A BRIEF HISTORY OF CME SCIENCE

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Abstract. We present here a brief summary of the rich heritage of observational and theoretical research leading to the development of our current understanding of the initiation, structure, and evolution of Coronal Mass Ejections.

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1. Introduction

The key to understanding solar activity lies in the Sun's ever-changing magnetic field. The potential role played by the magnetic field in the solar atmosphere was first suggested by Frank Bigelow in 1889 after noting that the structure of the solar minimum corona seen during the eclipse of 1878 displayed marked equatorial extensions, called 'streamers'. Bigelow (1890) noted that the coronal streamers had a strong resemblance to magnetic lines of force and proposed that the Sun must, in fact, be a large magnet. Subsequently, Henri Deslandres (1893) suggested that the forms and motions of prominences seen during solar eclipses appeared to be influenced by a solar magnetic field. The link between magnetic fields and plasma emitted by the Sun was beginning to take shape by the turn of the 20th Century. The epochal discovery of magnetic fields on the Sun by American astronomer George Ellery Hale (1908) signalled the birth of modern solar physics. This realization led to the modern emphasis on solar transient activity and its relationship to the solar magnetic field and its reconfiguration.

2. Historical Observations

The first terrestrial phenomena recognized to be of solar origin were geomagnetic disturbances. Colonel Sabine, in the middle of the 19th century (Sabine, 1852), noted that the frequencies of both geomagnetic storms and sunspots followed an 11-year cycle. The first step in associating geomagnetic storms with transient solar activity – what later became known as solar flares – rather than simply with the associated spot regions, was the memorable observations in 1859 by British amateur

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astronomers Richard Carrington and Richard Hodgson (Carrington, 1860). They independently witnessed a rapid intense flash of two bright ribbons on the Sun in visible light accompanied, essentially simultaneously, by a marked disturbance of the Earth's magnetic field detected at Kew Observatory in London. Some 17.5 hours later, one of the largest magnetic storms on record occurred. While Carrington was reluctant to suggest a physical connection between the visible event at the Sun and the geomagnetic storm, Balfour Stewart, the Director of Kew Observatory, claimed that they had caught the Sun in the act of producing a terrestrial event. The first systematic evidence for a flare-storm connection, however, didn't come until the work of Hale (1931) (see Cliver, 1994a,b, 1995 for a detailed history). Over a century and a half later, solar and space physicists are revisiting the remarkable event of 1859 in a concerted effort to apply 21st Century tools to model its solar and terrestrial effects (e.g. Tsurutani *et al.*, 2003).

The importance of the "chromospheric eruptions", as the early flares were known, for the Earth's space environment came through the study of these events and their apparent association with geomagnetic storms. Lindemann (1919) suggested that geomagnetic storms were caused by ejections of magnetically neutral matter from the Sun impacting the Earth's magnetic field several days afterwards, as illustrated in the top panel of Figure 1. The statistical association of large flares and

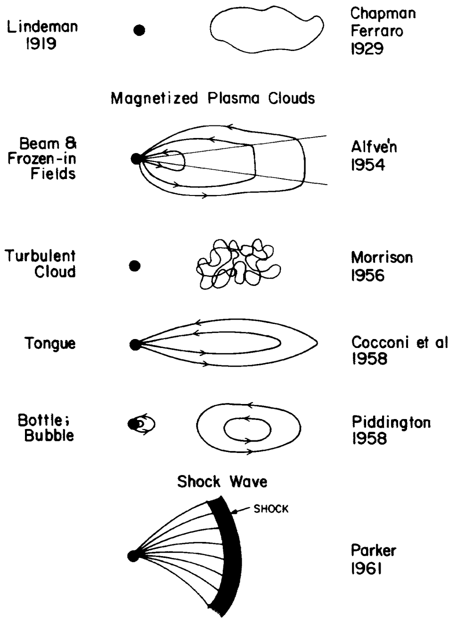

Figure 1. Early concepts of the structure of ICMEs, showing (from the top): unmagnetized material; a plasma cloud including frozen-in magnetic field loops; plasma including turbulent magnetic fields; a "tongue" of magnetic field loops rooted at the Sun; a disconnected "plasmoid" or "bubble"; and a shock wave ahead of a region of enhanced turbulence (Burlaga, 1991).

storms was solidified by Newton (1943), who surveyed all the large flares observed since 1892 and found a significant correlation between those flares and subsequent geomagnetic storms.

