.H., Hurlburt, N.E., Jurcevich, B.K., Katz, N.L., Kelly, G.A., Lemen, J.R., Levay, M., Lindgren, R.W., Mathur, D.P., Meyer, S.B., Morrison, S.J., Morrison, M.D., Nightingale, R.W., Pope, T.P., Rehse, R.A., Schrijver, C.J., Shine, R.A., Shing, L., Tarbell, T.D., Title, A.M., Torgerson, D.D., Golub, L., Bookbinder, J.A., Caldwell, D., Cheimets, P.N., Davis, W.N., DeLuca, E.E., McMullen, R.A., Amato, D., Fisher, R., Maldonado, H., Parkinson, C.: Solar Phys. **187**, 229–260 (1999).
91. Harra, L.K., Hara, H., Imada, S., Young, P.R., Williams, D.R., Sterling, A.C., Korendyke, C., Attrill, G.D.R.: Publ. Astron. Soc. Japan **59**, S801–S806 (2007).
92. Harrison, R.A.: Astron. Astrophys. **162**, 283–291 (1986).
93. Harrison, R.A.: Solar Phys. **166**, 441–444 (1996).
94. Harrison, R.A., Hildner, E., Hundhausen, A.J., Sime, D.G., Simnett, G.M.: J. Geophys. Res. **95**, 917–937 (1990).
95. Harrison, R.A., Sawyer, E.C., Carter, M.K., Cruise, A.M., Cutler, R.M., Fludra, A., Hayes, R.W., Kent, B.J., Lang, J., Parker, D.J., Payne, J., Pike, C.D., Peskett, S.C., Richards, A.G., Gulhane, J.L., Norman, K., Breeveld, A.A., Breeveld, E.R., Al Janabi, K.F., McCalden, A.J., Parkinson, J.H., Self, D.G., Thomas, P.D., Poland, A.I., Thomas, R.J., Thompson, W.T., Kjeldseth-Moe, O., Brekke, P., Karud, J., Maltby, P., Aschenbach, B., Bruninger, H., Kúhne, M., Hollandt, J., Siegmund, O.H.W., Huber, M.C.E., Gabriel, A.H., Mason, H.E., Bromage, B.J.I.: Solar Phys. **162**, 233–290 (1995).

96. Harrison, R.A., Sime, D.G.: J. Geophys. Res. **94**, 2333–2344 (1989).
97. Harrison, R.A., Simnett, G.M.: Adv. Space Res. **4**, 199–202 (1984).
98. Harrison, R.A., Waggett, P.W., Bentley, R.D., Phillips, K.J.H., Bruner, M., Dryer, M., Simnett, G.M.: Solar Phys. **97**, 387–400 (1985).
99. Hartman, J.: Astrophys. J. **9**, 69–85 (1899).
100. Henke, T., Woch, J., Mall, U., Livi, S., Wilkin, R., Schwenn, R., Gloeckler, G., von Stieger, R., Forsyth, R.J., Balogh, A.: Geophys. Res. Lett. **25**, L3465–L3468 (1998).
101. Henke, T., Woch, J., Schwenn, R., Mall, U., Gloeckler, G., von Stieger, R., Forsyth, R.J., Balogh, A.: J. Geophys. Res. **106**, 10597–10613 (2001).
102. Hetherington, B.: A Chronicle of Pre-Telescopic Astronomy, John Wiley and Sons (1996).
103. Hewish, A.: New Scientist **118**, 46–50 (1988).
104. Hewish, A.: Solar Phys. **116**, 195–198 (1988).
105. Hewish, A., Bravo, S.: Solar Phys. **106**, 185–200 (1986).
106. Hewish, A., Scott, P.F., Wills, D.: Nature **203**, 1214–1217 (1964).
107. Hewish, A., Symonds, M.D.: Planet. Space. Sci. **17**, 313–320 (1969).
108. Hick, P., Jackson, B.V.: Adv. Space Res. **14**, 135–138 (1994).
109. Hick, P., Jackson, B.V., Schwenn, R.: Astron. Astrophys **244**, 242–250 (1991).
110. Hildner, E.: Proc. AIAA Meeting (1974).
111. Hirshberg, J., Bame, S.J., Robbins, D.E.: Solar Phys. **23**, 467–486 (1972).
112. Holman, G.D.: In: The RHESSI Homepage, available via NASA/GSFC. http://hesperia.gsfc.nasa.gov/hessi/ramaty.html. Cited 10 November 2008.
