ENERGY AND MASS INJECTED BY FLARES AND ERUPTIVE PROMINENCES

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1. INTRODUCTION

The dynamic nature of the outer corona has been revealed in recent years by improved techniques of studying the corona with ground based instruments and from space. Rapid changes in the coronal brightness pattern takes the form of mass ejections in which the outward moving material generally appears to escape the Sun. These events are called coronal transients. Observations have shown that the excess mass and energy in coronal transients are supplied by material expelled from the chromosphere and lower corona in conjunction with Hα surface activity. The transients are the coronal response to release of mass and energy which are manifested by flares and eruptive prominences.

Many forms of mass motion are accessible for direct observations, such as: (1) surges, (2) flare sprays, (3) ascending prominences or suddenly disappearing filaments, and, possibly, (4) flare-waves (Moreton waves). Such events are commonly referred to as high-speed ejections. The equally spectacular, although less vigorous, post flare loops or loop prominence systems (Bruzek, 1964) have been classified as slow ascent events.

Munro et al. (1979) investigated 77 mass ejection Skylab transients and how they related to Hα surface activity. Thirty-four events were definitely or probably associated with Hα surface activity. Their results may be summarized as follows: (1) Coronal transients are more closely associated with erupting prominences than they are with flares. (2) About 70% of the transients were associated with erupting filaments or disappearing filaments. (3) Three-quarters of the number of transients were rooted in or near active regions. Hence, coronal transient production seems more probable when the surface magnetic fields are strong and complex (Hildner et al., 1976).

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We shall describe and discuss various types of dynamical events at chromospheric levels and in the lower corona, and also attempt to evaluate their significance with regard to coronal disturbances. The study by Rust et al. (1979) did not detect any close relation between surges and coronal transients. There are, on the other hand, strong evidences that ascending prominences and flare sprays are esential in the process which brings about observable coronal transients. Thus, it will be of particular interest to consider these two types of events when discussing the dynamics of the corona and the interplanetary medium.

2. SLOW ASCENT EVENTS

It has been suggested (Kopp and Pneuman, 1976) that loop prominence systems (LPS)might manifest a slow reconnection of the magnetic lines of force torn by the flare blast. As such the loop prominences will be the result of another dynamic event rather than its cause. Some LPS appear without being in observable connection with a flare. The gradual growth and rise of a loop system appears to be the result of cooling of the matter contained in the magnetic arches rather than a physical motion of individual loop structures.

An upward expansion and subsequent contraction ("rise and fall") which is observed in some limb flares does not seem to involve true mass motions (Švestka, 1976).

3. HIGH SPEED EJECTIONS

3.1 Radio bursts.

The presence of flare-associated streams of particles is established from observations of frequency drift rates in dynamic spectra of solar radio bursts. Groups of Type III bursts, which are thought to arise from high speed electrons propagating along coronal streamers, tend to occur during the flash phase of a flare (Sheridan, 1979).

Radio-interferometric observations of "moving Type IV mA" sources of emission are evidently generated by clouds of plasma that are ejected from the flare region (Dulk and Altschuler, 1973). In the case of two events recorded on October 3-5, 1977, the moving radio sources were very close to the leading edges of the associated eruptive prominences (Stewart et al., 1978). They found that the magnetic energy density of the two moving Type IV sources was larger than the kinetic energy density of the associated eruptive prominences. The temporal and spatial correlation between moving Type IV mA and identifiable features in a flare spray is clearly illustrated by Riddle et al. (1974).