The expulsion of hydrogen was also observed near the time of peak intensity of the majority of bright flares. These emissions occurred in specific directions, usually along nearly vertical trajectories, and exhibited all the characteristics of the well-known eruptive prominences. The initial velocity of a mass expulsion was around 500 km/s and, while its H brightness was several times that of normal quiescent prominences, it was still much fainter than the flare emission itself. The physical relationship between solar flares and prominences dates back to the *disparition brusques* phenomena catalogued in the late 1940s by researchers at Meudon Observatory. The factors which cause this relationship are important since filament eruptions appear to have a role in many of the coronal transients that make up the most energetic solar activity. However, despite the fact that solar prominences have been observed for several hundred years, they were not thought to play a role in geomagnetic storms. A relationship was suggested by Greaves and Newton (1928); but Hale disagreed, pointing out three years later (Hale, 1931) that erupting prominences generally fall back to the Sun. The connection between prominence eruptions and geomagnetic storms, while hinted at by Newton (1936), was not fully appreciated until the work of Joselyn and McIntosh (1981).

It was pointed out by Kiepenheuer (1953) that the sudden disappearance of a prominence could result as the prominence rises into the corona with an increasing velocity that may eventually exceed the velocity of escape. This process was studied in detail with the conclusion that the ejected plasma is accelerated as it rises. Such studies were the precursors to present-day investigations into the relationship between filament eruptions and flares, and preceded by as much as three decades the discovery of coronal mass ejections.

Combined with the apparently clear association between geomagnetic disturbances and solar flares, the observed acceleration of material associated with prominence eruptions suggested a physical mediator for the transfer of energy from the solar atmosphere to the Earth's. Given the incontrovertible evidence for the existence of corpuscular radiation from the Sun, a major effort to detect the particles in transit was performed. Waldmeier (1941) and Ellison (1943) independently detected a strong asymmetry in the wings of the H emission line of flares. Ellison interpreted this as being due to the absorption by hydrogen atoms expelled in all directions from the flare site. This asymmetry was subsequently confirmed with spectrohelioscopes at observatories around the world. Ellison did caution, however, that: "While these asymmetric profiles provide the strongest possible evidence for the general expulsion of hydrogen during flares, we must await further work in order to prove that this constitutes the initial departure of the geomagnetic storm particles". Coinciding with large flares, sudden increases in cosmic ray intensity were occasionally detected (e.g., Forbush, 1946; Meyer *et al.*, 1956), suggesting that flares were also able to accelerate charged particles to energies in excess of

5 GeV. The notion that the particles could be accelerated en route did not occur to researchers at the time.

Early cosmic ray studies also provided evidence for ejections of material from the Sun that are related to geomagnetic storms, and strongly suggested that this material was magnetized. Decreases in the galactic cosmic ray intensity that accompany some storms were reported by Forbush (1937), and these were later explained by the exclusion of the cosmic rays from "magnetic bottles" formed when the ejection of highly-conducting coronal material drags solar magnetic fields into interplanetary space. Such bottles may remain connected to the Sun (Cocconi *et al.*, 1958) or be disconnected plasmoid-like structures (Piddington, 1958), as illustrated in Figure 1. An alternative, a turbulent cloud with tangled magnetic fields, also shown in Figure 1, was proposed by Morrison (1956).

Gold (1955) noted that many geomagnetic storms have remarkably abrupt onsets and suggested that shocks generated ahead of fast ejections cause the sudden onsets as they arrive at the Earth. The possibility that a large solar flare could drive a hydrodynamic blast wave to the Earth in 1–2 days was demonstrated by Parker (1961) (Figure 1). This idea was subsequently "confirmed" by a series of calculations on interplanetary shocks and was supported by observations of shocks which became available with the advent of in-situ measurements of the interplanetary plasma and magnetic fields in the space era (e.g., Sonnet *et al.*, 1964). Nevertheless, Hundhausen (1972) noted a number of apparent discrepancies between shock wave models and observations, expressing some reservations about the association between large flares and interplanetary shocks. Thus, by this time, one year prior to the launch of Skylab, the physics of storm-causing interplanetary shocks was understood but the shocks themselves could not be directly related to any coronal events.

