OPTICAL EVIDENCE FOR PLASMA EJECTIONS AND WAVES IN THE SOLAR CORONA

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Abstract. Plasma ejections and waves in the solar corona are almost exclusively flare associated phenomena. Ejections of relatively cool and dense plasma are frequently observed in Hα whereas observations in coronal light (visible, EUV- and X-radiation) are still rather scarce. Occurrence of coronal waves is so far best known from their effects on the Hα chromosphere and, of course, from the production of radio bursts. Only in relatively few cases have observations been made in coronal lines and in coronal continuum by ground based as well as by satellite borne equipment. We may expect, however, that the white light coronagraph and the X-ray telescopes on board of the Skylab will detect quite a number of events in front of the solar disk and high in the solar corona and will considerably increase and improve our imperfect knowledge and understanding of coronal ejections and waves as it is presented in this review.

1. Plasma Ejections

Three large classes of ejections may be distinguished according to their origin and their appearance in Hα: (1.1) surges, (1.2) sprays, (1.3) eruptive prominences.

1.1. Surges

The simplest type of ejection occurring in the solar corona is the classical surge which grows out of the chromosphere with velocities 100–200 km s^{-1} in the form of a straight or slightly curvilinear spike or streamer remaining connected with the chromosphere and attaining a length of 10^5 km or more. In general, surges shrink again along the path of formation and disappear after a lifetime of 10–30 min; the material either fades or it returns into the chromosphere along the trajectory of ascent. However, in some cases material was observed moving along a large arch, ascending in one branch of the arch and eventually descending along the other one (Bruzek, 1969, Figure 4). On the solar disk surges appear in absorption, in their initial phase sometimes in emission; they originate close to spots and pores. Sometimes several surges form a group resembling a veil or a fan.

The trajectory of the moving plasma and its collimation into a small solid angle indicate that surges are confined by a more or less radial magnetic field. Roy (1973b) computed the configuration of the coronal magnetic field at the position of surges in the current free approximation from measured longitudinal photospheric fields and indeed found good agreement with the observed directions of surges. Magnetic fields in surges have been measured by Harvey (1969) and field strengths of the order 50 G decreasing with height in the surge and with its length have been found.

A number of authors (Giovanelli and McCabe, 1958; Gopasyuk *et al.*, 1963; Bruzek, 1969) observing in the center of Hα reported that more than 90% of the surges emanate from brightenings in Hα which are classified as flares, the majority of them however only as subflares, even in cases of very large surges. These surge-associated

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flares appear as bright points or blobs, sometimes rather *U*- or ring-shaped with a typical diameter of 25000 km. The flare first expands somewhat in height until at maximum intensity the surge rapidly grows out; the flare fades simultaneously and has virtually disappeared at the time of maximum development of the surge. At the limb, the surge assumes often flare brightness in its initial stage of development and shows the characteristic flare spectrum rather than a prominence spectrum. The brightness in the surge decreases with height and time as if the flare plasma relaxes after it is shot out from the chromosphere. This development indicates that it is the flare which provides the material for the surge, or rather that the flare is transformed into the surge. Apparently, the flare at the base of the surge and the surge are two phases of the 'flare-surge event'. That the growth of the surge is true mass motion and not due to a propagating condensation of coronal material is inferred from the Doppler effects observed on the solar disk.

It is remarkable that, in general, no brightening occurs at the base of the surge during the inflow of material into the chromosphere which takes place at speeds up to 150 km s^{-1}. This observation indicates that the infall of material does not necessarily produce a flare as Hyder (1967) suggested in his impact hypothesis.

It must be pointed out here that the majority of ejections associated with *larger* flares (importance 1 to 4) are not classical surges although many observers call them surges. They belong rather to classes (2) or (3) or to some intermediate type.

In a recent investigation Roy (1973a) found almost all surges of his sample associated with bombs and only a few of them with flares or subflares. This disagreement with the previous authors is apparently due to the fact that the majority of Roy's surges were very small (155 out of his 182 were <35000 km, i.e. importance S) whereas, for instance, the sample which I had studied (Bruzek, 1969) included only surges >40000 km (i.e. importance $\geqslant 1$). That suggests that, in general, very small surges are associated with bombs, large ones, however, preferably with (sub-)flares. One should keep in mind, however, that the majority of bombs is associated with rather small, surgelike absorption features which may be of different nature than 'proper' surges. Nevertheless Roy (1973b) found the same intensity-time relation between surge development and bomb development as it was described above for flares and associated surges, and he interpreted it also in terms of growing of the surge out of the bomb! This indicates that the same ejection mechanism is effective for bomb associated and flare associated surges.

