HISTORY AND BASIC CHARACTERISTICS OF ERUPTIVE FLARES

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Abstract. We review the evolution of our knowledge and understanding of the eruptive (dynamic, two-ribbon) flare phenomenon. Starting with the first observation of a white-light flare by Carrington and Hodgson in 1859, we cover in succession the highlights: Hale's invention of the spectroheliograph in 1892 and the spectrohelioscope in 1926 started flare observations in Hα. The institution of a world-wide flare patrol brought significant advances in knowledge of flares in the 1930s and 1940s and new 'windows' were opened to observe flares at short (SID) and long (radio) wavelengths. In the 1950s and 1960s metric radio bursts were related to trapped energetic electrons and shocks, and two-ribbon flares were associated with energetic protons in space. Radio and X-ray observations gave evidence for two basic types of flare processes: an impulsive phase followed by a long-duration or gradual phase. It was found that flares were often preceded by filament activations, and growing loop prominence systems were recognized as the limb counterpart of two-ribbon disk flares. The early 1970s brought Skylab observations of coronal mass ejections (CMEs) and arcades of coronal soft X-ray loops above two-ribbon flares. In the mid-1970s, the Kopp-Pneuman reconnection model, based on configurations proposed earlier by Carmichael, Sturrock, and Hirayama, provided a framework in which the newly discovered CMEs could be related to the basic characteristics of two-ribbon flares. The 1980s brought key new results from SMM and Hinotori including images of hard X-ray flares and large-scale coronal structures associated with eruptive flares. In the conclusion, we summarize the basic characteristics of eruptive flares.

1. Introduction

We divide the history of flare research into three main periods. The first period from 1859-1934 spans the careers of Carrington and Hale. This period is notable for the relative lack of progress. The published 'record' of major flares for this 75 year interval encompasses only about 35 events, consisting of fortuitous observations of white-light flares, reports by early spectroscopists of reversals of line emission near sunspots, and, after 1892, flares observed with the Hale spectroheliograph. The spectrohelioscope developed by Hale during the 1920s was responsible for the rapid advance in the knowledge of flares that took place in the next era of flare research from 1935-1963. With the widespread use of the spectrohelioscope, the opening of new electromagnetic windows at short and long wavelengths, and the first observations of solar particles, this 'middle era' of flare research has a data survey and classification character that is well-captured by the book 'Solar Flares' by Smith and Smith (1963). The modern era, since 1963, is characterized by space observations and a trend toward synthesis indicated by the development of increasingly sophisticated and comprehensive models of the flare phenomenon.

In the following sections we will stress those aspects of flare research that apply specifically to 'eruptive flares', the topic of this Colloquium, but it should be kept in mind that the distinction between eruptive and 'confined' or 'compact' flares (Pallavicini, Serio, and Vaiana, 1977; Švestka, 1986) is a relatively recent addition to the paradigm for understanding flares. In the concluding section we summarize the current picture of eruptive flares.

2. The Early Years of Flare Research, Carrington through Hale

The first recorded observation of a solar flare was made by R.C. Carrington in 1859 at his private observatory at Redhill, outside London. (For biographical information on Carrington, see Main (1859) and Anonymous (1875).) Carrington (1859) was engaged in his daily sunspot drawing in the forenoon on 1 September 1859 when he first noticed the flare (Figure 1). After confirming that it was not caused by stray light, he ran to find someone to verify the observation and when he returned 'within 60 seconds', he was 'mortified to find that it was already much changed and enfeebled.' The white-light emission was initially visible at points A and B and during the course of five minutes moved about 50 000 km to points C and D where it vanished as two rapidly fading dots of white light. Carrington expressed surprise that the 'conflagration' had in no way altered the appearance of the sunspot group which he had finished drawing before the occurrence. Fortunately, Carrington's observation was confirmed by Hodgson (1859), an amateur astronomer who was observing nearby. This event was almost certainly an eruptive flare based on its 'double ribbon' character (cf. Ellison, 1949) and the fact that it was followed within 18 hours by a severe geomagnetic storm. Carrington also noted a disturbance of the Kew magnetograms coincident with the flare but was reluctant to suggest a causal link between the flare and the geomagnetic activity. In fact, 78 years would pass before Bartels (1937) was able to provide the correct description of the prompt and delayed solar-terrestrial relationships manifested in this event.