113. Horbury, T., Balogh, A., Forsyth, R.J., Smith, E.J.: Ann. Geophys. **13**, 105–107 (1995).
114. Houminer, Z.: Nature Phys. Sci. **231**, 165–167 (1971).
115. Houminer, Z.: Planet. Space. Sci. **21**, 1617–1624 (1973).
116. Houminer, Z., Hewish, A.: Planet. Space. Sci. **20**, 1703–1716 (1972).
117. Houminer, Z., Hewish, A.: Planet. Space. Sci. **22**, 1041–1042 (1974).
118. Houminer, Z., Hewish, A.: Planet. Space Sci. **36**, 301–306 (1988).
119. Hovestadt, D., Hilchenbach, M., Bürgi, A., Klecker, B., Laeverenz, P., Scholer, M., Grünwaldt, H., Axford, W.I., Livi, S., Marsch, E., Wilken, B., Winterhoff, H.P., Ipavich, F.M., Bedini, P., Coplan, M.A., Galvin, A.B., Gloeckler, G., Bochsler, P., Balsiger, H., Fischer, J., Geiss, J., Kallenbach, R., Wurz, P., Reiche, K.-U., Gliem, F., Judge, D.L., Ogawa, H.S., Hsieh, K.C., Möbius, E., Lee, M.A., Managadze, G.G., Verigin, M.I., Neugebauer, M.: Solar Phys. **162**, 441–481 (1995).
120. Howard, R.A., Koomen, M.J., Michels, D.J., Tousey, R., Dewiler, C.R., Roberts, D.E., Seal, R.T., Whitney, J.T., Hansen, R.T., Hansen, S.F., Garcia, C.J., Yasukawa, E.: World Data Center A, Report UAG 48A (1975).
121. Howard, R.A., Michels, D.J., Sheeley, N.R., Jr., Koomen, M.J.: Astrophys. J. **263**, L101–L104 (1982).
122. Howard, R.A., Sheeley, N.R., Jr., Michels, D.J., Koomen, M.J.: J. Geophys. Res. **90**, 8173–8191 (1985).
123. Howard, T.A., Fry, C.D., Johnston, J.C., Webb, D.F.: Astrophys. J. **667**, 610–625 (2007).
124. Howard, T.A., Tappin, S.J.: Astron. Astrophys. **440**, 373–383 (2005).
125. Howard, T.A., Tappin, S.J.: Solar Phys. **252**, 373–383 (2008).
126. Howard, T.A., Tappin, S.J.: Space Sci. Rev. **147**, 31–54 (2009a).
127. Howard, T.A., Tappin, S.J.: Space Sci. Rev. **147**, 89–110 (2009b).
128. Howard T.A., Webb, D.F., Tappin, S.J., Mizuno, D.R., Johnston, J.C.: J. Geophys. Res. **111**, doi:10.1029/2005JA011349 (2006).
129. Hudson, H.S.: Solar Phys. **113**, 1–9 (1987).
130. Hudson, H.S., Lemen, J.R., St. Cyr, O.C., Sterling, A.C., Webb, D.F.: Geophys. Res. Lett. **25**, L2481–L2484 (1998).
131. Hudson, H.S, Haisch, B., Strong, K.T.: J. Geophys. Res. **100**, 3473–3477 (1995).
132. Hundhausen, A.J.: In Sonnet, C.P., Coleman, P.J., Wilcox, J.M. (eds.), Solar Wind, NASA Spec. Publ., SP-308, p.393 (1972a).
133. Hundhausen, A.J.: Coronal Expansion and Solar Wind, Springer-Verlag, New York, 1972b.

134. Hundhausen, A.J.: In Pizzo, V.J., Holzer, T.E., Sime, D.G. (eds.), Proc. 6th Int. Solar Wind Conf., p.192 HAO CO (1987).