One more characteristics of surges has to be mentioned which is most conspicuous with the smaller surges starting at penumbral borders; that is the tendency to recur many times (at a rate ≈ 1 h^{-1}) at the same position (Bruzek, 1969). A very spectacular sequence of countless surge repetitions over a period of >24 h has been described by Fortini and Torelli (1968). Also large surges may appear several times at the same place and in the same shape.

Studying the dynamics of his largest surges Roy (1973b, c) found that the rising motion of the surge material, as measured at its top, is accelerated as far as 10000–50000 km above the surface where a velocity of 100–175 km s^{-1} may be attained after

5–10 min. The following desceleration of the ascending material is larger than that produced by gravitation alone, and the downward acceleration of the returning material is less than gravitational acceleration. These observations imply that (1) an accelerating force is still acting on the surge after its material has left the chromosphere; the surge is not a pure ejection with its material moving freely in the corona; (2) the motion of the material is opposed by a kind of friction.

Various mechanisms have been proposed for the initial acceleration of the surge (Livshits and Pickel'ner, 1964; Uchida, 1969; Pickel'ner, 1969; Altschuler *et al.*, 1968; Lilliquist *et al.*, 1971) which cannot be reviewed here. There is observational evidence that the required energy may be provided by the underlying magnetic field: Rust (1968) and Roy (1973a, b) have observed that the magnetic flux in satellite magnetic polarities in surge active regions decreased at a rate of $1-3 \times 15$ Mx s^{-1}. Roy found for a series of well observed bombsurge events that the energy possibly provided by the changing magnetic flux as well as the thermal energy in the associated bombs and the kinetic energy of the surges were of the same order of magnitude, 5×10^{27} erg. The corresponding value for large flare-surges would be about 10^{30} erg!

The braking force observed during ascent and descent of the surge material is proportional to its velocity (Roy, 1973b, 1974). It can be interpreted as the Lorentz force acting if the material does not move exactly along the magnetic lines of force so that a small field component is perpendicular to the mass motion. A field component $B_{\perp} \approx 0.01$ G would already account for the observed effect. That means that a slight deviation from the force-free configuration, a slight twisting of the field otherwise unnoticeable would exist. It may be noted that in some large surges a helical flow has been observed.

1.2. Sprays

Another type of ejecta, the sprays, are much more vigorous than surges. They emanate also from flares, often from large flares with an explosive phase ('explosive' in this context means a rapid brightening and expansion of the flare). At the solar limb, sprays are preceded by a flare which rapidly forms a bright hill or even a large flare-bright prominence which suddenly disrupts and expels the spray material at high velocities. The trajectories of the moving plasma are spread over a large volume and not confined to a narrow cone as in surges. The spray plasma often appears in flare-bright clumps as if parts of the flare plasma were torn off. This may indicate that the flare plasma was highly turbulent before its ejection. This development suggests, as was pointed out by Smith (1968) and Gold (1968) that the flare plasma originally constrained by a closed magnetic field stretches the lines of force as its internal kinetic energy density increases until eventually the field bursts open and the plasma escapes. Nevertheless, McCabe (1971) was able to show for a typical spray event that the associated flare occurred clearly at the base of an existing open field structure and that the spray material moved outwards along the field lines. The ejected plasma attains its maximum velocity of up to 1000 km s^{-1} within a few minutes. After the initial very high acceleration (a few km s^{-2}) the ejected material moves slightly decelerated by gravitation; only a small fraction is seen to return to the solar surface, the main part of the material fades or escapes from the Sun due to its high velocity.

Observations of sprays on the solar disk are scarce and their identification is difficult. This is not a surprise if we consider the high velocities of the material and the narrow passband of the filters commonly used in the Hα patrol observations. Even for strongly inclined ejections the radial velocity component may amount to several hundred km s^{-1} corresponding to a Doppler shift 5 Å or more. So, probably the majority of sprays occurring in front of the disk simply escape observation through filters centered on Hα or shifted a few Å off the line center. A line shifting as far as about -10 Å off Hα would be required for an effective spray patrol.

The available disk observations in the center of Hα – which necessarily are inadequate – show sprays, or what is believed to correspond to sprays, as rapidly expanding material which starts bright and changes to dark, extending over a fairly wide arc. The material does not show always the clumpiness of the limb spray, it rather looks like a bright or dark semi-transparent cloud or veil. These expanding features may be confused with flare wave disturbances which have the same velocity of propagation (see below).

On the other hand, it is difficult in many cases (limb as well as disk events) to decide if we are observing a spray or a surge because there are ejections which are either intermediate in velocity and structure between classical sprays and classical surges or do not fit at all into the simple surge-spray classification scheme.