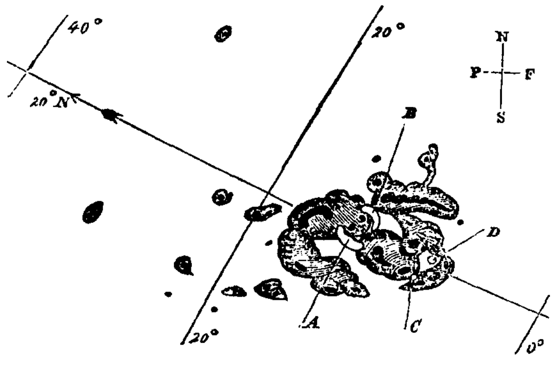

Fig. 1. The first reported flare, on 1 September 1859, observed by Carrington in white light.

Following the discovery by Janssen and Lockyer in 1868 that prominences could be viewed outside of eclipse using a spectroscope, prominence studies were the chief contributors to knowledge of eruptive solar phenomena in the 19th century. By 1871, Secchi and others had introduced a rudimentary but fundamental classification of prominences into active and quiescent types. Motions of prominences with speeds on the order of hundreds of km/s were observed above the limb through spectroscope slits (e.g., Fenyi, 1892) or deduced from Doppler shifts of spectral lines (Meadows, 1970, p. 70).

The lack of rapid progress in flare physics following Carrington's observation was due in part to the rarity of white-light flares. More to the point, the slow pace of flare research resulted from the lack of an instrument that could efficiently image flares in the narrow emission lines in which they are most prominent. Flares were occasionally observed with spectroscopes as 'brilliant reversals' in Hα when scientists placed the entrance slit over sunspot regions. Between 1869 and 1870, such reversals were reported by Secchi in Italy, Lockyer in England, and Young in the United States (Newton, 1940). In 1870, Young observed a two-ribbon flare on the disk through the widened slit of a spectroscope (Figure 2). Young thought that the flare ribbons were bright prominences observed on the disk. The invention of the spectroheliograph by G.E. Hale (1892a) and a related instrument by Deslandres made it possible for the first time to obtain images of the Sun in lines such as Hα or H and K of calcium. (For a biographical sketch of Hale, see Zirin (1968).) The basic principle of the spectroheliograph had originally been elucidated by Janssen in 1868. Two slits are used, the first isolates the part of the Sun's surface to be studied and the second isolates the spectral line forming the image. By moving the slits across a photographic plate in tandem, a monochromatic image of the entire Sun is built up.

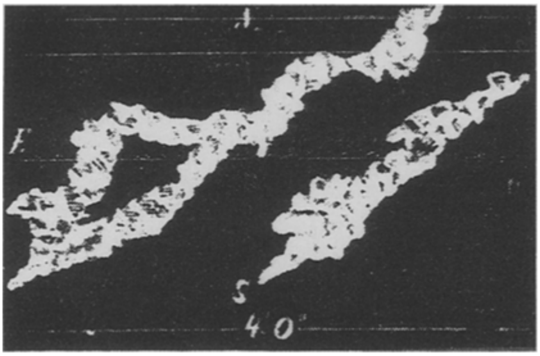

Fig. 2. Drawing by Young of a flare on 28 September 1870 observed through the widened slit of a spectroscope.

With the spectroheliograph, Hale obtained the first published photographs of a solar flare on 15 July 1892 (Figure 3). The image taken in the calcium K-line is grainy because of enlargement of the original plate (Hale, 1892b). Similar to the event reported by Carrington, the 15 July 1892 flare was observed in white light (Rudaux,1892) and was followed approximately one day later by a severe geomagnetic storm.