135. Hundhausen, A.J., Bame, S.J., Montgomery, M.D.: J. Geophys. Res. **75**, 4631–4642 (1970).
136. Hundhausen, A.J., Burkepile, J.T., St. Cyr, O.C.: J. Geophys. Res. **99**, 6543–6552 (1994).
137. Hundhausen, A.J., Sawyer, C.B., House, L., Illing, R.M.E., Wagner, W.J.: J. Geophys. Res. **89**, 2639–2646, (1984).
138. Illing, R.M.E., Hundhausen, A.J.: J. Geophys. Res. **90**, 275–282 (1985).
139. Ivanov, K.G.: Astronomicheskii Zhurnal **48**, 998 (1971).
140. Ivanov, K.G.: Soviet Astron. **17**, 94 (1973).
141. Jackson, B.V.: Solar Phys. **95**, 363–370 (1985).
142. Jackson, B.V.: Adv. Space Res. **6**, 307–310 (1986).
143. Jackson, B.V.: Adv. Space Res. **9**, 69–74 (1989).
144. Jackson, B.V.: Proc. 3rd COSPAR Coll. (Solar Wind 7), 623–634 (1992).
145. Jackson, B.V., Buffington, A., Hick, P.P., Altrock, R.C., Figueroa, S., Holladay, P.E., Johnston, J.C., Kahler, S.W., Mozer, J.B., Price, S., Radick, R.R., Sagalyn, R., Sinclair, D., Simnett, G.M., Eyles, C.J., Cooke, M.P., Tappin, S.J., Kuchar, T., Mizuno, D., Webb, D.F., Anderson, P.A., Keil, S.L., Gold, R.E., Waltham, N.R.: Solar Phys. **225**, 177–207 (2004).
146. Jackson, B.V., Buffington, A., Hick, P.P., Wang, X., Webb, D.F.: J. Geophys. Res. **111**, doi:10.1029/2004JA010942 (2006).
147. Jackson, B.V., Froehling, H.R.: Astron. Astrophys. **299**, 885–892 (1995).
148. Jackson, B.V., Hick, P.P.: Solar Phys. **211**, 345–356 (2002).
149. Jackson, B.V., Howard, R.A., Sheeley, N.R., Jr., Michels, D.J., Koomen, M.J., Illing, R.M.E.: J. Geophys. Res. **90**, 5075–5081 (1985).
150. Jackson, B.V., Leinert, C.: J. Geophys. Res. **90**, 10759–10764 (1985).
151. Jackson, B.V., Rompolt, B., Švestka, Z.: Solar Phys. **115**, 327–343 (1988).
152. Jacobs, I.: In: About the World Wide Web Consortium, available via W3C. http://www.w3.org/Consortium/. Cited 29 April 2008.
153. Janardhan, P., Balasubramanian, V., Ananthakrishnan, S.: In Wilson, A. (ed.), Proc. 31st ESLAB Symp., Noordwijk, The Netherlands, ESA SP-415, p.177 (1997).
154. Jones, R., Canals, A., Breen, A., Fallows, R., Lawrence, G.: Proc. 1st EGU Sci. Assem., Nice, France, EGU-A-00452 (2004).
155. Joselyn, J.A., McIntosh, P.S.: J. Geophys. Res. **86**, 4555–4564 (1981).
156. Kahler, S.W.: Ann. Rev. Astron. Astrophys. **30**, 113–141 (1992).
157. Kahler, S.W., Reames, D.V. Sheeley, N.R., Jr.: Astrophys. J. **562**, 558–565 (2001).
158. Kaiser, M.L., Kucera, T.A., Davila, J.M., St. Cyr, O.C., Guhathakurta, M., Christian, E.: Space Sci. Rev. **136**, 5–16 (2008).
159. Kanekal, S.G., Baker, D.N., Blake, J.B., Klecker, B., Mewaldt, R.A., Mason, G.M.: J. Geophys. Res. **104**, 24885–24894 (1999).