The presence of Type II bursts suggests that flares produce shock waves which presumably propagate ahead of mass ejection coronal transients (Hildner, 1977)

3.2 Flare waves.

A fast wave front-like disturbance is frequently seen to come out from the flare site. It is manifested as a line-of-sight motion in the Hα line wing, and it propagates over distances as large as 1 $R_\odot$ at the average speed of 600-800 km s^{-1} (Smith and Harvey, 1971). It is also detected as triggers of sympathetic flares (Becker, 1958), and occasionally as sequential brightenings of small points in the chromosphere (Rust et al., 1979). It has been suggested that this type of flare wave may be due to mass ejections along low loops, which lit up the chromosphere at the foot-points of the loops. Martin (1978) argues that this mechanism cannot account for the observed properties of some flare waves. Uchida et al. (1973) propose that flare waves are the skirts of coronal shock waves sweeping over the chromosphere. In that case, the mass and energy associated with flare waves will be that of coronal transients, i.e., respectively, of the order of 10^{16}g and 10^{31} erg (cf. Webb et al., 1979)

The existence of a slow wave disturbance which propagates at speeds of 60-200 km s^{-1} has been inferred from activation and disruption of filaments by distant flares (Bruzek, 1969; Rust and Švestka, 1978).

3.3 Surges.

Surges are ejections of chromospheric material from regions close to the flare proper (Westin, 1969). No clear evidence has been presented for mass motions associated with the flare core itself (Cheng, 1978; Webb et al., 1979). The average upward speed of surges ranges from 50 to 300 km s^{-1} and they may reach up to heights of 20 000 - 200 000 km before they fall back to the chromosphere along their original trajectories. Their initial acceleration is found to be 1-5 times $g_\odot$ (Roy, 1973; Platov, 1973). According to Schmahl (1978) the pressure gradient along the surge trajectory may be sufficient to drive a surge upwards.

In Figure 1 matter is seen to be injected upwards (Hα-0.9Å) near the flare, and at the same time a down stream (Hα + 0.9Å) is detected close to the spot. The observations indicate that the mass flow takes place within a closed magnetic loop.

Tandberg-Hanssen and Malville (1974) measured magnetic field strengths between 30 and 100 gauss in surges. Assuming a particle number density 10^{11} cm^{-3} in the "cool" ejecta implies that only the most violent surges (200 km s^{-1}) will be capable of disrupting the weakest fields. Mass motion in surges evidently takes place without causing noticeable perturbations to the local magnetic field.

Estimates of mass contained in surges are based on very uncertain values of their volumes as well as of mass density. In the case of the Sept. 5, 1973 event, Webb et al. derived $M_{surge} = 10^{15} - 10^{16}$ g. Somewhat lower values were obtained by Rust et al. (1979), and Smith et al. (1977) concluded from their X-ray and Hα data that about 10^{14} g was injected by a surge of Aug. 21, 1972.

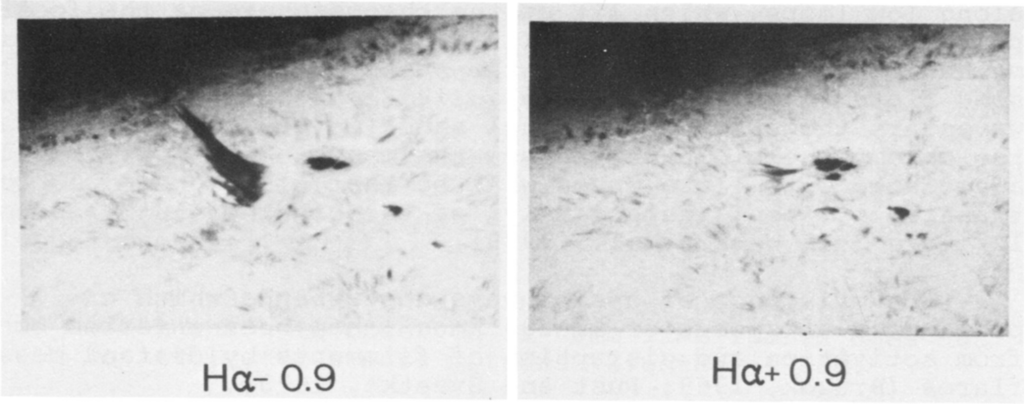

Figure 1. Hα filtergrams of a small surge of January 13, 1974, recorded by the author with the UBF of the vacuum tower telescope of Sacramento Peak Observatory.