While the spectroheliograph represented a significant advance in solar observation, the instrument was cumbersome and not well-suited for observing rapidly changing phenomena such as flares (cf., Hale, 1926). Thus Hale developed the spectrohelioscope, an instrument that allowed the entire Sun to be scanned visually at selected wavelengths. The spectrohelioscope operated on the same principle as the spectroheliograph, except that the two slits were rapidly oscillated in tandem across the face of the Sun to give a continuous view of solar activity. The compelling nature of visual spectrohelioscopic observations is indicated by Hale's (1931) description of a large flare in January 1926 as 'the most remarkable solar phenomenon I have ever seen' - this coming after some 40 years of studying the Sun. Hale (1929) designed the spectrohelioscope to be an inexpensive instrument that could be used for patrol work and made arrangements to have the new instrument distributed to observatories around the world. At his urging, the patrol was formalized under the auspices of the IAU and flares have been reported routinely since 1934. For the years prior to 1934, the major flare 'record' consists largely of lists compiled by Newton (1930, 12 'sudden and intense local brightenings of the Sun's surface'), Hale (1931, $\sim$ 20 'violent' solar eruptions), Newton (1940, seven cases of bright reversals of spectral lines). and Neidig and Cliver (1983, eight white-light flares). In all there are only $\sim$ 35 independent events on these lists.

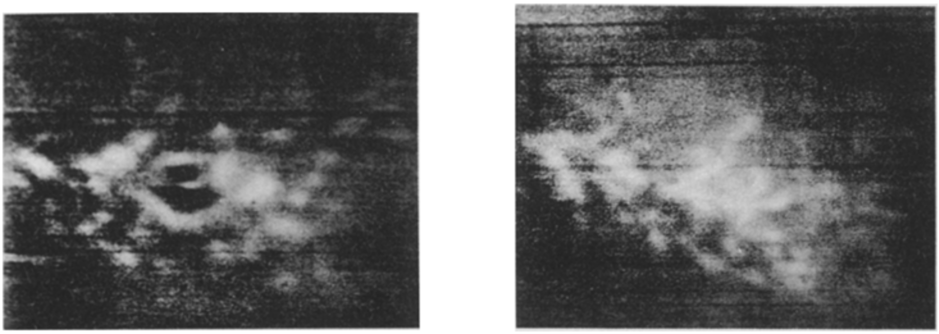

Fig. 3. The first published photographs of a flare, on 15 July 1892, taken by Hale in calcium K-line with the spectroheliograph. The left-hand frame at 1658 UT is shortly after flare onset, the right-hand frame at 1737 UT shows the maximum development.

Hale's 1931 paper entitled 'The Spectrohelioscope and Its Work, Part III. Solar Eruptions and Their Apparent Terrestrial Effects' represented a long overdue study of the connection between flares and geomagnetic storms suggested by Carrington's 1859 event. Given Hale's stature in the astronomical community, it also probably served to dispel doubts about the 'legitimacy' of solar-terrestrial studies lingering from Lord Kelvin's address to the Royal Society of London in 1892. In that address Lord Kelvin concluded that 'magnetic action of the Sun, or...hurricanes in his atmosphere' could not possibly be the source of magnetic storms at Earth (cf. Bartels, 1937; Sturrock, 1987).