While there had been indications of large, transient disturbances traveling through the Sun's outer corona in solar radio records and coronagraph observations from earlier unmanned spacecraft, it took the as-then unprecedented sensitivity of the Skylab coronagraph to put these observations in perspective. Skylab observations showed "gargantuan loops rushing outwards from the Sun at remarkable speeds" with the frequently observed "expulsion from the Sun of an eruption bigger than the disk of the Sun" (see Eddy, 1979, chapter 7). The first quantitative summary of the Skylab coronal disturbances (Gosling *et al.*, 1974) strongly indicated that these transients were the long-sought eruptions of coronal material required to produce the high-speed solar wind flows responsible for geomagnetic storms: measured speeds ranged from $<$100 km/s to $>$1200 km/s (Gosling *et al.*, 1976). These events came to be known by a variety of names such as "plasma clouds", "solar mass ejections", "mass ejection coronal transients", "coronal mass ejection events" and then simply "coronal mass ejections".

The detailed observations of CMEs by Skylab led Eddy (1974) to scour eclipse records for evidence of similar phenomena. The paucity of reports of such coronal transients was readily explained by the combination of the Skylab CME occurrence rate, the typical CME speed and the short duration of eclipse totality, resulting in

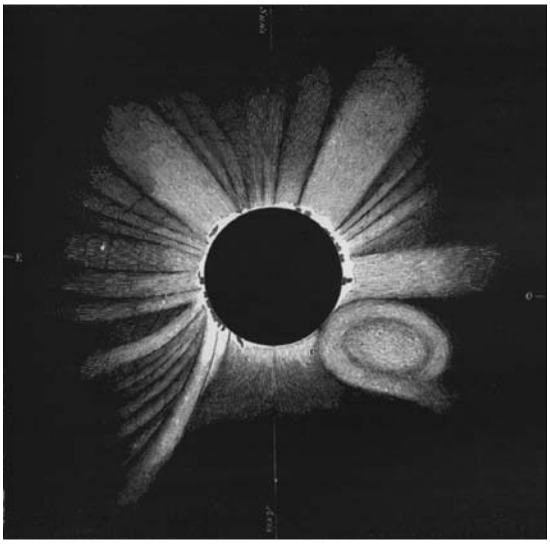

Figure 2. Drawing of the corona as it appeared to Tempel at Torreblanca, Spain during the total solar eclipse of 18 July 1860 showing what may be the first observation of a CME (see Eddy, 1974).

the expectation of one chance per century of capturing a CME during an eclipse. Despite these slim odds, Eddy (1974) found signs of a transient, very similar in form to the Skylab CMEs (see Figure 2) in a drawing of the Spanish eclipse of July 18, 1860, made by the Italian astronomer Gugliemo Tempel with supporting evidence from other observers. Other examples include a disconnection event from 16 April 1893 (Cliver, 1989) and a 3-part structure observation from an eclipse on 29 May 1919[1].

Following Skylab, several space-based coronagraphs were flown to study the transient Sun. The Solar Maximum Mission (SMM), launched in 1980, significantly advanced our knowledge of solar flares and coronal mass ejections. The nine years of SMM coronagraph observations resulted in a dramatic shift in the paradigm of the Sun-Earth interaction and brought CMEs to the fore of solar-terrestrial research. A complete summary of the contribution of SMM to our understanding of solar transients can be found in Strong *et al.* (1998). The theme of solar-terrestrial interactions continued into the 1990's with the launches of the Yohkoh and SOHO satellites. Observations by Yohkoh/SXT have demonstrated that CMEs typically produce a response in the hot corona even when this response does not include typical flare emissions. In particular, intriguing "dimmings" of the X-ray corona preceding arcade formation suggest that a significant volume (and mass) of gas is ejected from the flare site, consistent with coronagraph observations in white light. The quantitative relationship between this ejected mass and that seen in the CME, however, has yet to be established.

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[1] Memoirs of the RAS, 64, plates 18 and 19, 1929; E. W. Cliver personal communication

Coronal mass ejections returned to the fore of solar activity research with the launch of SOHO in 1995. The combination of three white light coronagraphs, collectively known as LASCO, together with a full disk EUV imager (known as the Extreme Ultraviolet Imaging Telescope, EIT) has demonstrated the coronal consequences of these large-scale magnetic reconfigurations. While the characteristics of the CMEs observed by LASCO are similar to those observed in previous coronagraphs, there are several new aspects: (i) many CMEs are accompanied by a global response of the solar corona, (ii) many show acceleration to the edge of the LASCO field of view (32 R_s), (iii) partial disconnection is a frequent occurrence, (iv) CMEs are occurring more frequently than had been expected at solar minimum, and (v) CMEs undergo extensive internal evolution as they move outward. (see Howard *et al.*, 1997) In addition, LASCO has a greater ability to detect CMEs moving well out of the plane of the sky, in particular 'halo' CMEs which may be directed towards the Earth. The dimming events, discovered by Yokhoh, have been confirmed in EUV observations by EIT and also by the TRACE spacecraft. (e.g. Thompson *et al.*, 1998; Wills-Davey and Thompson, 1999)