Besides the flare sprays which consist of ejected flare plasma there is another type which contains material from erupting prominences (see next section).

1.3. Eruptive prominences

Quite another class of plasma ejections in the solar corona are the eruptive prominences. These are a flare associated phenomenon, at least in the more vigorous types, but the moving material is originally prominence plasma.

The eruption of a filament or prominence consists in a concurrent growth and rise which takes place at an increasing rate until the prominence bursts open and/or disappears high in the corona. The observed maximum velocities may exceed the escape velocity. A part of the erupted material may, however, return to the solar surface. We may distinguish three different types according to the particular circumstances of occurrence, i.e. to the relationship to flares and to the temporal development. The three types are: (a) During the flash and maximum phase of a nearby flare an active region filament, even a very small one, may grow and rise rapidly and move away from the flare as if blown away – and sometimes also disrupted – by the flare; in some cases the plasma is finally driven away as a spray. The whole phenomenon lasts about 15 min. It seems likely that it is produced by a flare-produced shock or by a kind of 'flare wind' i.e. by a stream of particles accelerated by the flare process. (b) An active region filament may start to ascend and expand slowly but also at an accelerated rate several tens of minutes prior to a flare. It finally attains a velocity of several hundred km s^{-1} and disappears high in the corona just at the onset or during the flash of a flare which forms two bright ribbons on both sides of the disappeared filament. The duration of this eruption process is up to one hour. This is the classical DB-flare event. The eruption (the 'Disparition Brusque') is a preflare phenomenon probably induced by an instability of the magnetic field preceding flare occurrence. (c) Quiescent prominences outside active regions sometimes ascend and finally disappear in the course of several hours. The rising motion starts with a few km s^{-1} but may attain also high velocities in the final phase. In many cases the eruption is followed by flarelike brightenings (Bruzek, 1957; Hyder, 1967) or even major flares (Dodson and Hedeman, 1970). There are indications that these eruptions in some cases are initiated by a disturbance emanating from a distant active region either from newly emerging magnetic flux or from a flare. In the majority of cases, however, there is no clear evidence for an external cause. It has to be assumed that the eruption is due to an instability of the prominence-supporting magnetic field.

1.4. Observations in coronal light

In the preceding sections the ejections of dense and cool plasma visible in Hα have been considered. In a few instances ejections have been observed also in higher temperature lines: Neupert mentioned the observation of a surge on the solar limb in He II λ304 on OSO-7; Kirshner and Noyes (1971) reported on the observation of an ejection seen in the C III line λ977 with the OSO-6 spectroheliograph. The amount of the C III emission was found consistent with the assumption that the C III ions occupy sheets with thickness 100 km surrounding the cooler Hα emitting threads. This transition sheet is believed to be formed by heat conduction from the hot corona.

Observations of fast changes ('transients') in visible coronal lines are difficult and rather scanty. An extensive observing material in the green coronal line λ5303 has been collected at the Sacramento Peak Observatory, New Mexico in the years 1957 through 1972. In recent studies of this unique material Dunn (1971) and DeMastus *et al.* (1973) detected 30 fast transient events, 18 out of them were classified as ejections. They are described as expulsions of material from the lower corona or the chromosphere which appear as ascending clouds either large and diffuse or small and concentrated; several were definitely surgelike (Kleczek and Hansen, 1962). Almost all observed coronal ejections were found to be associated with Hα surges or eruptive prominences.

A spectacular ejection of coronal plasma clouds visible in white light has been observed by OSO-7 (Brueckner, these proceedings).

2. Coronal Waves

We have to expect that explosive flares and fast flare ejecta – which have supersonic or superalfvenic velocities – produce shocklike wave disturbances in the solar corona. Well known are the type II radio bursts which are evidence for the propagation of a flare-produced shock wave through the higher corona. In recent years evidence for waves has been found also in optical observations of the corona in monochromatic and in white light. Moreover, flare-related chromospheric disturbances have been observed in Hα which provide indirect evidence for the propagation of a wave or shock in the corona. These are: (a) the oscillation of a distant filament (winking filament); (b) a bright or dark chromospheric disturbance rapidly moving away from the flare (flare wave). The majority of these Hα phenomena have been observed at the Lockheed Solar Observatory and a comprehensive study has been presented recently by Smith and Harvey (1971). The Hα disturbances will be discussed first.