In only6 of 54 cases was there a noticeable change in brightness or size of X-ray emitting regions with surge activity, which indicates that very little heating of the corona takes place. A maximum value for the sum of kinetic and potential energy was found to be $5 \cdot 10^{29}$ erg, or possibly more, in a surge associated with the Sept. 5 flare (Webb et al., 1979).

Surges are neither causing nor seen to be associated with coronal transients (Rust et al., 1979).

3.4 Eruptive prominences.

Ascending prominences and flare sprays.

Very high speed ejecta occurring in conjunctionwith flares were coined flare sprays by Warwick (1957). The sprays seemed to emanate from the flare itself, and the material showed a characteristic clumpiness as it was ejected (Valniček, 1964; Smith, 1968). The velocity as a rule exceeded the velocity of escape. The slowly accelerating, ascending prominences seen at the limb were found to be identical to suddenly disappearing filaments on the disk. Hence, they consist of "cool" material situated in the low corona prior to the eruption. Valniček (1964) concluded that ascending prominences and sprays were distinctly different types of ejecta. However, Tandberg-Hanssen et al. (1980) found that sprays are extant active region filaments. We will also show in the following that the speed-height curves for ascending prominences and sprays do not group into separate types (Engvold, 1980).

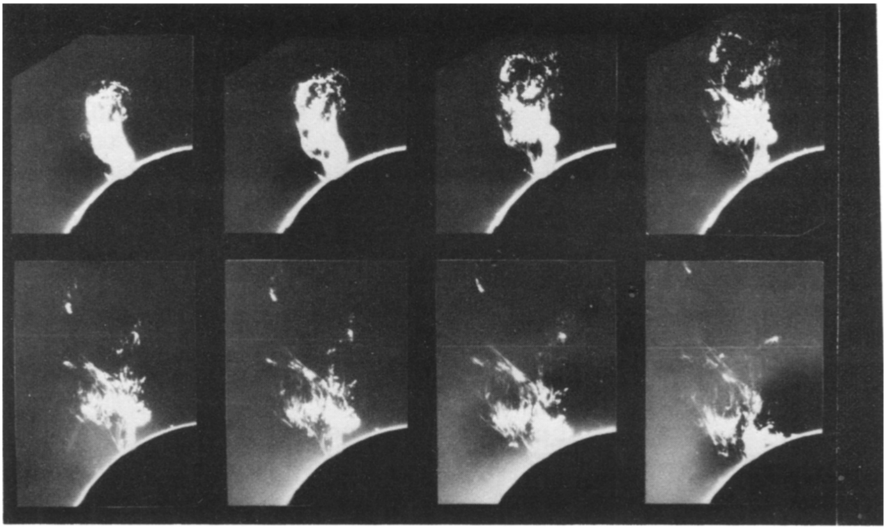

Figure 2. Hα photographs of the flare spray of October 28, 1972 (R. T. Hansen, HAO, Mauna Loa Observatory).

Observations of eruptive prominences.

Excellent observations of eruptive prominences have been obtained and studied over the past 100 years. The nature of the phenomena has made them rather difficult observational objects on which to compile a systematic surveillance. The first systematic morphological investigation was carried out by Pettit (1925, 1940). His study was based on about 60 events observed from 1885 to 1939. A spectacular event of May 29, 1919, from Pettit's data is shown in Figure 3.

We have studied Pettit's data, as well as more recent compilations of observations by various authors, and a number of events which have been reported and described in the literature (Engvold, 1980). It amounts to a total of about 300 individual eruptives. Speed-height relations could be derived for 118 of the events.