3. Coming of Age as a Discipline, Systematic Observations and New Windows

Once the spectrohelioscope patrol began, knowledge of flares and their relationship with active regions and prominences advanced rapidly. McMath *et al.* (1937) reported a flare-associated ejection of prominence material with outward speed $\sim$ 700 km/s, greater than the escape velocity, that was visible to a height of 10^6 km and was followed by a 'fountain' type prominence (system of post-flare loops). Waldmeier (1938) documented the double-ribbon character of major flares and Giovanelli(1939) identified sunspot area and magnetic complexity as key variables for flare occurrence. Separation of flare ribbons, with typical speeds of 1-10 km/s, was noted by Dodson (1949) for double-ribbon flares on 8 and 10 May 1949. Direct comparisons of magnetograms with flare positions, first made by Bumba (1958) and Severny (1958), indicated that flare ribbons lie adjacent and parallel to neutral lines (cf., Ellison, McKenna, and Reid, 1961).

During the 1940s, the term 'flare' came into common usage, supplanting the previously used expression 'bright chromospheric eruption' (Richardson, 1944). While the term 'bright chromospheric eruption' is unwieldy, it retains an important aspect of certain events (mass motion) that is lost in the simpler term (cf., Dodson and Hedeman, 1968; Hudson, 1987).

In the decade following the establishment of the Hα patrol, several new 'windows' were opened to the observation of flares. In 1935, Dellinger noted that sudden disappearances of short-wave radio signals during that year occurred at intervals of approximately 54 days, twice the rotation period of the Sun, and suggested a solar origin. Within a few months, observers using Hale spectrohelioscopes confirmed this suggestion, opening up the study of flares and the ionosphere via sudden ionospheric disturbances (SIDs; Dellinger, 1937). For many years, SIDs were thought to result primarily from Lyman-α emission during flares, but rocket flight experiments in the 1950s and satellite measurements in the early 1960s showed that enhanced soft X-ray emission during flares was the principal cause of SIDs (Kreplin, Chubb, and Friedman, 1962).

A statistical study by Newton (1943) relating solar flares to geomagnetic storms gave early insights into the nature of coronal mass ejections (CMEs). Newton concluded that the semi-angle of the corpuscular stream associated with a solar flare could be as large as 45°, based on the locations of great flares that preceded intense storms. A full cone of 90° is consistent with measurements of the limb span of larger 'curved front' CMEs (Howard *et al.*, 1985). Newton obtained an average flare-to-storm delay time of slightly over a day, implying, in retrospect, peak transient wind speeds $\sim$ 1200 km/s, at the high end of *in situ* measurements of the solar wind during the past 25 years (Cliver, Feynman, and Garrett, 1990).

Appleton and Hey (1946) were the first to definitively associate enhanced radio emission with solar flares. Metric type II (Wild and McCready, 1950) bursts were discovered by Payne-Scott, Yabsley, and Bolton (1947) and attributed to disturbances (later identified with magneto-hydrodynamic shock fronts) moving through the corona with speeds $\sim$ 500-750 km/s. Type IV bursts identified by Boischot in 1957 gave evidence of outward propagating plasmoids. Apart from prominence eruptions observed in the Hα line, these 'moving' type IV bursts represent the first evidence of flare-associated mass ejections. Dodson, Hedeman, and Owren (1953) reported that major bursts at 200 MHz had an 'early' component occurring near flare onset and a second component beginning at or after the flare maximum, thereby anticipating the classification of metric radio emission into two distinct phases by Pick (1961) and Wild, Smerd, and Weiss (1963). Covington and Harvey (1958) presented evidence for two distinctive types of microwave bursts, impulsive and long-duration, and surmised that they represented thermal and nonthermal emissions, respectively. Today, the early metric component and impulsive microwave burst are identified with the flare flash phase (Ellison, 1946), and the delayed metric and long-enduring microwave emissions represent, in turn, evidence for particle acceleration and plasma heating, associated with prolonged energy release in eruptive flares.

Flare-associated 'cosmic ray' intensity increases at Earth were first reported for the flares of 28 March 1942, 7 February 1942, and 25 July 1946 (Forbush, 1946). The long durations of solar energetic particle (SEP) events, in comparison with the durations of associated flares (e.g., Meyer, Parker, and Simpson, 1956), has been problematical from the beginning of SEP observations. The traditional explanation following Reid (1964) to account for these long durations has been a brief injection of particles followed by diffusion over relatively short mean free paths, $<$0.1 AU at $\sim$ 10 MeV. A counter viewpoint is that particle acceleration in eruptive flares can occur in association with interplanetary shocks that are well-removed in space and time from the associated flare (see Reames, 1991, these Proceedings).