2.1. Evidence from Hα observations

The flare wave, in many cases, becomes visible only outside the associated active region propagating into a limited cone of about 90° with velocities 400–1000 km s^{-1} to distances of up to 500000 km. If the motion is extrapolated back into the flare region it is found that the disturbance starts during the explosive phase of the flare. In well developed events, such as the classical cases of 20 September 1963 and 28 August 1966 the disturbances are led by a curved dark or bright front depending on the wavelength of observation. If observed at Hα−0.5 Å a narrow bright front is followed by a broader, more diffuse, dark feature; at Hα+0.5 Å bright and dark is exchanged. In the line center of Hα usually a faint bright front is seen. This brightening and darkening is interpreted as due to a Doppler shift produced by a propagating down-up motion of the dark chromospheric elements; the velocity amplitude is about 30 km s^{-1}. This motion may be a depression produced by a passing wave front followed by a relaxation. Actually, the motion need not to be strictly vertical, it may have a horizontal component and rather be a tilting motion of the chromospheric elements (spicules, mottles). If the flare wave reaches a filament a similar effect occurs: the filament first becomes redshifted (and disappears in the line center) that is depressed, then blueshifted, again redshifted and so on for 2–5 times. That means, the filament is excited to a damped oscillatory motion by the passing flare wave. Periods of oscillation in the range 6–40 min were found (Dodson and Hedeman, 1964; Smith and Ramsey, 1966). Again, the motion may rather be an increase and decrease of inclination as suggested by Kleczek and Kuperus (1969). Limb observations of oscillating prominences would clarify the exact type of motion, but are not available so far.

In a number of cases such filament oscillations were observed following a flare without the arrival of a visible flare wave. If we assume that these oscillations are also excited by a disturbance emanating from the explosive flare we find the same velocity of propagation and we may conclude that the same type of disturbance is acting even if it has no observable effects on the chromosphere.

Smith and Harvey (1971) concur with the above interpretation of the Hα flare disturbance as a depression and relaxation of chromospheric elements (Dodson and Hedeman, 1968) for only about 50% of the events included in their study. They contend that nine cases – according to their different characteristics – should be interpreted as material ejected into the corona rather than as a Doppler shift of chromospheric elements. Following the description given by the authors one is led to the conclusion that these ejections probably are sprays. It is interesting to note that in all but one of the above nine cases filament oscillations were observed inferring a flare disturbance travelling with the typical wave velocity (500–750 km s^{-1}). Thus, although no typical chromospheric wave was observed, the filament was reached by a flare disturbance.

These observations show once more the difficulties to recognize the true nature of the chromospheric disturbances just from observations in a narrow wavelength range around Hα.

Theoretical interpretations of the Hα flare wave in terms of a flare produced MHD coronal wave have been given by Anderson (1966), Meyer (1968), and Uchida (1968). Uchida suggested that the flare emits a MHD fast-mode wavefront which expands into the solar corona. The observed travelling chromospheric disturbance is excited at the intersection of this wave front with the chromosphere which sweeps along the chromosphere ('sweeping skirt' model). Recently, Uchida *et al.* (1973) elaborated this basic hypothesis and applied it to selected observed events taking into account the actual physical conditions prevailing above the disturbance. They computed the propagation of a fast-mode MHD wavefront through the solar corona using the distribution of the coronal magnetic fields as computed from measured photospheric fields and the coronal electron densities as derived from *K*-coronameter data. They found that the progression of the fast wave mode and its intersection with the chromosphere agreed remarkably well with the observed positions of the front of the Hα disturbance. Unfortunately, the two cases for which detailed results are published belong to the nine events which Smith and Harvey considered as ejections and not as a wave disturbance. It is therefore at least doubtful whether the results are conclusive in these two particular cases.

2.2. Coronal observations

Shocks produced in the corona by flares and ejected plasma should, of course, become evident in the corona itself by some characteristic effects. The best known coronal phenomenon produced by a shock wave are the type II radiobursts. Sprays, on the other hand, are frequently associated with type II bursts (McCabe, 1971; Stewart *et al.*, 1974; Riddle *et al.*, 1974), i.e. they are actually associated with a shock. There is also strong evidence that the coronal wave inferred from the chromospheric flare disturbance just discussed is identical with the shock producing the type II burst (Wild, 1969). The statistical correlation of ejections and chromospheric waves with type II bursts, however, is rather poor. Only 30% of spray flares (Smith, 1968) and 18 out of 50 Hα flare disturbances (Smith and Harvey, 1971) were found associated with a type II burst. A possible explanation for this poor correlation will be given below.