CME research also extends to their interplanetary and heliospheric effects, with significant effort being devoted to identifying and measuring in-situ the characteristics of the material ejected into interplanetary space during CMEs. Such material was first identified in the early space era through regions of plasma with unusual characteristics, such as enhanced helium abundances (Hirshberg *et al.*, 1970) commencing a few hours following some interplanetary shocks. These regions extended over periods of $\sim$1 day, suggesting scale sizes of $\sim$0.2 AU, and were initially referred to by terms such as "shock driver", "piston", "plasma cloud", "solar mass ejection", and "ejecta", under the supposition that this plasma was the material ejected from the Sun that generated the shock. At the time of these first observations, it was assumed that the ejected material originated, or at least contained a component, from solar flares that was accelerated through some explosion, or piston process. Subsequent combined CME observations by coronagraphs and in-situ measurements made by spacecraft off the limbs of the Sun (e.g., Schwenn, R. 1983; Sheeley *et al.*, 1985; Lindsay *et al.*, 1999) or near the Earth (e.g., Webb *et al.*, 2000) have demonstrated the clear association (though not necessarily one-to-one, e.g., Cane *et al.*, 2000)) between CMEs launched in the general direction of the observing spacecraft and the subsequent detection of shocks and the related ejected material. The interplanetary manifestations of CMEs are currently frequently termed "Interplanetary Coronal Mass Ejections" (ICMEs), although this does imply an association with CMEs that is arguably not completely proven.

ICMEs are characterized by an array of signatures, most of which had been identified by the early 1980's with the exception of certain compositional signatures which are only observable under all solar wind conditions with the later generation of specialized instruments, such as the Solar Wind Ion Composition Spectrometer (SWICS) on the Advanced Composition Explorer (ACE) satellite. The in-situ signatures of ICMEs are summarized by Zurbuchen and Richardson (this volume).

It was also clear from early in-situ observations (e.g., Bryant *et al.*, 1962) that CME-driven shocks can accelerate particles as they move out through the heliosphere such that major solar energetic particle events include, and may even be dominated by, shock-accelerated particles (e.g., Cane *et al.*, 1988). See the papers in this volume by Cane and Lario, and by Klecker *et al.* for further discussion of this topic.

3. Theories

The observational developments, as in any scientific field, progressed hand-in-hand with theoretical considerations. The development of theoretical models of solar activity has as rich a history as the observational side of solar physics (see Alexander and Acton, 2001 for a more complete discussion of the early developments in flare theory). However, it was realized very early that most solar phenomena had something to do with the magnetic field and its variability. Consequently, the major improvements in our theoretical understanding of solar activity has come about through our ability to investigate the interplay between the plasma and the magnetic field. An important series of models worth mentioning briefly here appeared in the 1960s and 1970s. The first of these, by Carmichael in 1964, proposed that magnetic field lines high above the photosphere could be forced open by the solar wind. Developments of this line of thinking appeared from Sturrock and Coppi (1966), Hirayama (1974) and Kopp and Pneuman (1976) earning this class of the models the sobriquet of the CSHKP model. Since these early models, there have been major advancements in the development of theories to explain the initiation and evolution of solar eruptive transients (Forbes *et al.*, this volume). The development of theoretical models is a small but vibrant area of solar research and the synergy with observation only helps to improve the subtlety and relevance of the theoretical ideas.

4. Overview

As this volume indicates, the study of the formation and development of Coronal Mass Ejections at the Sun and their impact on the heliosphere is a burgeoning field of research with important consequences for our understanding of the Sun and its interaction with the interplanetary medium and planetary magnetospheres. The recent ubiquitous interest in Space Weather is a fitting testament to the heritage provided by the 150 year effort to understand the Sun-Earth connection.

There is still much to learn about solar eruptive events, but it is clear that flares, CMEs, and ICMEs are all important components of the Space Weather system. Studies of these phenomena will continue to drive our need to understand solar variability and increase our ability to predict these events and their potential terrestrial effects.

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