4. The Modern Era, Space Observations and Synthesis

In 1963, the *AAS-NASA Symposium on Solar Flares* (Hess, 1964) was a watershed meeting for the phenomenon that we call now eruptive flares. Kiepenheuer suggested that eruptive quiescent filaments should be viewed as 'soft' versions of two-ribbon flares. Kleczek arrived at the fundamental conclusion that there is not enough plasma in the corona to condense into the loop prominences and that material must be transported from lower atmospheric layers into the loops. Avignon, Caroubalos, Martres, and Pick emphasized the close association of type IV radio bursts with two-ribbon flares. A key breakthrough at this Symposium was Petschek's model of field-line reconnection which, for the first time, made the reconnection process realistically applicable to flares. Finally, Carmichael presciently proposed the general magnetic configuration in which eruptive flares occur (Figure 4, upper left) and the relationship of eruptive flares with the yet-to-be-discovered coronal mass ejections.

Bruzek's landmark paper in 1964 established two basic tenets of the modern view of eruptive flares: (1) flare ribbons represent the chromospheric base of coronal loop prominence systems (post-flare loops), and (2) individual loops do not expand during such flares, rather the apparent growth of such systems is due to the formation of higher and higher loops while the lower ones fade in place. This fact, deduced from Hα data, was later confirmed by Skylab for loop systems observed in soft X-rays (Moore *et al.*, 1979) and by SMM in hard X-rays (Švestka *et al.*, 1987). The successive formation of higher temperature loops gave evidence that, in contrast to 'compact' flares (Pallavicini, Serio, and Vaiana, 1977), energy release in eruptive flares is not short-lived but continues for many hours.

The unique association of loop-prominence systems, type IV radio bursts (i.e. trapped accelerated electrons) and strong proton streams in space (by Ellison, McKenna, and Reid, 1961) with two-ribbon flares clearly indicated that this type of flare represented a special class of the flare phenomenon. Sturrock (1968) proposed the first quantitative model of such flares, invoking reconnection to account for particle acceleration, ejected plasma, and the formation of the two bright ribbons in the chromosphere (Figure 4, upper right).

Knowledge of ejections from flares increased substantially in the 1970s. Wave fronts generated in flares were critically summarized by Smith and Harvey (1971) and interpreted as shock waves by Uchida, Altschuler, and Newkirk (1973). During 1970 - 1973, 13 abrupt depletions of localized regions of the inner solar corona were detected by the Mark I coronameter at Mauna Loa (Hansen et al., 1974), and other coronal disturbances were observed by the NRL coronagraph on OSO-7 (as reported in Proceedings of the *IAU Symposium* 57 (Newkirk, 1974) by Brueckner (see also Tousey, 1973), and Stewart *et al.*) In 1973-1974, the coronagraph on Skylab obtained well-resolved photographs of coronal mass ejections (CMEs) (then called coronal transients, see MacQueen *et al.* in Newkirk, 1974). It was found that many CMEs are not associated with flares, but rather with eruptions of quiescent filaments (Gosling *et al.*, 1974). This gave impulse to the creation of the term *dynamic* (Švestka, 1986) or *eruptive flare* (following Priest's suggestion): it includes not only two-ribbon flares but all instabilities related to erupting filaments and any coronal configuration of a similar nature.

The above discoveries stimulated new efforts at modelling erupting flares. First Hirayama (1974) modelled the flare-associated dynamic events (Figure 4, middle), including evaporation of chromospheric gas into coronal loops. His pioneering work was followed two years later by the widely accepted Kopp and Pneuman (1976) model of field opening and sequentially reconnecting field lines (Figure 4, below). We will talk here about the K-P model, but one should not forget the earlier work of Carmichael, Sturrock, and Hirayama.

