DYNAMICS OF FLARE SPRAYS

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Abstract. During solar cycle No. 20 new insight into the flare-spray phenomenon has been attained due to several innovations in solar optical-observing techniques (higher spatial resolution cinema-photography, tunable pass-band filters, multi-slit spectroscopy and extended angular field coronagraphs). From combined analysis of 13 well-observed sprays which occurred between 1969–1974 we conclude that (i) the spray material originates from a preexisting active region filament which undergoes increased absorption some tens of minutes prior to the abrupt chromospheric brightening at the ‘flare-start’, and (ii) the spray material is confined within a steadily expanding, loop-shaped (presumably magnetically controlled) envelope with part of the material draining back down along one or both legs of the loop.

1. Introduction

Over the years several schemes have been devised to classify prominences, and among the parameters used in these classifications the motion of the prominence plasma has played an important role. With the advent of space observations renewed interest in prominences and in prominence-corona interactions has developed, and of prime importance for these interactions is the motion of ascending prominences. There is a bewildering diversity in the way different prominences rise in the solar atmosphere and associate with coronal responses; i.e., coronal transients. A study of the dynamics of rising prominences may shed light on the physical processes involved in the acceleration mechanisms responsible for these mass ejections.

Valniček (1964) showed that at least two classes of ascending prominences could be distinguished using height-vs-time or velocity-vs-time plots for the rising prominence material. Eruptive prominences (disparitions brusques) start to ascend slowly in the atmosphere, whereafter the material is accelerated to great velocities (200–800 km s\(^{-1}\)) after many minutes or hours (Valniček’s type II). On the other hand, spray prominences and fast ejections (which may be two names for the same basic phenomenon) are being shot out of the flare region at great speeds, reaching high velocities (500–1200 km s\(^{-1}\)) in a few minutes (Valniček’s type I). Recent space observations show that both sprays and eruptive prominences are associated with coronal transient phenomena (white-light change, type II/IV radio bursts). While the physics of neither sprays nor eruptive prominences is well understood, the latter
are more easily observed in the early stages of their development, and the relationship to preexisting prominences is well documented.

On the other hand, in the case of sprays it is very difficult to ascertain where the ejected material comes from, even though the occurrence of high-speed ejecta near the start of flares has been known for many years (e.g., Dodson et al., 1953). Warwick (1957) defined the spray-prominence phenomenon more than 20 years ago, but the nature of such sprays and their association with coronal transients still pose puzzling questions.

One difficulty, already pointed out by Bruzek (1969), is that routine flare patrols with narrow wavelength-band filters inevitably miss ejecta with sight-line velocities greater than about 100 km s\(^{-1}\). Furthermore, what is observed are ‘blobs’ of material that happen to have slightly less sight-line velocities, resulting in the familiar ‘clumpiness’ reported for spray prominences. Within this limitation, however, the motions of flare sprays are well documented, as systematically discussed several times in the literature (Smith, 1958; Zirin, 1968; Bruzek, 1969), and a particularly well-observed spray has been described in detail by McCabe and Fisher (1970).

2. Observations

As indicated in the introduction, the sudden onset of sprays and their frequent large sight-line velocities require, for their proper study, observing techniques not commonly found in patrol-type instruments. However, the last several years have seen the realization of facilities that have made possible observations which have changed our view of flare sprays considerably.

These improved observing techniques include:

(i) High-resolution cinematography.

(ii) Tunable, or broad-band, filters.

(iii) Multi-slit spectroscopy.

(iv) Extended field-of-view coronagraphs.

For our work reported in this paper we have consulted data obtained by all four techniques, relying in particular on observations from the Mauna Loa Observatory.

As part of the Nobel Symposium on 'Mass Motions in Solar Flares', Smith (1968) presented a list containing most of the sprays which had been studied over the period 1937–1966. In Table I we supplement that list with additional flare sprays which have been documented during solar cycle No. 20. The conclusions drawn in this paper are founded on intensive studies of a number of the events listed in Table I.

