CME Structure and Particle Acceleration

Igor F. Nikulin

Sternberg Astronomical Institute (GAISH), Lomonosov Moscow State University,
Universitetskii prosp. 13, Moscow, 119992 Russia

Abstract. The differences of the ejection-image structures in the chromospheric lines and the coronal continuum are considered. The outer, more diffusive scattering envelope of the ejection seems to be produced by the excessive free electrons due to the Compton effect. The resulting electric field accelerate the particles while the hard radiation is acting. The directed motion of the accelerated particles induces the magnetic fields.

Keywords: Coronal Mass Ejections; Particle Acceleration; X-Ray Bursts; Magnetic and Electric Fields

1. INTRODUCTION

The coronal mass ejections (CME) are one of the most energetic phenomena in the Solar system, which determine the space weather [2, 3]. A cloud of the magnetized plasma with a mass of a few billion tones is ejected from the coronal base into the interplanetary space with a velocity about 400–900 km/s due to some physical processes, which are still insufficiently studied. If the cloud is ejected in the direction to the Earth, then the magnetic storms and aurorae can develop. These phenomena can be associated both with the outbursts of filaments/prominences and the flares. As usual, the speed of ejection in the case of flares are substantially greater (up to 2000 km/s and even more).

2. STRUCTURE AND DYNAMICS OF CME

Apart from the insufficiently clear mechanism of acceleration of the outbursts, there is some uncertainty in their characteristic structure. This problem was unnoticeable when the outbursts of prominences and flares were observed only from the Earth. Detection of the outbursts by ground-based coronographs were very rare and had a low quality, because of the considerable amount of scattered light. However, launching the solar coronographs (OSO-7, SMM) beyond the atmosphere considerably increased the number of observable outbursts, their contrast and quality, as well as have shown substantial differences of the outburst structure in the chromospheric lines from their pictures in the coronal continuum. The coronal ejections of prominences and flares are typically associated with the loop–arc structures, surrounding a kernel of the outburst at some distance (Figure 1). Such loops are seen in the pictures by spaceborne coronographs, such as C2 and C3 SOHO, and the ground-based ones (for example, MLSO on 02.07.2015 and 15.01.2016); but they are not visible in the chromospheric lines, e.g., Balmer lines of hydrogen or lines of neutral or ionized helium.

*E-mail: ifn@sai.msu.ru
These loops are sometimes diffuse and sometimes are composed of a few separated layers, but most often they possess a weakly filamentary structure.

Such loops are commonly interpreted as the magnetic ones, i.e., connecting the opposite magnetic regions in the region of outburst. However, this is usually not confirmed by the detailed comparison with magnetograms. Moreover, the magnetic loops are not always located perpendicularly to the line of sight and, consequently, should usually represent the elongated eclipses (up to the stretching into a straight line). Since this is usually not observed, one should assume that the outburst is actually surrounded by a dynamic envelope, like a bubble, rather than by the loops. Such a conclusion is well confirmed by observations of the coronal outbursts directed both to and away from the Earth (Figure 2), i.e., along the Sun–Earth axis (see also the images on 21.06.2015, 10.09.2014, 05.03.2013, and 04.11.2013). So, one can see a concentric envelope (halo) about the Sun, which moves away with the outburst and expands, but is always located at some distance from it.

The above-mentioned general pattern is further complicated by the fact that the outburst seen in the chromospheric lines often possesses a loop structure. Then, it has the additional differences from the outer envelope, namely, the outburst itself (kernel) is localized inside the envelope and lower, there are clearly expressed structural features (but they do not have the shape of a bubble), and its speed is a bit less.

How can such a loop be formed, and what processes are responsible for this? Why is it located at a substantial distance from the outburst, and how is this distance determined? Why is it not seen in the chromospheric lines? Why are the structures of the outburst and its envelope so different? The answers to these questions are important not only for the theory of nonstationary solar processes and the formation of interplanetary medium. It is surprising that the dramatic difference in the images of outbursts in the lines and the coronal continuum was not paid attention before. So, how can we explain this difference in
the images, why is the outer envelope of the outburst not seen in the chromospheric lines, and why is it often more diffuse?

3. THE MECHANISM

As follows from observations, the ejections are always associated with a considerable burst of hard-ray emission (from keV to MeV and sometimes even up to the gamma-radiation). The especially large and hard fluxes of the pulsed radiation usually follow the flares. Leaving apart the problem of origin of this radiation, let us consider its interaction with the environmental medium, which is a hydrogen–helium plasma with small admixture of other elements. The harder is the incident radiation, the stronger will be the Compton effect, i.e., transfer of some part of the energy and momentum of the incident quantum to free or weakly-bound plasma electrons. The corresponding Compton electrons will be ejected forward (i.e., from the photosphere, in the same direction with incident radiation); while protons, which are three orders of magnitude more massive, should remain behind due to inertia. As a result, the electric field will develop. Such a process is inevitable under the presence of hard emission and the specified direction of its propagation [4].