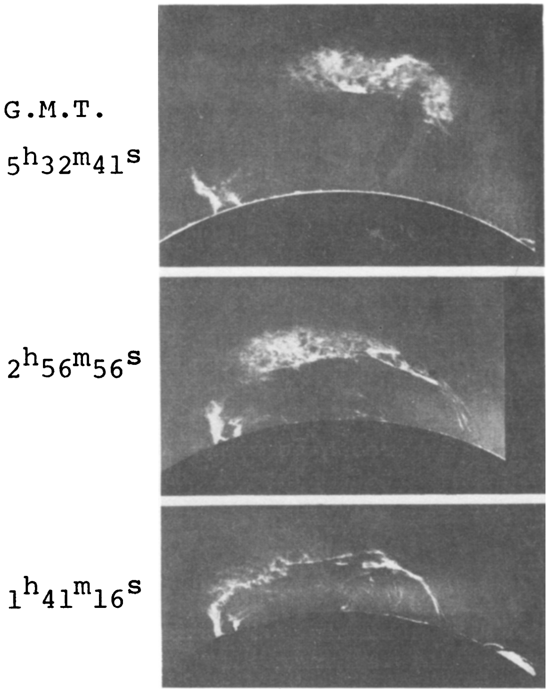

Figure 3. A large **eruptive prominence** of May 29, 1919 (Pettit, 1925). (Yerkes Observatory)

The d'Azambujas (1948)comprehensive study of prominences and filaments covers the period 1919-1937. They introduced the term "disparition brusques" (DB) for sudden disappearance of a filament. Extensive and detailed studies of DB's have been made by Bruzek (1951), Smith and Booton (1962), Smith and Ramsey (1964), and Westin and Liszka (1970). We have examined, with special regard to DB's, the synoptic charts and catalogues of filaments and active regions published by Observatoire de Paris, Meudon (cf. Martres and Zlicaric, 1977). Our study covers the Carrington rotations 1389-1662, i.e. from July 1957 through December 1977.

The speed-height relations.

The variation of ascending velocity with height is intimately connected to the propelling force acting on the matter. As such it is of interest to study the shape of acceleration curves of various eruptive prominences.

Measurements of ascending velocities often refer to the upper and leading edge of a prominences where also the velocity tends to be highest (McCabe, 1971; Engvold and Rustad, 1974). Various parts and fragments of a prominence may move differently (Waldmeier, 1958; McCabe and Fisher, 1970; Sakurai, 1976). Curved trajectories of ejected matter are evidence of strong influence by magnetic fields. The initial rise of erupting prominences takes place without substantial distortion of their shapes. Schmahl and Hildner (1977) concluded that the prominences and the corona around it are permeated by a magnetic field which becomes unstable everywhere nearly simultaneously.

The flare spray shown in Figure 2 is typical of a high speed case. A rather unique high speed event was observed by Valniček (1962) on Sept. 16, 1961. The ejected matter, which showed little tendency to fragmentation, was accelerated up to 1400 km s^{-1} at a height of 250 000 km before it faded. Another peculiar high speed event was recorded with the OSO-7 coronagraph on Dec. 14, 1971. Three plasma clouds were seen moving outwards in the corona at speeds of about 1000 km s^{-1} (Brueckner, 1972; Kosugi, 1976). The event was preceeded by an eruptive prominence and the clouds were evidently parts of a peculiar coronal transient.

We have compared the speed-height relations of 118 events (Engvold, 1980). Some examples are shown in Figure 4. Smooth curves are derived on the basis from 2 to 5 points obtained from published tables and graphs.

There are no particular regions in the speed-height diagram that seem to be void of observed cases. This is in conflict with the concept of two particular curves of motion (Valnicek, 1964). The many different speed-height relations that have been measured can hardly be attributed to the effect of motion at an angle to the plane of the sky.

Eruptive prominences appear with widely different upward acceleration, ranging from 5 m s^{-2} to nearly 3 km s^{-2} (ten times $g_{\odot}$). The acceleration varies with time.