2.1. Flare sprays viewed in projection above the solar limb

An examination of the overall shape of the envelope containing the spray elements shows that it may be described as ‘loop-shaped’, and one can nearly always distinguish two legs of the loop, which continue to ‘tie’ the spray to the chromosphere as the envelope expands. The broad-band observations have drastically reduced the
'clumpiness' of the ejected material, referred to by earlier observers, and most of the matter is observed in the, more-or-less continuous-looking, expanding loop. There are indications in the literature that loop-shapes, at least for some flare sprays, may have been considered before (see Dodson and Hedeman, 1968). However, that loop structures are a basic characteristic of sprays could not have been realized before the advent of broad-band, extended field-of-view coronagraph observations. Even with these instruments the large sight-line velocities still produce a 'bits-and-pieces' picture of the spray material.

It is, therefore, also not surprising that for most of these events the standard (non-coronagraphic) flare-patrol observers reported the sprays to be surges. This is due to the fact that one leg of the loop structure is typically brighter than the other and/or contains large sight-line velocities.

Close observation also shows that material drains down along one or both legs back into chromosphere, while material in the upper part of the loop rapidly moves outward. In a few cases the outermost extremity of the loop seems to become detached, forming a separate 'bubble'. Some indication of this behaviour is furnished by Figure 1, which shows a time sequence of the sprays of 28 October, 1972 and 11 January, 1973.

The spray phenomenon seems to be intimately associated with flares. Predictably, therefore, about half of the prominences originated from flares on the visible disk; for the remainder, the flare was not well defined, probably because it was just at the limb or beyond (12 August, 1972; 28 October, 1972; 11 January, 1973; 21 August, 1973; 17 January, 1974). In a few cases the spray originated from a flare situated well onto the visible disk (e.g., 12 March, 1969; 11 January, 1973; 5 July, 1974), and these fascinating observations will be discussed in the next subsection.

Exceptionally fine high-resolution filtergrams are available from Sacramento Peak Observatory for 21 August, 1973, and these show quite clearly the movement of prominence knots up one side of the loop and downward on the other. With less certainty such motions have been inferred for the 12 August, 1972 spray (Riddle et al., 1974) and for the 17 January, 1974 event by comparison of Mauna Loa Hα films with Naval Research Laboratory photographs of the same prominence in He II, 304 Å from Skylab data. In addition to this up- or down-motion, one at times also observes a spiralling of the down falling material. It is likely that this helical motion is responsible in part for the clumpy 'bits-and-pieces' appearance when viewed with narrow band pass filters.

In the several instances for which concomitant coronal observations were available (12 August, 1972; 11 January, 1973; 21 August, 1973; 17 January, 1974) major disruptions in the overlying corona were observed either as 'depletions' of the lower corona (Hansen et al., 1974) or as rapidly rising white-light plasma clouds observed with satellite-borne coronagraphs (Howard et al., 1976; MacQueen et al., 1976) in association with the flare sprays. Consequently, it seems that the flare spray (or spray prominence) phenomenon is indicative of, and only is one facet of, a very widespread disturbance, affecting a large part of the solar atmosphere (Hildner, 1977).
<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Associated flare time (UT), position</th>
<th>Observed spray time (UT)</th>
<th>Speed (km s(^{-1}))</th>
<th>Radio-responses type II and/or type IV</th>
<th>Transient observed from satellite(^a)</th>
<th>Comments</th>
<th>References</th>
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<td>11 Jan 73</td>
<td>00:35–01:27 N 13–W 80</td>
<td>00:36–01:12</td>
<td>414</td>
<td>II 00:47–01:02 IV 00:37–01:07</td>
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<td>Stewart et al. (1974a)</td>
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<td>spacecraft</td>
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<td>4</td>
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<td>II 21:48–21:56</td>
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*Observations made from OSO-7 or Skylab spacecraft of an associated white-light coronal transient.