160. King, J.H.: Interplanetary magnetic field data 1963–1974, NSSDC (1975).
161. Klein, L.W., Burlaga, L.F.: J. Geophys. Res. **87**, 613–624 (1982).
162. Kohl, J.L., Esser, R., Gardner, L.D., Habbal, S., Daigneau, P.S., Dennis, E.F., Nystrom, G.U., Panasyuk, A., Raymond, J.C., Smith, P.L., Strachan, L., van Ballegooijen, A.A., Noci, G., Fineschi, S., Romoli, M., Ciaravella, A., Modigliani, A., Huber, M.C.E., Antonucci, E., Benna, C., Giordano, S., Tondello, G., Nicolosi, P., Naletto, G., Pernechele, C., Spadaro, D., Poletto, G., Livi, S., von der Lühe, O., Geiss, J., Timothy, J.G., Gloeckler, G., Allegra, A., Basile, G., Brusa, R., Wood, B., Siegmund, O.H.W., Fowler, W., Fisher, R., Jhabvala, M.: Solar Phys. **162**, 313–356 (1995).
163. Koomen, M., Howard, R.A., Hansen, R., Hansen, S.: Solar Phys. **34**, 447–452 (1974).
164. Korreck, K.E., Zurbuchen, T.H., Lepri, S.T., Raines, J.M.: Astrophys. J. **659**, 773–779 (2007).
165. Lazarus, A.J., Binsack, J.H.: Ann. I. Q. S. Y. **3**, 378–385 (1969).
166. Lazarus, A.J., Ogilvie, K.W., Burlaga, L.F.: Solar Phys. **13**, 232–239 (1970).
167. Lazarus, A.J., Richardson, J.D., Decker, R.B., McDonald, F.B.: Space Sci. Rev. **89**, 53–59 (1999).
168. Leamon, R.J., Canfield, R.C., Jones, S.L., Lambkin, K., Lundberg, B.J., Pevtsov, A.A.: J. Geophys. Res. **109**, doi:10.1029/2003JA010324 (2004).

169. Leinert, C., Link, H., Pitz, E., Salm, N., Kluppelberg, D.: Raumfahrtforschung **19**, 264–267 (1975).
170. Lepping, R.P., Berdichevsky, D.: Recent Res. Devel. Geophys. **3**, 77–96 (2000).
171. Lepping, R.P., Jones, J.A., Burlaga, L.F.: J. Geophys. Res. **95**, 11957–11965 (1990).
172. Lepping, R.P., Wu, C.-C., McClernan, K.: J. Geophys. Res. **108**, doi:10.1029/2002JA009640 (2003).
173. Lepri, S.T., Zurbuchen, T.H., Fisk, L.A., Richardson, I.G., Cane, H.V., Gloeckler, G.: J. Geophys. Res. **106**, 29231–29238 (2001).
174. Liewer, P.C., De Jong, E.M., Hall, J.R., Howard, R.A., Thompson, W.T., Culhane, J.L., Bone, Laura, van Driel-Gesztelyi, L.: Solar Phys. **256**, 57–72 (2009).
175. Liu, Y., Richardson, J.D., Belcher, J.W.: Planet. Space Sci. **53**, 3–17 (2005).
176. Lynch, B.J., Gruesbeck, J.R., Zurbuchen, T.H.: J. Geophys. Res. **108**, doi:10.1029/2005JA011137 (2005).
177. Lynch, B.J., Zurbuchen, T.H., Fisk, L.A., Antiochos, S.K.: J. Geophys. Res. **108**, doi:10.1029/2002JA009591 (2003).
178. Lyot, M.B.: Mon. Not. R. Astron. Soc. **99**, 578–590 (1939).
179. MacIntosh, S.W.: Astrophys. J. **693**, 1306–1309 (2009).
180. MacQueen, R.M.: Phil. Trans. R. Soc. Lond. A. **297**, 605–620 (1980).
181. MacQueen, R.M., Burkepile, J.T., Holzer, T.E., Stanger, A.L., Spence, K.E.: Astrophys. J. **549**, 1175–1182 (2001).
182. MacQueen, R.M., Csoeke-Poeckh, A., Hildner, E., House, L., Reynolds, R., Stanger, A., Tepoel, H., Wagner, W.: Solar Phys. **65**, 91–107 (1980).
183. Marubashi, K.: In Crooker, N., Joselyn, J.A., Feynman, J. (eds.), Geophys. Monog. Ser. **99**, p.147, AGU, Washington DC (1997).
