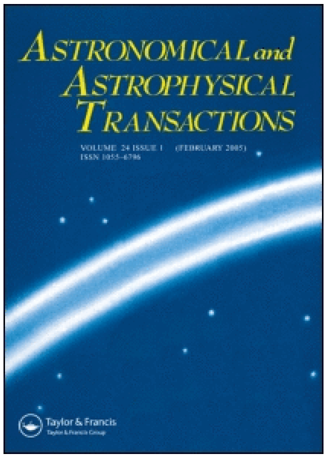

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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V. I. Ivanchuk [a]; N. I. Pishkalo [a]
[a] The Astronomical Observatory of Kiev University, Kiev, Ukraine

Online Publication Date: 01 August 1993
To cite this Article: Ivanchuk, V. I. and Pishkalo, N. I. (1993) 'Mass and energy sources of coronal mass ejections', Astronomical & Astrophysical Transactions, 4:2, 57 - 63
To link to this article: DOI: 10.1080/10556799308205365
URL: http://dx.doi.org/10.1080/10556799308205365

Astronomical and Astrophysical Transactions, 1993,
Vol. 4, pp. 57–63
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MASS AND ENERGY SOURCES OF CORONAL MASS EJECTIONS

V. I. IVANCHUK and N. I. PISHKALO

The Astronomical Observatory of Kiev University, Observatornaya Str., 3, 254053, Kiev, Ukraine

(March 25, 1992; in final form May 6, 1992)

The existing mechanisms and models for the mass and energy sources of coronal mass ejections (CME) are shown to be insufficient for the explanation of the observations. It was found out that the mass of the CME may grow substantially during the lifetime of the event. The mean growth rate of the CME mass is about 10^{12} g s^{-1}, which is comparable with the mass outflow rate in the solar wind. To ensure such a value of the CME mass growth rate, a hydrodynamical plasma flow of $\langle N_e \cdot V_\uparrow \rangle = 10^{16}$ particles cm^{-2} s^{-1} must exist at the CME loop base in the lower corona and the transition region. These outflows can be one of the CME's energy sources.

1. INTRODUCTION

Coronal mass ejections (CME) are the most powerful nonstationary process in the solar corona and solar wind. During the last 15–20 years, extensive investigation of their properties established the main physical parameters and quantitative characteristics. The mass of the ejections amounts to $10^{14} - 5 \cdot 10^{16}$ g, and the CME velocities range within 15–16000 km $\cdot$ s^{-1}. The total energy of an ejection reaches 10^{30}–10^{32} erg, and the energy of an ejection usually exceeds that of associated flares. The CME occurrence rate seems to vary over the cycle of the solar activity from 1–2 events per day near the maximum to 0.2–0.5 ejections per day near the minimum of the solar activity (Kahler, 1987; Ivanchuk, 1989).

CMEs should contribute considerably to the mass and energy transported by the solar wind. According to the estimates made by a number of authors, this contribution can reach 3–10% of the respective integral characteristics of the solar wind.

Among a large number of unresolved questions related to the nature and the factors of the CME origin, the problem of the CME mass sources should be also considered. Is the mass delivered impulsively from a "point explosion," as suggested in the models developed by Steinolfson (1982), or is it ejected in the form of "finished" coronal features, as suggested by analogy with the ejection of an eruptive prominence from a quiescent filament? Possibly, on occasions there also occurs an avalanche-type "sweeping" of the coronal material which is within the range of the ejection activity. The appearance of "dark voids" or "depleted regions" in the corona after the CME passage is often attributed to such a "sweeping."

Hildner *et al.* (1975b) and Rust and Hildner (1976) and, subsequently, Illing and Hundhausen (1985) and Wolfson *et al.* (1987) substantiate the assumption that CMEs are a "detachment" of finished coronal features, for example arch systems surrounding a quiescent filament. The moment of the detachment (i.e., the CME onset) is preceded by a long period (1–2 days) of the additional material and energy accumulation within a certain volume of the corona. As a result, hydromagnetic stability in some or other feature is broken here and an ejection is produced.

In our opinion, a number of facts prove that all of these models neglect the main process occurring during the development of the CME, namely the CME mass can grow or decrease intensively during the event itself (Dzyubenko *et al.*, 1984). Thus, a feature created in the process of the ejection itself rather than a "finished" feature is ejected from the corona. Below we consider some facts and arguments which support such a conclusion. A short preliminary report of the results which are discussed here is given by Ivanchuk and Pishkalo (1989).