Comments for Table I

1. Flare spray observed to originate from pre-existing filament on the disk.
2. Flare spray observed to originate from pre-existing prominence above the limb.
3. Flare observed on the visible disk, but no conclusive observation made of pre-existing filament.
4. Flare spray presumably originated from invisible disk, observed only above limb.
5. Coronagraph observations of the prominence did not begin until after event was already in progress.
6. No coronagraph observations of Hα prominence above limb; observed only as filament disruption on solar disk.
7. Velocity determination from leading edge of overall envelope of spray-loop; generally this is greater than that of individual knots or blobs.
2.2. **Flare sprays viewed in projection against the solar disk**

Keeping in mind the conclusion drawn from the limb observations discussed in the previous subsection, namely that sprays take the shape of large expanding loop structures, we now turn to the observations of flare sprays as seen projected against the disk. Due to the rapidity with which the phenomenon starts out – the spray material is accelerated to velocities of 500–1000 km s\(^{-1}\) in a few minutes – these observations are among the most difficult solar-activity observations to obtain. Nevertheless, the last several years' efforts have provided us with convincing evidence of the origin of the spray material. Of particular interest is the flare spray of 5 July, 1974 which originated from a well-observed pre-existing active-region prominence (filament). At the time of the event the active region was about 10° from the S–W limb. Filtergrams of high spatial resolution from Big Bear Solar Observatory provide excellent coverage of the activation of the pre-event filament, which was subsequently seen in projection above the limb as spray material traveling out to a height of 2R\(\odot\). Other examples of pre-flare filaments becoming high-speed ejections...
are furnished by the events of 29 July, 1973 and 26 October, 1973. Although over-the-limb observations are not available for these two events to confirm unequivocally that the ejections were indeed sprays, their high projected speeds and their association with type IV radio bursts make this identification highly plausible.

From our study of disk observations of the start of spray prominences we arrive at a picture of the phenomenon as sketched in Figure 2. This picture of a 'typical' flare spray is a generalization of the events cited above, and also depends on interpretation of observations of flares studied at the Lockheed Solar Observatory (Martin and Ramsay, 1972).

3. Discussion and Conclusions

From Table I we see that even though some of the ejecta moved at great velocities, the spread in observed speeds is considerable, and does not easily conform to Valniček’s type I curve. In order to explore this problem further and, in particular, to determine whether spray ejecta fit a range of velocity curves, we have in Figure 3
plotted the observed heights, $h$, versus time, $t$, for a number of events in Table I. We offer this diagram as 'modified Valniček curves', and draw the following conclusions:

(a) The observed parts of the height-versus-time curves (velocity curves) for most spray prominences are straight lines, indicating constant velocity for the ejected material. The pronounced deceleration inferred from previously published curves is not evident.

(b) The velocity curves for sprays cover a wide range, and the concept that the motion of the ejecta may be represented by one particular curve is misleading. Rather, a substantial part of the height-time space of Figure 3 is more or less filled with velocity curves for sprays. However, in conjunction with point (b) above it should be kept in mind that even the lowest-lying curves (for the slowest-moving sprays) reveal conditions different from those of eruptive prominences; i.e., dispersions brusques. The latter clearly indicates the increasingly important effects of accelerating forces during the observing period. This is portrayed by the positive derivative, $\frac{dh}{dt} > 0$, of the velocity curves for dispersions brusques; for sprays, on the other hand, the acceleration phase is very brief and occurs at lower heights. Hence, the acceleration phase would seldom be seen in over-the-limb observations of sprays. However, it does not necessarily follow that these differences between velocity curves for sprays and dispersions brusques reveal fundamental differences in the basic physics involved in the ejection mechanisms. The pre-existing quiescent prominence (filament), giving rise to a dispersion brusque, differs from the active-region prominence (filament) that gives rise to a spray, but this does not preclude a basically similar physical mechanism operating in both cases. There is reason to believe that an instability in the magnetic-field configuration in either case is
Fig. 3a–b. Height vs time plots for flare sprays observed from 1969 through 1974. Heavy lines in (a) are for flare sprays photographed at the limb by the High Altitude Observatory at Mauna Loa, Hawaii. Because some originated behind the limb and flare starting times are unknown, zero time for all events is taken to be the projection to zero height of the straight line part of the velocity curve. The curve for 27 October, 1973 is the tangential velocity from Hα disk movies. (b) refers to sprays photographed with Lockheed’s multi-slit spectrograph on the disk of the Sun. The curves for 3 July, 1972 and 18 February, 1973 give line-of-sight velocities from the spectral blue shift. In the case of 5 September, 1973 we give the tangential velocity from motion across the disk. The resultant of both the radial and tangential velocity is given for the 5 July event. Again, when possible, the straight line portion is made to intersect the X-axis at zero time, and in addition, velocities are assumed to approach zero height at the time of the flare or to be tangent to the X-axis.
responsible for the ejection of the prominence material (Tandberg-Hanssen, 1974; Sakurai, 1976).