184. Maunder, E.W.: Mon. Not. R. Astron. Soc. **65**, 2–34 (1904).
185. McComas, D.J., Riley, P., Gosling, J.T., Balogh, A., Forsyth, R.: J. Geophys. Res. **103**, 1955–1967 (1998).
186. McLean, D.J., Labrum, N.R. (eds): Solar radiophysics: Studies of emission from the sun at metre wavelengths, Cambridge Univ. Press, Cambridge and New York (1985).
187. Meyer, P., Parker, E.N., Simpson, J.A.: Phys. Rev. **104**, 768–783 (1956).
188. Michels, D.J., Howard, R.A., Koomen, M.J., Sheeley, N.R., Jr.: In Kundu, M.R., Gergely, T.E. (eds.), Radio Physics of the Sun, p.439, D. Reidel, Hingham MA (1980).
189. Michels, D.J., Sheeley, N.R., Jr., Howard, R.A., Koomen, M.J., Schwenn, R., Mulhauser, K.H., Rosenbauer, H.: Adv. Space Res. **4**, 311–321 (1984).
190. Mierla, M., Davila, J., Thompson, W., Inhester, B., Srivastava, N., Kramar, M., St. Cyr, O.C., Stenborg, G., Howard, R.A.: Solar Phys. **252**, 385–396 (2008).
191. Mierla, M., Schwenn, R., Teriaca, L., Stenborg G., Podlipnik, B.: Adv. Space Res. **35**, 2199–2203 (2005).
192. Mitchell, A.C.: Terr. Magn. Atmosph. Electr. **37**, 105–146 (1932).
193. Morrison, P.: Phys. Rev. **95**, 646 (1954).
194. Moullard, O., Burgess, D., Salem, C., Mangeney, A., Larson, D.E., Bale, S.D.: J. Geophys. Res. **106**, 8301–8314 (2001).
195. Müller-Mellin, R., Kunow, H., Fleißner, V., Pehlke, E., Rode, E., Röschmann, N., Scharmberg, C., Sierks, H., Rusznyak, P., McKenna-Lawlor, S., Elendt, I., Sequeiros, J., Meziat, D., Sanchez, S., Medina, J., Del Peral, L., Witte, M., Marsden, R., Henrion, J.: Solar Phys. **162**, 483–504 (1995).
196. Munro, R.H., Sime, D.G.: Solar Phys. **97**, 191–201 (1985).
197. Newton, H.W.: Observatory **62**, 317–326 (1939).
198. Newton, H.W.: Mon. Not. R. Astron. Soc. **103**, 244–257 (1943).
199. Ogilvie, K.W., Burlaga, L.F.: Solar Phys. **8**, 422–434 (1969).
200. Parker, E.N.: J. Geophys. Res. **62**, 509–520 (1957).
201. Petschek, H.E.: In Hess, W.N. (ed.), Physics of Solar Flares, NASA SP-50 (1964).
202. Plunkett, S.P., Brueckner, G.E., Dere, K.P., Howard, R.A., Koomen, M.J., Korendyke, C.M., Michels, D.J., Moses, J.D., Moulton, N.E., Paswaters, S.E., St. Cyr, O.C., Socker, D.G., Wang, D., Simnett, G.M., Bedford, D.K., Biesecker, D.A., Eyles, C.J., Tappin, S.J., Schwenn, R., Lamy, P.L., Llebaria, A.: Solar Phys. **175**, 699–718 (1997).

203. Pudovkin, M.I.: J. Geophys. Res. **100**, 7917–7919 (1995).
204. Qiu, J., Hu, Q., Howard, T.A., Yurchyshyn, V.B.: Astrophys. J. **659**, 758–772 (2007).
205. Ranyard, C.A.: Mem. R. Astron. Soc. **41**, 520 (1879).
206. Reid, G.C., Leinbach, H.: J. Geophys. Res. **64**, 1801–1805 (1959).
207. Reinard, A.A.: Astrophys. J., **682**, 1289–1305 (2008).
208. Richardson, I.G., Cane, H.V.: J. Geophys. Res. **109**, doi: 10.1029/2004JA010598 (2004).
209. Richardson, J.D., Paularena, K.I., Wang, C., Burlaga, L.F.: J. Geophys. Res., **107**, doi:10.1029/2001JA000175 (2002).