2. RESULTS AND DISCUSSION

When the CME surface brightness distribution on the corona images is known, one can determine the amount of material (M) in the ejection. The inspection of the images of a number of CME events in their development and direction determinations of the total mass of some ejections (Hildner *et al.*, 1975a; Dulk *et al.*, 1976) suggest that the mass of CME change substantially during their development. We have been able to confirm this by measuring M for three loop-shaped CME using ejection isodenses for several moments of their development given in a number of papers. The results of these measurements are listed in Table 1. For the events of 10 July 1973 and 14/15 September 1973 the table also gives the values of $M(t)$ estimated in published papers. Although they somewhat differ from those obtained by the authors, they confirm the same trend. The amount of loop-shaped CME's material (above the level of $r = 1.6–2.0 R_\odot$) grows with time. The mass growth rate lies within the range

$$\Delta M/\Delta t = (6 - 55) \cdot 10^{11}\ \mathrm{g\,s^{-1}}. \tag{1}$$

The mean value of $\Delta M/\Delta t$ is close to $2 \cdot 10^{12}\ \mathrm{g\,s^{-1}}$, but it is presumably overestimated because it is based on a small sample. For some footpoints

Table 1 The time change of the mass for some CME

CME	M_1, 10^{15} *g*	M_2, 10^{15} *g*	t_1, *UT*	t_2, *UT*	$\Delta M/\Delta t$, 10^{11} $g\,s^{-1}$	*Reference, note*
10.VI. 1973	4.0	5.5	09:30	09:42	21	Hildner *et al.*, 1975a
	8.7	14.0	09:30	09:46	55	Using observations from
	8.7	15.0	09:30	10:02	33	Hildner *et al.*, 1975a
14/15.IX. 1973	2.5	2.9	00:32	00:41	7.4	Dulk *et al.*, 1976
	1.8	2.2	00:32	00:50	3.7	For N-part of CME
	1.60	1.85	00:32	00:41	4.6	Using data from Dulk *et*
	1.05	1.20	00:32	00:41	2.8	*al.* (1976) for N, S and
	2.65	3.05	00:32	00:41	7.6	N + S parts of the CME, respectively
29.VI. 1980	0.18	0.25	02:47.5	02:49	7.2	Using data from Gary *et*
	0.18	0.62	02:47.5	02:58	7.0	*al.* (1984)

(branches) of the ejection loops, the individual values of the mass growth rate can be taken to be (3–30) · 10^{11} g s^{-1}. Note that these values are comparable with the mass outflow in the entire corona associated with the solar wind (about 10^{12} g s^{-1}). The above results suggest several further trends: 1) it is most likely that $\Delta M/\Delta t$ decreases with time and 2) the mass growth rate of an ejection appears to be larger for more massive transients.

Recent observations with the high-performance "Mark-III" K-coronameter (the Mauna-Loa Observatory) allowed to study the early stage of several dozens of transients (Fisher *et al.,* 1981; Mac Queen and Fisher, 1983). It was found that the appearance of loop-shaped CME in the altitude range $r = 1.1$–$2.2R_\odot$ accessible to "Mark-III" observations fits the following scenario. First, a domed region of decreased density grows in the site of the future ejection and eruptive prominence. This feature moves upwards at the velocity $V = 50$–120 km s^{-1}. At the rear of this region, within a certain time interval there appears a "cool" eruptive prominence which normally "melts away" gradually to turn into clusters of coronal material. On the sides of the "depleted region", there begin to form and grow upwards bright "columns" with the velocity of 100–300 km s^{-1}. Gradually, the "columns" become interconnected to from a weak-brightness loop. Its brightness increases; it continues moving upwards together with the depleted region and the eruptive prominence that converts to a coronal stage. A number of CME show the acceleration $g = 0.10$–0.25 km s^{-2} during their rise.

Figure 1 gives kinematic characteristics of different components of such an ejection for the event of 5 August 1986 according to Fisher *et al.* (1981). One can see that the formation of the CME starts with an ejection of a small or even "negative" mass (the appearance of a dark void). After than, the ejection mass begins to grow due to the material injection from below (rather than due to the "raking-up" of the material by the dark void moving upward).

The masses of loop-shaped CMEs and related features ("filled bottle" and "curved front"), according to measurements in the range $r = 1.6$–$10R_\odot$, average to $\langle M \rangle = (3$–$10) \cdot 10^{15}$ *g* (Howard *et al.,* 1985; Jackson and Hildner, 1978). They are observed there $\tau = 1$–2 hr after their origination or "onset" in the lower corona. Assuming that $M_0 \ll \langle M_{CME} \rangle$ during the production of an ejection, one

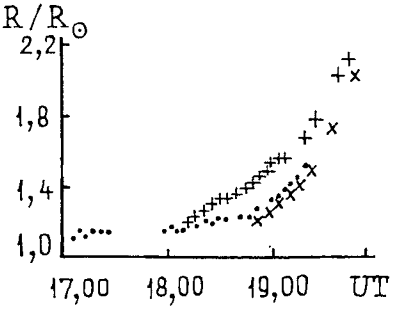

Figure 1 The time variation of the heights of different CME components on 5 August 1980: · · ·: the height of a loop-shaped eruptive prominence, + + +: the position of the upper boundary of a dark void, × × ×: the height of bright "columns".

can estimate the growth rate of the ejection mass:

$$\frac{\Delta M}{\Delta t} = \frac{\langle M_{\mathrm{CME}} \rangle}{\tau} = 3 \cdot 10^{11} – 3 \cdot 10^{12}\ \mathrm{g\,s^{-1}}, \tag{2}$$

which is very close to the values obtained above from the direct measurements of the CME masses.