The apparent difference in the velocity curves may, therefore, be due to the way we observe dispersions brusques and sprays. Also in the case of sprays, where we record mainly straight lines, the material has been accelerated from rest, but it is very difficult to observe this short-lived initial phase. We submit that in both cases the velocity curve is similar, maybe S-shaped (see Figure 4) or — more likely — not bending over at large heights. In the case of sprays, we mainly observe the upper part $A$ of the curve, while for dispersions brusques the lower parts $B$ are more easily observed. It is likely that deceleration does not occur, but is inferred due to our inability to follow exactly the same ‘blob’ of material.

This picture would indicate that the two types of ejection are different mainly because of their different time scales; i.e., the abruptness by which they are initiated. The accelerating forces in both cases derive from magnetic-field action. In both cases large-scale magnetic rearrangements are at play, involving large areas of the corona, as testified to by the fact that white-light transients are observed to move out through the corona above both dispersions brusques and sprays (Gosling et al., 1976) albeit at different speeds in the two cases.

The loop-shape in which the ejected material is observed to move out through the corona makes us conclude that the spray is confined by magnetic forces in large flux tubes, as these tubes rapidly expand and move out triggered by an instability. If this picture is more or less correct – the details are uncertain since the loops often are difficult to observe in their full extent – the strength of the magnetic field poses an important question. We may try to answer it by considering the magnetic stresses necessary to confine the spray material in the flux tubes.
Daigne (1971) considered the moving type IV radio emission which followed the spray of 11 December, 1968. He deduced a magnetic field of about 5 G at a height of 0.6\( R_\odot \) in the corona, using a method developed by Ramaty and Lingenfelter (1968), which assumes that the radio emission is due to synchrotron radiation. Inside the confining flux tubes the magnetic field must be considerably stronger. From a simple comparison of magnetic energy density, \( B^2/8\pi \), and kinetic energy density, \( \frac{1}{2}mv^2 \), i.e.,

\[
B = 4.5 \times 10^{-12} \sqrt{n} \nu,
\]

we find that a field of about 20 G is necessary to confine material of particle density \( n = 10^{10} \text{ cm}^{-3} \) moving out at 500 km s\(^{-1}\). Fields of this strength normally are not thought to be found high in the atmosphere, but little is known about coronal magnetic-field distribution, and Engvold et al. (1976) estimated a magnetic field in excess of 30 G in the eruptive prominence of 8 June, 1974 at coronal heights. As evidence is increasing that solar magnetic flux, in general, is confined to flux tubes of high field strengths (Howard, 1967; Chapman and Sheeley, 1968; Harvey and Livingston, 1969; Stenflo, 1973; Tarbell and Title, 1977), rather than being spread more homogeneously at low field strengths, the existence of the necessary flux tubes for spray confinement, even at coronal heights, may be less controversial.

References