Evidently, the larger is the flux and harder the radiation, the stronger will be the field. A gap with an electric field should appear: the outer region (envelope) should be charged negatively; and the region near the photosphere (the outburst and below), positively. This field will not only accelerate the protons outward but also decelerate the electrons and prevent them from the escape, despite of accelerating action by the
hard radiation. An excess of the free electrons will be formed in the walls of the bubble. As a result, its brightness should quickly increase, as is seen, for example, in the film by the ground-based coronograph MLSO/HAO/KSOR of the event on 02.07.2015 (https://www2.hao.ucar.edu/mlso/gallery/3-part-cme-2). A pair of frames from this film is presented in Figure 3. One can see only a top part of the outburst in the beginning of the event. Subsequently, a diffuse boundary appears at some distance in front of it. This boundary moves away from the outburst, becomes more contrast and brighter in the course of time. The coronal magnetic fields—already existed before the outburst and compressed by the kinetic energy of Compton electrons—can play an important role in trapping the electrons and forming the bubble walls. Effect of the hard radiation and accelerated electrons on the surrounding structures is detectable by bending the neighbouring coronal rays outward from the burst as well as by the sharper boundary of the rays from that side. The accelerating electric field will exist while the hard radiation is present. Such acceleration mechanism is justified by perfect identity between the temporal structures of the X-ray and microwave emission by the flares [6], i.e., the rate of electron acceleration (characterized by the microwaves) is completely determined by the rate of energy input (characterized by the X-rays).

The Compton effect is most expressed in the range of radiation energy 0.01–5.0 MeV; the corresponding interval being wider for the light elements [4]. The photoelectric effect prevails at the less energies, and the creation of pairs at the greater energies. The above-mentioned energy range is quite typical for the X-ray solar flares of classes C–X.

These processes are well illustrated by the frame sequence in one of the first extra-atmospheric observations of CME by SMM apparatus (Figure 4). The ejection itself took place on 18.08.1980. An obscuring disc of the coronograph covered only 160% of the solar diameter, i.e., the outburst could be observed much closer to the Sun than by LASCO SOHO without C1 (C2 – 2R⊙, C3 – 3.72R⊙). In the first frame (10:04 UT), its visible part reminds a fan, and the disturbances of the neighbouring coronal structures are already noticeable. In the second and third frames (11:43 and 11:54 UT), one can see formation of the envelope.
FIG. 4: Development of the outburst on 18 August 1980 (SMM). The outer diffuse envelope of the approximately circular shape is well seen.

and growth of its density, appearance of the top part of the outburst, and formation of a gap between the outburst and the envelope. In the fourth and fifth frames, the envelope and outburst are separated most clearly; the structure of the outburst being much more contrast than the envelope. One more difference between the outburst and envelope is that the shape of envelope is approximately circular, and its structure is uniformly diffuse. (However, it should be kept in mind that the quality of SMM images was less than in SOHO). In the last frame, taken over an hour later, the envelope already dissipated, and structure of the flying outburst is well seen.

The diverse structure and dynamics of CME envelopes still have to be studied in more detail, since their powerful electrodynamic processes determine not only shape of the bubble but also the velocity and direction of motion of its details as well as the structure and intensity of magnetic fields in the envelope and physical parameters of the shock wave at front of the outburst. As suggested by frontal parts of the envelopes (which are often very nonuniform), the primary wave of electrons—usually corresponding to the most powerful X-ray pulse—can break away from the envelope and go into the interplanetary space, using the negatively-charged envelope as an accelerating shield.

So, why is the envelope of the outburst not visible in the chromospheric lines? In the case of narrow-band line observations, Thomson radiation corresponding to this band (i.e., the radiation by the outburst envelope scattered by free electrons) should be much weaker, $10^{-5} - 10^{-6}$ times [1], and therefore it will be unnoticeable. On the other hand, coronographs recording the coronal continuum integrate the radiation scattered by electrons over a wide spectral range, up to 2000Å [8]. So, this accumulated radiation can exceed the narrow-band emission in the strong chromospheric lines, resulting in the considerable difference between the images of outbursts in the coronal continuum (C2, C3 SOHO) and in the lines. This
becomes especially noticeable after injection of additional electrons into the envelope by the X-rays. Therefore, only the outburst itself will be seen in the emission of lines, while one can see also the surrounding envelope in the pictures from coronographs.