The above picture of the formation and evolution of CME is confirmed by the detection of X-ray precursors (XRP) of the flares. Using the data obtained with the hard X-ray spectrometer HXIS on the SMM (3.5–5.5 KeV) and the integral X-ray telescope on GEOS (3–8 KeV), Harrison *et al.* (1985) and Simnett and Harrison (1985) have shown that several tens of minutes before the beginning of a powerful flare the X-ray emission of extensive lower-lying arches is intensified. Their size is $1 = 10^{10}$ cm and they are located near the future flare. The mean characteristics of these X-ray precursor arches are: $T_e = 10^7$ K, $ME = 3 \cdot 10^{46}\ \mathrm{cm^{-3}}$, $N_e = 10^9\ \mathrm{cm^{-3}}$, and $M_{\mathrm{XRP}} = 5 \cdot 10^{13}$ g. A small part of such an arch shows an upward motion at the velocity 20–50 km s^{-1}.

The study of kinematic characteristics of the CME produced after an X-ray precursor and associated flares reveals that the ejection from an X-ray precursor arch represents just the physical onset of the CME itself. Figure 2 gives a picture

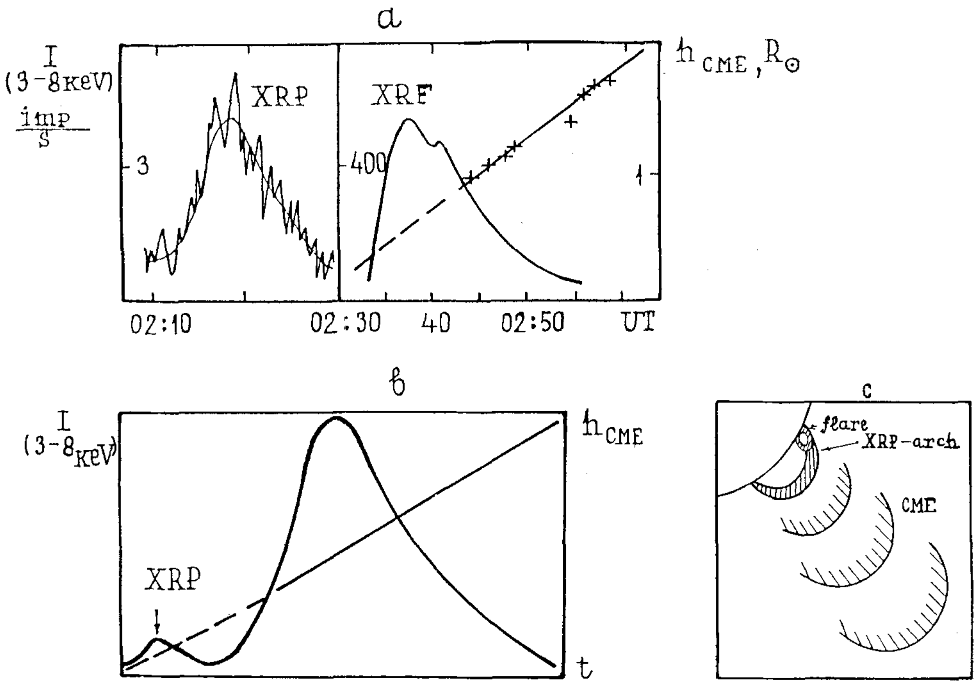

Figure 2 The development of the X-ray precursor, X-ray flare (of importance M3) and CME on 29 June 1980. a) The time variation of the intergral flux (3–8 KeV) according to the satellite counter data; +++: the position of the forward edge of the CME. b) The same, schematically. c) The schematic picture showing the conversion of the ejection from an X-ray precursor to a CME according to the hypothesis of Harrison *et al.*, (1985) and Simnett and Harrison (1985).

of the development of the XRP, the flares and the CME of 29 June 1980. Since $M_{CME} = 5 \cdot 10^{13}$ g, our suggestion that the ejection mass is close to zero at the moment of the start of the CME, as well as the estimates of $\Delta M/\Delta t$, receives further confirmation.