The K-P model successfully explained the successive formation of new loops, the velocity pattern of the growth of the loops and the separation of the bright ribbons, as well as the long-lasting release of energy. Sakurai's (1985) modelling of X-ray loops with the current-free approximation provided evidence that the magnetic structure of the loops had to be greatly simplified shortly before their appearance, most likely through field-line reconnection.

The original K-P model,however, also had several deficiences.

First, it did not specify any reason for the initial opening of the magnetic field structure. Only later years brought suggestions for the opening mechanism: internal, through loss of equilibrium (Martens and Kuin, 1989) or MHD instability (Sturrock, 1989; Priest and Forbes, 1990), or external, through newly emerging flux (Rust, Nakagawa, and Neupert, 1975), flux cancellation (Van Ballegooijen and Martens, 1989), or slow-mode waves (Rust and Švestka, 1979).

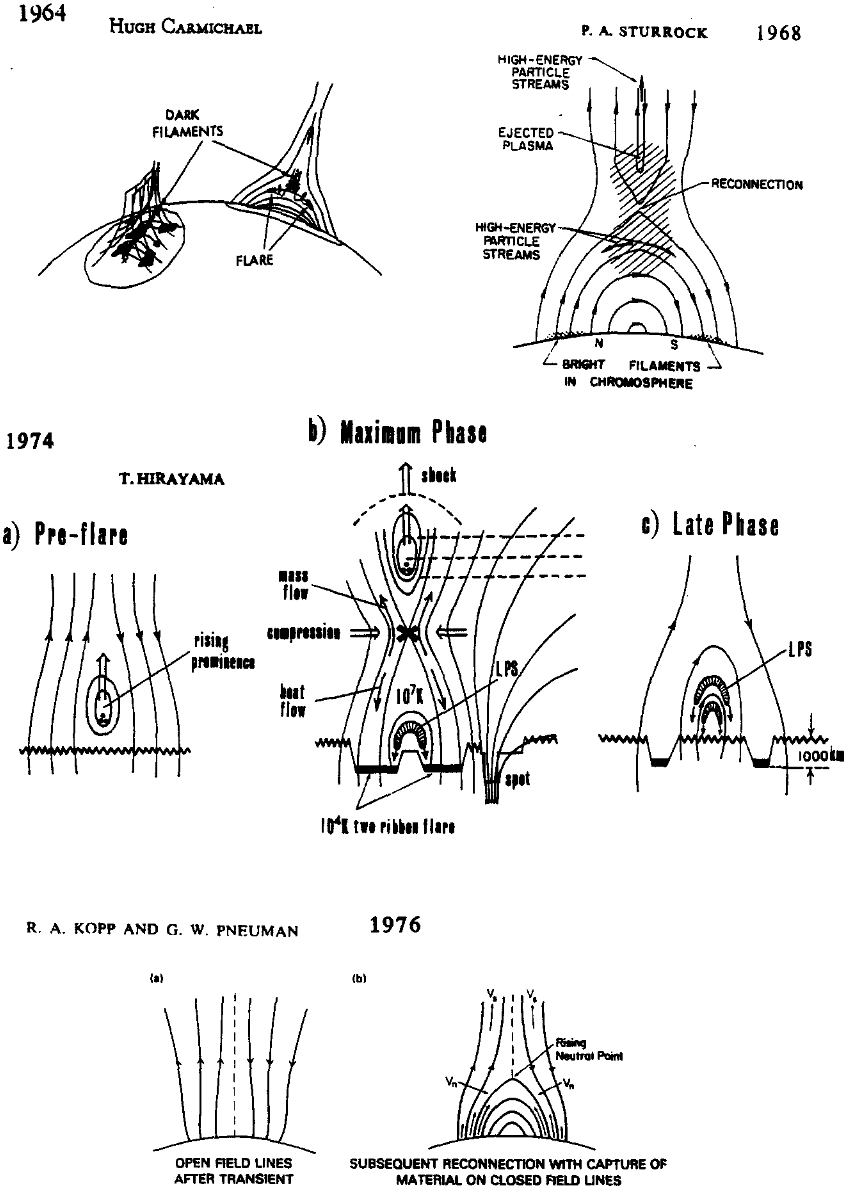

Fig. 4. The basic coronal configuration first proposed for eruptive flares by Carmichael (in Hess, 1964, *upper left*), later improved by Sturrock (1968, *upper right*), Hirayama (1974, *middle*), and eventually by Kopp and Pneuman (1976, *bottom*).

Second, the loop temperatures derived by K-P seemed high enough at the time when the model was proposed, but became too low, by almost an order of magnitude, when hard X-ray data became available. K-P supposed that a gas-dynamic shock propagates downwards from the reconnection site and heats the upflowing plasma to 3 - 4 million degrees. In 1983 Cargill and Priest showed that, in the context of the K-P model, one can heat the loops to the observed temperatures in excess of 20 million degrees by slow MHD shocks.