Some prominences decelerate in their upward motion (Pittini, 1979; Waldmeier, 1979). An initial acceleration of a flare spray of March 1, 1969, was followed by a persistent deceleration of all fragments of the ejecta (McCabe and Fisher, 1970). At least 15% of all recorded cases exhibit a deceleration in the later phase of the eruption.

We divide the speed-height diagram into three equally large sectors and count the number of recorded events in each. The result of such a rather arbitrary division becomes 53% low-speed, 33% medium-speed, and 14% high-speed cases.

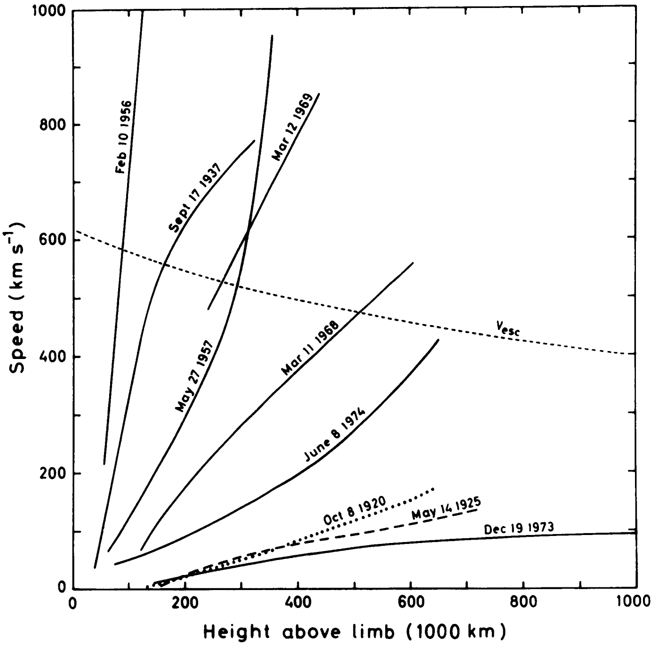

Figure 4. Some speed-height relations for eruptive prominences.

Active region relation.

The association of rapidly ascending prominences with flares (flare sprays) is well established (Waldmeier, 1939; Warwick, 1957; Smith and Booton, 1962). Tandberg-Hanssen et al. (1980) concluded from their study of Hα disk observations that sprays are eruptive active region filaments.

We have sorted DB filaments (Paris Observatory catalogues) into three groups according to their location relative to the nearest active region; I: polar filaments and filaments located more than 8-10° away from active regions, II: filaments lying next to and within about 8-10° from an active region, and III: filaments located within an active region. We use the definition of active regions as outlined by the Ca$^+$K emission which is adopted in the catalogues of Paris Observatory. The distribution of suddenly disappearing filaments is: 49.7% (I), 37.6% (II), and 12.8% (III).

The fraction of active region filaments among DB's is the same as previously found for high-speed eruptive prominences. The equality of the two numbers (12.8% and 14%) is fortuitous, but it suggests that between 10% and 20% of all eruptive prominences are likely to be high-speed events (sprays).

Frequency of occurrence.

The frequency of occurrence of eruptive prominences is essential in an evaluation of the mass and energy they contribute to the corona and the interplanetary medium. Determination of an absolute rate of eruption for a given period of time calls for a systematically recorded sample and good time coverage. Such data is not easily obtained.

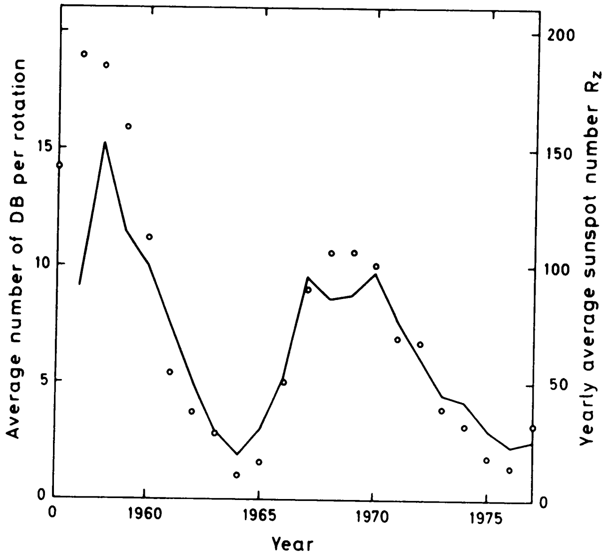

Figure 5. The variation of number of "disparition brusques" during two solar cycles.