4. MAGNETIC FIELDS

Unfortunately, the problem of origin of the magnetic fields in space, in general, and in the Sun, in particular, was studied by now only from the viewpoint of amplification by various theoretical mechanisms of the fields already existing and rising from the solar interiors rather than a creation of the field in situ, which is required by the short characteristic times of variation of the observed magnetic fields. Evidently, a presence of the electric currents—a directed motion of the electric charges—is a necessary prerequisite for the formation of magnetic fields. The mechanism of creation of the electric fields with the acceleration times corresponding to the characteristic scales of variation in the fluxes of hard emission ($10^{-1} - 10^{-3}$ s), as described above, assumes the minimal times of acceleration of the particles, formation of the electric currents and the respective magnetic fields. This can show a way for explanation of many problems of variation of the solar magnetic fields, especially, in the dynamic processes.

5. DISCUSSION

The observations of outbursts by coronographs enable us—by their comparison with ground-based or space-born hydrogen and helium images—to identify the regions of intensive Thomson scattering, i.e., where the electrons prevail in the envelope. Such observations can be performed only by the wide-band coronographs (K-corona). However, there are some problems with observation of the initial phase of the outburst, before it goes beyond the edge of the coronograph’s obscuring disc. This phase can be observed at the solar disc or near the limb in UV lines, but there might be some difficulties in searching for a unique correspondence. The unobservability of the bubbles (electron envelopes of the outbursts) in the chromospheric and UV lines is a clear evidence for another origin of their emission. Therefore, the should be a favourable opportunity to separate the physically different zones, namely, the region of Thomson scattering by free electrons and plasma emission in the lines with the electric field between these zones (Figure 5).

In fact, this is the first case when, by comparing the images of outbursts in the coronal emission and filterheliograms or spectropheliograms, it is possible to detect a presence of the extended electric fields in the very remote object, such as the Sun. As a result, one can determine a localization of the particle-acceleration regions as well as the mechanism of their acceleration, namely, by the electric field. The problem of particle acceleration is ultimately reduced to the question how form a charge separation for a sufficiently long time? In the case under consideration, such separation is supported by the energy of hard radiation of the outburst. This mechanism of particle acceleration seems to be suitable for all the processes involving the directed fluxes of hard radiation. Of course, the so clear pattern of separation of the envelope and the outburst, as in Figures 1 and 4, is not always observed. It depends on the power and temporal structure of the X-ray bursts, surrounding coronal structures, and the magnetic fields, which can restrict the solid angle of the outburst. So, the above-mentioned separation is the result of equilibrium between the pushing field of radiation and
the electric field contracting this gap.

Thereby, it becomes possible to explain the old puzzle discussed, for example, in the book by Waldmeier [11]: Why do the outbursts with velocities much less than parabolic leave the Sun? This refers, first of all, to the ejection of prominences whose initial velocities are usually small and increase quite slowly, as was demonstrated in the above-cited book by the results of many researchers. In that time, there were attempts to explain such a fact by the radiation pressure. So, one can say that this idea is reborn now at a new level. The case is that, under the presence of electric field, the outbursts get not a solitary pulse, resulting in the escape from the Sun, but rather a continuous traction in this field, which gradually brings them into the escape zone during the period of action of the hard radiation. As distinct from the flares, the ejection velocities of the prominences are usually much less, especially in the beginning of the process. This seems to be explained by the relatively weak X-rays during ejection of the prominence and, respectively, by the weak accelerating field. In general, such cases are typical for the ejection of the prominences; and they are described, for example, in our paper [9] by the data of original observations.

So, it seems rather plausible that the Moreton [7] waves, often formed during the powerful solar flares, represent just a trace of the expanding base of the electron envelope of outburst on the solar surface. In some sense, this is in agreement with the hypothesis by Uchida [10] that this wave represents the bottom part of the coronal MHD shock wave propagating along the solar surface.

6. CONCLUSIONS

1. There is a considerable difference in the structure of CME observed in the chromospheric lines and in the coronal continuum. This difference seems to be caused by the escape of electrons due to the Compton effect into the outer envelope, concentric with respect to the outburst, and the respective amplification of Thomson scattering in this region.

2. To accelerate the charged particles, an initial energy in the form of a hard-energy radiation pulse in the range 0.01–5.0 MeV is necessary.
3. The corresponding directed emission can produce by the Compton effect (the ejection of electrons and a delay of protons due to their inertia) the accelerating electric field, whose polarity is positive near the radiation source and negative in the envelope.

4. The intensity and the range of influence of the electric field is proportional to the intensity and energy of X-ray emission.

5. Lifetime of the electric field should be immediately related to the period of action of the hard radiation.

6. The presented scheme of the particle acceleration seems to be applicable not only for the processes in Sun but also for any space objects possessing the fluxes of hard radiation.

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