How high is the velocity of mass flow into the CME? The rate of growth of the "columns" ($V = 100$–$300\ \mathrm{km\ s^{-1}}$) observed with the K-coronameter "Mark-III" during the development of loop-shaped ejections seems to give the lower bound for this velocity. But the same values are shown by the CMEs of such types as streamers and rays. In this case there are also growing linear structures which appear to be filled with the material of open magnetic configurations. According to the measurements reported by Howard *et al.* (1985), the apparent growth rates of these features are $V = 100$–$500\ \mathrm{km\ s^{-1}}$.

It should be noted that these or somewhat lower mass flow velocities appear to be typical not only of CME events but also of many "quiet" fine coronal details. For example, from the study of dynamical displacements and changes of white coronal thin details by the basis method during the total solar eclipse of June, 30 1973 in Africa, it was found out that 9 fine streamlets had disappeared, 13 streamlets had appeared and several ones had noticeable changes during the time interval of 80 min (Vsekhsvjatsky *et al.*, 1976). If these changes are interpreted as the manifestation of the material entering or leaving from the corresponding details, the lower value of the mean speed of the mass flow in these details is 50–200 $\mathrm{km\ s^{-1}}$.

Thus, for ascending mass flow into the CME we have

$$V_{\uparrow} \geq 100\text{–}500\ \mathrm{km\ s^{-1}},$$

i.e., the velocity of hydrodynamic flow here must exceed the sound speed and, possibly, also the Alfvén velocity.

If the flows in loop-shaped CME originate from their chromospheric footprints having a typical size $l = 5 \cdot 10^9$ cm, then one can estimate the mean characteristics of the ascending flows using the values of $\Delta M/\Delta t$ given above. Neglecting their possible inhomogeneities, we obtain

$$N_e V_{\uparrow} = 10^{16}\ \text{particles} \cdot \mathrm{cm^{-2}\ s^{-1}},$$

which for $N_e = 10^9\ \mathrm{cm^{-3}}$ in the lower corona yields an independent estimate of the ascending flow velocity $V_{\uparrow} = 100\ \mathrm{km\ s^{-1}}$.

The kinetic energy flux transported by these hydrodynamic flow is

$$\frac{dM}{dt} \cdot \frac{V_{\uparrow}^2}{2} = 10^{26} - 5 \cdot 10^{27}\ \mathrm{erg\ s^{-1}},$$

i.e., this can serve as one of the energy sources of complex processes of coronal ejections ($E_{CME} = 10^{30}$–10^{32} erg).

From such known microtransient events as (chromospheric spicules, macrospicules, UV high-energy jets or "bullets" (Brueckner and Bartoe, 1983), coronal superfine streams (Ivanchunk, 1969), etc., UV high-energy jets ($V_{\uparrow} = 400\ \mathrm{km\ s^{-1}}$) and superfine streams ($V_{\uparrow} \geq 100$–$500\ \mathrm{km\ s^{-1}}$) which are observed in quiet regions of the solar atmosphere, have the characteristics which make them the best candidates for the mass injectors into the CME. In the case of the CME appearance the occurrence rate and power of these microtransient events at their footpoints must, evidently, be intensified significantly as compared with quiet regions.

According to Harrison *et al.* (1985) and Simnett and harrison (1985), the X-ray precursors (i.e., the CME onset) are produced by accelerated protons with the energies of 100–1000 KeV appearing in magnetic loops; these protons cause the heating and evaporation of the chromosphere and lower corona. If this is so, then by allowing for the above conclusions about the long-duration mass injection into the coronal ejections from below, it should be postulated that generation of the protons and evaporation of the material from the chromosphere and lower corona accompanies nearly all the coronal phase of the CME lifetime.

CONCLUSION

Thus, the estimations of the mass of coronal mass ejections at several moments of their lifetime at various heights, in a range of $r = 1.2\text{–}6.0R_\odot$, based on observations on the Skylab's and SMM's coronographs and the K-coronameter "Mark-III" and the study of the X-ray precursors of solar flares at the heights of $r \geq 1.2R_\odot$ show that the mass of the CME can grow substantially during the event itself. The mean growth rate of the CME masses is close to 10^{12} g s^{-1}. This value is comparable with the total mass outflow rate in the solar wind. To explain such the value of the growth rate of the CME mass, the hydrodynamical plasma flows of $\langle N_e \cdot V_\uparrow \rangle = 10^{16}$ particles cm^{-2} s^{-1} must exist and be intensified at the bases of the CME in the lower corona and transition region. Possibly, these plasma flows are connected with UV high-energy jets (Brueckner and Bartoe, 1983) and coronal superfine streams (Ivanchuk, 1969). These outflows may be one of the CME energy sources.

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