210. Richter, I., Leinert, C., Planc, B.: Astron. Astrophys **110**, 115–120 (1982).
211. Rickett, B.J.: Solar Phys. **43**, 237–247 (1975).
212. Riley, P., Linker, J.A., Lionello, R., Mikič, Odstrcil, D., Hidalgo, M.A., Cid, C., Hu, Q., Lepping, R.P., Lynch, B.J., Rees, A.: J. Atmos. Solar. Terr. Phys. **66**, 1321–1331 (2004).
213. Rodríguez-pacheco, J., Cid, C., Blanco, J.J., Sequeiros, J.: Solar Phys. **213**, 121–145 (2003).
214. Roelof, E.C., Simnett, G.M., Tappin, S.J.: Astron. Astrophys. **316**, 481–486 (1996).
215. Rust, D.M., Kumar, A.: Astrophys. J. **464**, L199–L202 (1996).
216. Sabine, E.: Phil. Trans. R. Soc. Lond. **142**, 103–124 (1852).
217. Sanderson, T.R., Marsden, R.G., Heras, A.M., Wenzel, K.-P., Anglin, J.D., Balogh, A., Forsyth, R.: Geophys. Res. Lett. **19**, L1263–L1266 (1992).
218. Scherrer, P.H., Bogart, R.S., Bush, R.I., Hoeksema, J.T., Kosovichev, A.G., Schou, J., Rosenberg, W., Springer, L., Tarbell, T.D., Title, A., Wolfson, C.J., Zayer, I., MDI Engineering Team: Solar Phys. **162**, 129–188 (1995).
219. Schröder, W., Wiederkehr, K-H.: J. Atmos. Solar Terr. Phys. **63**, 1649–1660 (2001).
220. Schwabe, S.H.: Astronomische Nachrichten **20**, 234–235 (1843).
221. Schwenn, R., Rosenbauer, H., Muehlhaeuser, K.-H.: Geophys. Res. Lett. **7**, 201–204 (1980).
222. Schwenn, R., Watanabe, T., Kakinuma, T., Kojima, M.: Proc. Nagoya Univ. Res. Inst. Atmospherics **36**, 11–28 (1989).
223. Sime, D.G., MacQueen, R.M., Hundhausen, A.J.: J. Geophys. Res. **89**, 2113–2121 (1984).
224. Sime, D.G., Hundhausen, A.J.: J. Geophys. Res. **92**, 1049–1055 (1987).
225. Simnett, G.M.: Astron. Astrophys. **416**, 759–764 (2004).
226. Simnett, G.M., Harrison, R.A.: Adv. Space Res. **4**, 279–282 (1984).
227. Simnett, G.M., Harrison, R.A.: Solar Phys. **99**, 291–311 (1985).
228. Sisko, G., Crooker, N.U., Clauer, C.R.: Adv. Space Res. **38**, 173–179 (2006).
229. Sonnet, C.P., Colburn, D.S., Davis, L., Smith, E.J., Coleman, P.J.: Phys. Rev. Lett. **13**, 153–156 (1964).
230. Stanger, A.L.: SMM C/P CME Event: 14 April 1980 — Day of Year (DOY): 105 Available via HAO. http://smm.hao.ucar.edu/smm/smmcp_events/1980apr14.html. Cited 29. August 2000
231. Stern, D.P.: Rev. Geophys. **40**, 1–30 (2002).
232. Sterling, A.C., Hudson, H.S.: Astrophys. J. **491**, L55–L58 (1997).
233. Sterling, A.C., Hudson, H.S., Thompson, B.J., Zarro, D.M.: Astrophys. J. **532**, 628–647 (2000).
234. Švestka, Z.F: Solar Phys. **160**, 53–56 (1995).
235. Švestka, Z.F., Jackson, B.V., Howard, R.A., Sheeley, N.R., Jr.: Solar Phys. **122**, 131–143 (1989).
236. Sweet, P.A.: In Lehnert, B. (ed.), Proc. IAU Symp. **6**, 123 (1958).
237. Tappin, S.J.: PhD thesis, Univ. Cambridge (1984).
238. Tappin, S.J.: Solar Phys. **233**, 233–248 (2006).
239. Tappin, S.J., Buffington, A., Cooke, M.P., Eyles, C.J., Hick, P.P., Holladay, P.E., Jackson, B.V., Johnston, J.C., Kuchar, T., Mizuno, D., Mozer, J.B., Price, S., Radick, R.R., Simnett, G.M., Sinclair, D., Waltham, N.R., Webb, D.F.: Geophys. Res. Lett **31**, doi:10.1029/2003GL018766 (2004).