Third, the original K-P process failed to bring enough plasma from the chromosphere into the coronal loops to explain their observed density, at times greater than 10^{12} cm^{-3} (Heinzel and Karlický, 1987), and the total mass between 10^{16} and 10^{17} g established earlier by Kleczek (in Hess, 1964). Only improved theories of the evaporation process, proposed by Forbes and Malherbe (1986) and, in several studies, by Canfield, Fisher, and Gunkler, could keep the K-P model valid. Following Fisher (1986) one can distinguish two types of evaporation: an explosive one, if the chromosphere is heated by particle flows, and a non-explosive evaporation through conduction. The explosive evaporation occurs during the impulsive phase, whereas later on, when the 'post'-flare loops are formed, only the conductive evaporation is active, propagating at 0.2-0.4 of the sound speed. This agrees very well with evaporation speeds actually observed in a loop system by Schmieder *et al.* (1987).

Thus we conclude that the K-P model, with the modifications mentioned above, can adequately explain eruptive flare processes.

In 1982, (Švestka *et al.*, 1982a), using HXIS observations from SMM, discovered X-ray giant post-flare arches above eruptive flares. The giant arches represent the lowest and most dense parts of stationary type IV bursts and, later on, type I radio noise storms. It seems clear that the two structures in Figure 5, respectively observed by Wild (1969) at Culgoora at metric radio waves and by HXIS on SMM below 3.5 Å X-rays, are essentially the same phenomenon. Similar and probably related structures were also observed on radio waves by other authors, e.g. Gopalswamy and Kundu (1987). Kopp and Poletto (1990) demonstrated (as Sakurai did for 'post'-flare loops) that the arches can be fit by a current-free field. This implies that the arches also form through field-line reconnection, but different authors disagree so far as to where, when, and why this reconnection happens.