As for optical coronal observations, Dunn (1971) found about 20 fast events in the Sacramento Peak green line coronal film which may either interpreted as the visible propagation of a shock into the corona or as the effect of a travelling shock on coronal structures. Almost all of them were associated with Hα flares or ejections. Unfortunately, so far no coronal observation is available at the time and above the position of an observed chromospheric flare wave, that means, we have not yet a direct optical identification of the coronal wave which produces the Hα chromospheric disturbance.

Different types of green line fast events have been observed. The first class includes fast expanding arches or shells emanating from a flare (see Orrall and Smith, 1961) and accelerated expanding arches which explode at flare onset quite analogue to the behaviour of preflare erupting prominences (Bruzek and DeMastus, 1970). The second class includes the features classified by Dunn (1971) as Realignments and Disruptions of existing coronal structurs. The classical case of a disruption is Evans' whip (Evans, 1957; Dunn, 1971). A somewhat similar case occurred in the 22 February 1967 event (Bruzek and DeMastus, 1970). Realignments are described as large arches seen to snap into new positions almost instantaneously which is suggested to be due to a shock.

Only about 50% of the events classified as coronal expansions were associated with type II bursts although the expansions may be considered as shocks which are expected to propagate further into the corona. In this context an observation of De-Mastus *et al.* (1973) may be important. They found that some of the moving coronal features are trapped that is, their motion was more or less suddenly stopped in lower levels of the corona – probably by the magnetic field – so that they could not reach the level where the type II shock appears. This may also be the explanation for the poor statistical correlation of fast Hα events (ejections and waves) with type II bursts: shocks produced by or associated with Hα events may not reach the type II level in all cases.

Also in the white light (electron) corona different types of fast changes have been detected in *K*-coronameter observations (Hansen *et al.*, 1973). They were found associated with fast Hα or 5303 Å events; in particular, Hα sprays were associated with white light expanding arches and an erupting prominence was associated with a white light disruption.

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DISCUSSION

Altschuler: I would like to make a comment on the interesting observation early in your talk that the flare has almost disappeared at the maximum stage of the surge. It seems to me that the visible Hα flare material cannot be the same matter as in the Hα surge, because we cannot accelerate matter once it becomes neutral. Probably there is a large amount of material in an ionized state, and it is this matter which is accelerated upward. The ionized material then cools and illuminates the surge trajectory in Hα.

Athay: The material emitting Hα is certainly very significantly ionized.

Sturrock: Some time ago, you published data on a surge-flare showing that the flare had a ring-like structure. Is this case unique or typical?

Bruzek: I have only observed that one case.

Uchida: Moreton waves can be produced by quite weak flares, contrary to what seems to be generally believed. I examined Mrs Martin's data and found this to be so. Further, the propagation velocity of Moreton waves is fairly independent of the importance of the flare. As I have shown, this can only be so with the MHD fast-mode hypothesis.

On a separate matter, could you give us the estimated mass involved in large spray events? This is quite essential in discriminating between different flare models.

Bruzek: The mass estimate would be 10^{16} to 10^{17} g.

Aller: What is the typical position of a surge with respect to that of the flare or subflare?

Bruzek: In most cases, surges are not associated with large flares; a small subflare is often found at the base of the surge.

Giovanelli: The old Hale spectrohelioscope was a flexible instrument for studying ejections on the disk since the wavelength shifter enabled observation to be made over some ± 10 Å from Hα and within 1 second. It was interesting to find ejected absorbing matter associated with the early stages of some flares, presumably of the type now called 'sprays'. This often took the form of irregular blobs seen quite separate from the bright flare. Perhaps 10 min later, irregularly-shaped and distributed falling matter would be seen quite separate from the rising material. I could never see any continuity in the rise and fall of individual blobs. We do seem to have lost a great deal of instrumental capability in going over, almost universally, to photographic observations at only one or two wavelengths in or near the core of Hα.

Jefferies: Such downward moving material is characteristic of loops which form after major flares.

Meyer: You mentioned that we have not yet a direct observation of the coronal transient events. There is one other indirect observation of the fast-mode wave propagation in the corona by the 'winking filaments'. From the amplitude that these filaments receive when hit by the coronal wave one estimates a rather small energy in the fast-mode Moreton-wave. The indications are that these are only slightly non-linear. Most of the heat energy released in the flare goes obviously into the acoustic-type shock wave which continues as an interplanetary shock. This is also physically reasonable. An explosively released energy will expand the medium in the direction of least resistance and this is upwards towards the lower density. The horizontal expansion that excites the Moreton wave is resisted by the magnetic fields, which in the higher coronal regions exert stronger pressure than does the gas before the explosion. So one should probably keep this large difference in energy between the two modes in mind, even if both forms are excited by the same event.