240. Tappin, S.J., Hewish, A., Gapper, G.R.: Planet. Space Sci. **31**, 1171–1176 (1983).
241. Tappin, S.J., Howard, T.A.: Space Sci. Rev. **147**, 55–87 (2009).
242. Taylor, H.E.: Solar Phys. **6**, 320–334 (1969).

243. Torsti, J., Valtonen, E., Lumme, M., Peltonen, P., Eronen, T., Louhola, M., Riihonen, E., Schultz, G., Teittinen, M., Ahola, K., Holmlund, C., Kelhä, V., Leppälä, K., Ruuska, P., Strömmer, E.: Solar Phys. **162**, 505–531 (1995).
244. Tousey, R.: In Rycroft, M.J., Runcorn, S.K. (eds.), Space Research XIII, Akademie-Verlag, Berlin p.713–730 (1973).
245. Trella, M., Greenfield, M., Herring, E.L., Credland, J., Freeman, H.R., Laine, R., Kilpatrick, W., Machi, D., Reth, A., Smith, A., In: SOHO Mission Interruption Join NASA/ESA Investigation Board: Final Report, available via ESA. http://sohowww.estec.esa.nl/whatsnew/SOHO_final_report.html. Cited 31 August 1998.
246. Tsuneta, S., Acton, L., Bruner, M., Lemen, J., Brown, W., Caravalho, R., Catura, R., Freeland, S., Jurcevich, B., Morrison, M., Obawara, Y., Hirayama, T., and Owens, J.: Solar Phys. **136**, 37–61 (1991).
247. Tsuneta, S., Ichimoto, K., Katsukawa, Y., Nagata, S., Otsubo, M., Shimizu, T., Suematsu, Y., Nakagiri, M., Noguchi, M., Tarbell, T., Title, A., Shine, R., Rosenberg, W., Hoffmann, C., Jurcevich, B., Kushner, G., Levay, M., Lites, B., Elmore, D., Matsushita, T., Kawaguchi, N., Saito, H., Mikami, I., Hill, L.D., Owens, J.K.: Solar Phys. **249**, 167–196 (2008).
248. Tsurutani, B.T., Gonzalez, W.D., Lakhina, G.S., Alex, S.: J. Geophys. Res. **108**, 1268, doi:10.1029/2002JA009504 (2002).
249. Utton, T.: A Super Highway for Aliens?, The Daily Mail, London, January 15 (2003).
250. Vaquero, J.M.: Adv. Space Res. **40**, 929–941 (2007).
251. Vitkevich, V.V., Vlasov, V.I.: Soviet Astron. **13**, 669–676 (1970).
252. Vlasov, V.I.: Geomag. Aeron. **21**, 324–326 (1981).
253. Vlasov, V.I.: Geomag. Aeron. **22**, 446–450 (1982).
254. Vlasov, V.I., Shishov, V.I., Shisova, T.D.: Geomag. Aeron. **25**, 211–214 (1985).
255. von Steiger, R., Schwadron, N.A., Fisk, L.A., Geiss, J., Gloeckler, G., Hefti, S., Wilken, B., Wimmer-Schweingruber, R.-F., Zurbuchen, T.-H.: J. Geophys. Res. **105**, 27217–27236 (2000).
256. Vršnak,B., Warmuth, A., Temmer, M., Veronig, A., Magdalenic, J., Hillaris, A., Karlicky, M.: Astron. Astrophys. **448**, 739–752 (2006).