Many more eruptives occur about maximum compared to minimum sunspot number (Engvold, 1980). About 40% of the events appear within three yearly intervals centred about the times of sunspot maxima as compared to only 6% about sunspot minima. Figure 5 shows the yearly average number of of DB's per solar rotation. It may be seen from the same Figure that the average numbers of DB is proportional to the relative Sunspot Number (Waldmeier, 1978). A similar good correspondnece is obtained for the DB's recorded in the period 1919-1931 and which are tabulated by d'Azambuja and d'Azambuja (1948). The results suggest that the number of DB's increases by factors 10-15 from sunspot minimum to maximum.

An average of about 14% of all filaments observed during one solar rotation were reported to exhibit a sudden disappearance. The percentage is evidently larger, and it varies little with phase of the solar cycle.

In possibly as many as half of all cases a new filament will reform and later erupt from the same region. The average time intervals between two such eruptions is found to be about 5 days (Engvold, 1980).

The chances of detecting an eruptive prominence at the limb (EPL) is critically dependent on the time coverage. From tables of EPL observations during 1957 by Koeckelenbergh and Peeters (1957) we see that the number of recorded events per month is proportional to the duration of observations. Since and EPL lasts typically 1-3 hours (Pettit, 1940), we may define the time coverage as the time actually spent at the telescope during one day, plus two hours. A total of 143 EPL's was recorded with a time coverage of nearly 1000 hours during 1957 at the Royal Belgium Observatory (Koeckelenbergh and Peeters, 1957). The rate thus becomes approx. 1300 yr^{-1}. Since the observed EPL's are associated with the limb near portions of the sun the true rate of eruptions must be still larger. The filament catalogues for 1957 yield a rate of 460 DB's yr^{-1}. Similarly, we get for the year 1971; 700 EPL's yr^{-1} and 200 DB's yr^{-1}. The fact that the deduced rates for EPL's are larger than for DB's indicates that many filament disappearances pass unobserved.

The available data does not yield a definite number for the rate of erupting prominences. The derived number must be regarded as lower limit values. We conclude that there may be more than 3-4 eruptive prominences/filaments every day during years of maximum solar activity.

About 350 coronal transients occurred during the Skylab period (Hildner et al., 1976). A corresponding number of 100 DB's was recorded. According to the results above one might expect the number of erupting prominences and the number of coronal transients to be compatible.

The mass ejected by eruptive prominences.

The mass supplied to the corona by one eruptive prominence may be estimated as the pre-eruption mass minus the downfalling part. The Hα coronagraph observations of a flare spray of March 1, 1969(McCabe and Fisher, 1970) shows clearly that some fragments move outwards whereas the trajectories for others turn back towards the solar surface.

Schmahl and Hildner (1977) inferred a column density of ground-state hydrogen in the pre-eruptive state of the Dec. 19, 1973, prominence, based on an estimate on LyC opacity at 625Å. By integrating over the areal extent of the prominence they derived a total mass $M_{prom} = 2 \cdot 10^{15}$g. Allowing for the filamentary appearance we estimate about $5 \cdot 10^{27}$ cm^3 for the volume occupied by a typical quiescent prominence. We assume 10^{11} cm^{-3} for the number density of hydrogen (Tandberg-Hanssen, 1974; Hirayama, 1978) and get $M_{prom} = 10^{15}$g. The results suggest that $2 \cdot 10^{15}$g may be adopted as a typical value for the pre-eruption mass of a prominence (see also Rust et al., 1979).