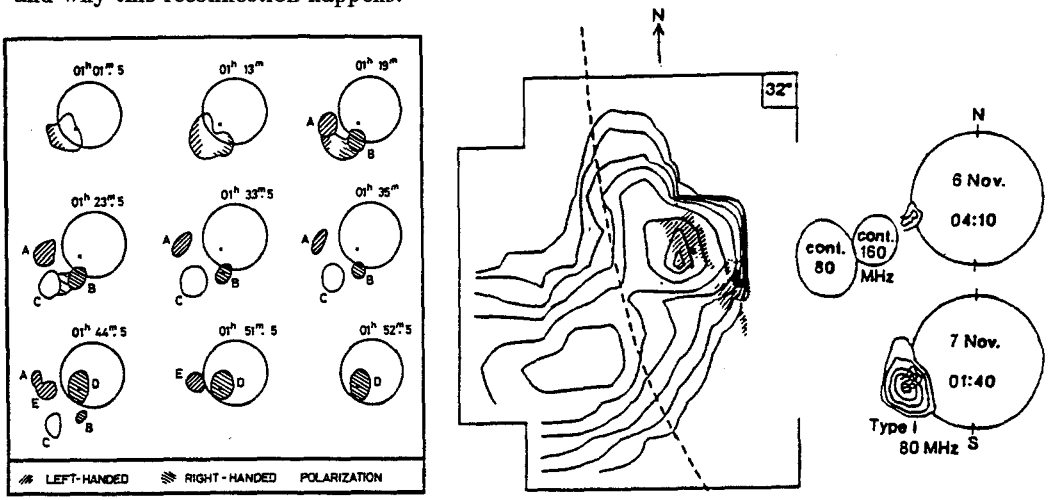

Fig. 5. *Left*: Wild's (1969) images of moving (A,B,C) and stationary (D) type IV bursts on metric radio waves. —it Middle: HXIS image of the giant arch of 6 November 1980 in 3.5 - 5.5 keV X-rays. (*Dashed curve*: solar limb.) *Right*: Type IV burst associated with this arch early on November 6 and type I noise storm above the arch on November 7 (Švestka *et al.*, 1982b).

In some eruptive flares with long-lasting X-ray bursts the X-ray spectrum progressively hardens. This was observed by ISEE-3 (Vilmer, Kane and Trottet, 1982), Hinotori (e.g. Takakura *et al.*, 1984), as well as by SMM (e.g. Cliver *et al.*, 1986). This again points to a magnetic trap above the flare site, in which the energy-dependent collisional loss of confined electrons causes the hardening (Tsuneta, 1983).

In concluding this necessarily brief review of the modern era of eruptive flare research, we mention recent studies of CME timings (e.g., Harrison *et al.*, 1990; cf., Smith and Ramsey, 1964) and size scales (Kahler *et al.*, 1989) relative to flares which, when coupled with analyses of the energy contained in flare mass motions (e.g., Webb *et al.*, 1980), indicate that the 'flare' part of 'eruptive flares' may be properly viewed as a consequence of the 'eruptive' part. The evolution of our understanding of the relationship between eruptive flares and CMEs is reviewed by Kahler (1992).

5. Conclusions

In conclusion, we want to emphasize the basic characteristics of eruptive flares as we understand them (we are aware that there is not unanimous agreement on this question, but that's one of the reasons why the Colloquium was held).

The preflare magnetic field in the Carmichel/Sturrock/Hirayama/Kopp and Pneuman configuration becomes unstable (due to an instability or an outer trigger), opens, and the open field lines subsequently reconnect. A dark filament, if present, manifests the field opening by its eruption and an associated CME may propagate into interplanetary space. The field reconnection is manifested as the sequential appearance of progressively higher flare loops formed at temperatures in excess of 20 million K, and by continuous energy release, lasting for many hours. In many events, post-flare coronal arches brighten for tens of hours in the corona following eruptive flares; these arches appear to be the lowest and densests parts of magnetic traps above the flare sites which, in their higher parts, produce moving (CME-associated) and stationary (arch-associated) type IV radio bursts; the stationary bursts gradually evolve into radio noise storms.

The consequences of the field-line opening depend very much on the strength of the involved magnetic field. In very old remnants of active regions, eruptions of quiescent filaments produce *disparitions brusques*, without any chromospheric brightenings; in somewhat stronger fields a few Hα bright patches appear, which eventually merge into two bright Hα ribbons when the field opens in an (even spotless) active region. These ribbons, parallel to the zero line, become very bright in *two-ribbon flares* which appear in fully developed regions; the most energetic of them are the *proton* or *cosmic ray flares*. Because the basic process is the same in all these phenomena, we call them collectively **eruptive flares**. All eruptive flares, from the disparitions brusques to the cosmic-ray flares, may be associated with **mass ejections** in the solar corona.

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