257. Wang, C., Richardson, J.D.: Geophys. Res. Lett **29**, doi:10.1029/2001GL014472 (2002).
258. Watanabe, T.: Proc. COSPAR, Plenary Meet. (1977).
259. Watanabe, T., Kakinuma, T.: Publ. Astron. Soc. Japan **24**, 459–467 (1972).
260. Watanabe, T., Kakinuma, T., Kojima, M., Shibasaki, K.: J. Geophys. Res. **78**, 8364–8366 (1973).
261. Webb, D.F.: In IAU Colloq. 133: Eruptive Solar Flares, pp.234–247 (1992).
262. Webb, D.F.: Proc. 37th COSPAR Sci. Assem., Montréal, Canada., p.3444 (2008).
263. Webb, D.F., Cheng, C.-C., Dulk, G.A., Edberg, S.J., Martin, S.F., McKenna-Lawlor, S., McLean, D.J.: In Sturrock, P.A (ed.), Solar Flares: A Monograph From Skylab Workshop II, Colo. Assoc. Univ. Press, Boulder CO, p.471 (1980).
264. Webb, D.F., Mizuno, D.R., Buffington, A., Cooke, M.P., Eyles, C.J., Fry, C.D., Gentile, L.C., Hick, P.P., Holladay, P.E., Howard, T.A., Hewitt, J.G., Jackson, B.V., Johnston, J.C., Kuchar, T.A., Mozer, J.B., Price, S., Radick, R.R., Simnett, G.M., Tappin, S.J.: J. Geophys. Res. **111**, doi:10.1029/2006JA011655 (2006).
265. Webb, D.F., Jackson, B.V.: J. Geophys. Res. **95**, 20641–20661 (1990).
266. Webb, D.F., Jackson, B.V., Hick, P., Schwenn, R., Bothmer, V., Reames, D.: Adv. Space Res. **13**, 71–74 (1993).
267. Wild, J.P., McCready, L.L.: Aust. J. Sci. Res. **3**, 387–398 (1950).
268. Wild, J.P., Murray, J.D., Rowe, W.C.: Aust. J. Phys. **7**, 439–459 (1954a).
269. Wild, J.P., Roberts, J.A., Murray, J.D.: Nature **173**, 532–534 (1954b).
270. Wild, J.P., Sheridan, K.V., Trent, G.H.: In Bracewell, R.N. (ed.), Proc. Paris Symp. Radio Astron., IAU/URSI, Stanford Univ. Press, Stanford, CA, p.176 (1959).
271. Wild, J.P., Smerd, S.F., Weiss, A.A.: Ann. Rev. Astron. Astrophys. **1**, 291–366 (1963).
272. Wilhelm, K., Curdt, W., Marsch, E., Schühle, U., Lemaire, P., Gabriel, A., Vial, J.-C., Grewing, M., Huber, M.C.E., Jordan, S.D., Poland, A.I., Thomas, R.J., Khne, M., Timothy, J.G., Hassler, D.M., Siegmund, O.H.W.: Solar Phys. **162**, 189–231 (1995).

273. Wilson, R.M., Hildner, E.: Solar Phys. **91**, 169–180 (1984).
274. Wilson, R.M., Hildner, E.: J. Geophys. Res. **91**, 5867–5872 (1986).
275. Woo, R.: J. Geophys. Res. **98**, 18999–19004 (1993).
276. Woo, R., Armstrong, J.W.: Nature **292**, 608–610 (1981).
277. Woo, R., Armstrong, J.W.: Nature **304**, 756 (1983).
278. Woo, R., Armstrong, J.W., Sheeley, N.R., Jr., Howard, R.A., Michels, D.J., Koomen, M.J., Schwenn, R.: J. Geophys. Res. **90**, 154–162 (1985).
279. Yashiro, S., Gopalswamy, N., Michalek, G., St. Cyr, O.C., Plunkett, S.P., Rich, N.B., Howard, R.A.: J. Geophys. Res. **109**, doi:10.1029/2003JA010282 (2004).
280. Zhang, J., Wang, J.: Astrophys. J. **554**, 474–487 (2001).
281. Zhang, G., Burlaga, L.F.: J. Geophys. Res. **93**, 2511–2518 (1988).
282. Zhao, X.-P.: J. Geophys. Res. **97**, 15051–15055 (1992).
283. Zirker, J.B.: Total Eclipses of the Sun, Princeton Univ. Press (1995).

Springer

http://www.springer.com/978-1-4419-8788-4

Coronal Mass Ejections
An Introduction
Howard, T.
2011, XXIV, 244 p., Hardcover
ISBN: 978-1-4419-8788-4