Possibly less than 10% of the prominence mass was actually observed to fall back into the chromosphere in a case of June 8, 1974 (Engvold et al., 1976). The many spectral lines recorded in the Dec. 19, 1973 case (Schmahl and Hildner, 1977; Rust et al., 1979), allowed one to study how temperature and density changed as the eruption progressed. Up to a height of about 2 $R_\odot$ the prominence material experienced only a slight warming and rarefaction. Above approx. 3 $R_\odot$ the matter was subject to rapid dispersion and heating. The downfalling material along fine vertical threads which appear in EUV lines was estimated to be only about 1% of the pre-eruptive mass. The comprehensive Skylab observations illustrate clearly the short-coming of data consisting of one "cool" line only, if one wishes to determine what becomes of the initial pre-eruptive matter.

The two-ribbon flare-like brightenings which are frequently seen to accompany prominences are further evidence for downfalling material (Hyder, 1967).

Thus, there are evidences that some of the matter contained in pre-eruptive prominences returns to the solar surface. We cannot specify very accurately what this fraction typically may be. The available data suggests that close to $2 \cdot 10^{15}$g of matter may be dispersed in the corona and interplanetary medium by one single eruptive prominence. This is a rather insignificant fraction, i.e. about 1%, of the total mass contained in the corona (Tandberg-Hanssen, 1974). However, the proton flux at the base of solar wind streams (10^{14} cm^{-2} s^{-1}; Zirker, 1976) taken over the surface area associated with a prominence (approx. $3 \cdot 10^{19}$ cm^2) corresponds to the mass of one eruptive prominence every three days.

The energy of eruptive prominences.

The study of mass motion made by the Skylab Workshop on Solar Flares (Rust et al., 1979) concludes that the magnetic field must be the ultimate source of energy which drives the observed phenomena. Stewart et al. (1978) estimated the magnetic energy density of two moving Type IV sources of radio emission and concluded that both the eruptive prominence and the source motions are controlled by magnetic fields.

From an observed speed-height relation one may measure the speed and height of a prominence immediately before it fades and disappears in Hα or Ca^+ K (Figure 4). From the observations compiled by Engvold (1980) we adopt typical values for the speed (U) and the corresponding height (R) in the corona to estimate the kinetic and potential energies, respectively,

$$E_k = \tfrac{1}{2} M_p U^2 \quad \text{and} \quad E_p = M_p \, g_\odot \, R_\odot (1 - R_\odot / R)$$

of the "cool" matter of eruptive prominences.

Table I

Kinetic and potential energies of eruptive prominences

Type of event	U ($km \ s^{-1}$)	R	E_k	E_p	E_k+E_p
			(	10^{30} erg	)
High-speed (Spray)	800	1.35 $R_\odot$	6.4	1.0	7
Medium-speed	450	1.65 $R_\odot$	2.0	1.5	4
Low-speed (Ascend. prom.)	200	1.85 $R_\odot$	0.4	1.8	2

The results for, respectively, high-speed, medium-speed, and low-speed eruptive prominences are presented in Table I. (We have neglected the negative sign in the gravitational potential energy since we are interested in only the change of the E_p.) The mass $2 \cdot 10^{15}$g is assumed for all eruptive prominences.

The relative importance of kinetic and potential energy appears to change from high-speed to low-speed events. However, within the accuracy of our estimates they are compatible. Particular cases, such as of February 10, 1956 (Menzel et al., 1956; Warwick, 1957), may have exceeded the tabulated values substantially.

The tabulated energies exceed by several orders of magnitude the amount of energy liberated as radiation during the eruptive phase.

The persistent acceleration of many eruptive prominences implies a steady transformation of electromagnetic energy into motion and gravitational potential energy. This is in agreement with the fact that E_k+E_p of coronal transients appears to be higher than of the associated eruptive prominences (Rust et al., 1979).

Webb et al. (1979) estimated that $>10^{31}$ erg of magnetic energy was delivered into the interplanetay space by transport of ambient magnetic field by a coronal transient.

4. CONCLUDING REMARKS

A study of energy and mass injected by flares and eruptive prominences requires data with good spectral, spatial, and time coverage. In the cases of a few individual events these requirements have been met partly. A large number of cases, which are recorded in spectral lines of typically chromospheric temperatures, may be used to map the initial phases of mass ejection events. We have not attempted to estimate the mass and energy carried in particle streams at the flare site as evidenced by radio bursts.

Flare sprays and ascending prominences all consist of matter situated in the low corona prior to the disruption. Sprays and ascending prominences may be united in the term eruptive prominences. The leading edge of eruptive prominences shows upward acceleration in the range 0.01-10 times $g_\odot$. Fragments of eruptive prominences occasionally slow down. Eruptive prominences are driven by and move with the magnetic field. They preceed coronal transients. Surges follow preexisting magnetic lines of force. Surges are neither causing nor associated with coronal transients. The mass of eruptive prominences is typically about $2 \cdot 10^{15}$g. The sum of their kinetic and potential energies amounts to $10^{30} - 10^{31}$ erg. The mass and energy of surges are evidently less than, but not very different from, eruptive prominences. The number of eruptive prominences varies proportionally with the sunspot number. Possibly more than 3-4 prominences may erupt every day during years of maximum solar activity.

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DISCUSSION

Moore: What is your opinion, as an observer, on whether filament eruptions and flares are essentially the same thing; i.e., whether both are driven by the same basic mechanism?

Engvold: Two-ribbon flares, which seem to be a very common type morphologically, are concurrent with large eruptions, filaments and with formation of loop prominence systems. The evidences suggest to me that the infall-impact mechanism, which was proposed by Hyder, is valid. Hence, two-ribbon flares as well as eruptive prominences (and so-called 'post-flare' loops) both seem to be the result of the action of some other agent.

McIntosh: The statistics of increasing filament disappearance with increasing sunspot number are misleading for two reasons: (1) the frequency of disappearing filaments per solar rotation is not correlated with sunspot number, flare occurrence or rate of emerging magnetic flux; (2) 50% of filament eruptions occur away from sunspots. It is clear from observations used to compile the 1964-1974 atlas of Hα synoptic charts that large-scale merger among long-lived magnetic features is related to filament eruption between merging features. Also, large-scale shear may be another factor of importance to erupting filaments. Would you please comment?

Engvold: I have not checked the correlation of number of suddenly disappearing filaments with the sunspot number per solar rotation, in the data used here. I agree, the fact that the correlation is strong in the yearly averages does not necessarily imply that sunspots or active regions are responsible for the eruptions. It may be important to note that the number of filaments (or rather the total filament area projected into the disk) is nearly proportional to the sunspot number (when properly averaged). The good correlation mentioned above may, therefore, simply mean that the probability that a given filament will erupt is always nearly the same and independent on solar activity.

Tandon: You gave the estimates of kinetic and gravitation energy to calculate the total energy of eruptive prominences. What is the order of magnetic energy associated with them, and will it not upset the total energy computations?

Engvold: The observations suggest that erupting prominences are magnetically controlled and, surely, we would expect the associated magnetic energy to be greater than the sums of kinetic and gravitational energy listed in my Table I.

Webb: In your discussion of DBs in active regions, you noted that 13% of all DBs in your sample occur in active regions. This % seems remarkably small since filaments in the ARs come and go all the time. Do you believe there could be an observability effect here?

Engvold: We cannot exclude the possibility that there may be a selection in the data in the sense that suddenly disappearing active region filaments more easily escape detection than those occurring outside active regions. Suddenly disappearing filaments may not be recorded as such in the data used here if they re-form within one day.

Martres: The filaments are listed as "plage filaments" when their lifetime is 2 days or longer.