Fast Coronal Transient (CME) with Twisted Legs

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Abstract

Using a set of eclipse pictures we present evidence of morphological peculiarities in the legs of several powerful CMEs. These phenomena apparently originate in a coronal condensation of the inner corona. The extended rays in the intermediate corona associated with the CME show twisted, slightly diverging, thread-like structures aligned in a quasi-radial direction. On the basis of these observations, we discuss a possible scenario and energetics for the formation of CMEs as a result of the kink instability, producing a relatively cool cavity.

1. Introduction

Coronal plasma is fully magnetized: everywhere magnetic structures are present in a wide range of scales (from 1 arcsec post-flare loops to large-scale structures). At the same time we observe a variety of explosive events associated with a wide range of spatial scales and energy scales, such as fast disturbances that originate at the photospheric or chromospheric levels, including flares, the sudden disappearance of filaments or filament eruptions; and rearrangement of the magnetic topology producing large energy processes of ejection of magnetic fields into the intermediate corona. The most popular scenario for CME’s is an initial large-scale disturbance following a filament eruption, with a subsequent apparent motion of a large-scale loop-like features, preceeded by a cavity-like region. The origin of coronal transients and/or CMEs (we use the terminology CME, although the events we are considering could be classified strictly as a propagating magnetic disturbance) is not yet firmly established.

Several scenarios have been suggested: 1) emergence of a new magnetic flux region near the filament with subsequent magnetic reconnection; 2) effect of shearing, presumably, by differential rotation of magnetic arcs or helmet streamers (Ref.1); 3) reconnection of the magnetic field in a flare region followed by a large release of magnetic energy as shocks, etc. (Ref.2). CMEs are generally considered to be the result of magnetic energy release on large scales within a narrow energy range $10^{31}$ - $10^{32}$ erg and are insensitive to the detailed structure of small-scale magnetic fields (Ref.3), while flare events show a broad energy range from $10^{27}$ to a few times $10^{32}$ erg, apparently representing an energy release process on smaller scales. Solar flares are driven by small-scale photospheric flows (shearing or twisting), while CMEs represent an energy input by photospheric motions on the scale of a supergranule. Kest et al. 1994 (Ref.4) recently observed stable vortices with characteristic velocities $0.5 - 1$ km/s on scales $\sim 10,000$ km and persisting for at least several hours within an active region. Yohkoh data indicate the association of a CME near the east limb with a large solar flare in active region NOAA 7420 on 6 February 1990. If a CME represents the result of an MHD instability of large-scale magnetic fields driven by large-scale photospheric vortices, the magnetic energy might be stored in the azimuthal field by long-lived photospheric vortical motions. If then, small-scale magnetic loops (on a scale of a granule or mesogranule) are associated with some of the monopolar active regions, we should expect the formation of an MHD instability (for example, kink instability) on smaller spatial scales, producing associated solar flares and filament eruptions (Ref.5).

Here we consider observational evidence in the form of twisted legs of a CME, observed during the total solar eclipse of February 15, 1980. Similar cases have been observed in the past (Ref.6,7). We discuss a possible scenario of CME events driven by a large-scale photospheric vorticity (on the scale of a supergranule, or $\sim 10,000$ km), producing significant large-scale twisting of a loop interconnecting two monopolar regions, and a subsequent kink instability. We also show that the energy of photospheric vortices is consistent with the observed energetics of CMEs.

2. Observations.

The CME was observed at the north–west limb during the total solar eclipse on February 15, 1980 and is known in the literature by the name "tennis racket event" (Ref. 8). We have selected several pictures obtained by different authors (Chiffaudel and P. Diego in Kenya; C. Keller from a jet over the Indian Ocean, (Ref.9) and J. Durst in India (Ref.10)) of this dynamic event and processed them in order to increase the signal to noise ratio as much as possible. The images were digitized and processed using the Madmax algorithm (Ref.8) (Fig. 1 and 2).

![Figure 1](image)

Figure 1. The "tennis racket" event observed during the February 15, 1980 solar total eclipse. At left, as observed at 8h 20m, U.T. The processed im-
age shows the outer regions; note the extension of the rays coming from the "twisted legs".

At right, as observed at 8h 50m. U.T. Processed picture by Los Alamos Group (Ref.9). Note the upward extension of the loops.

Figure 2  A. Large-scale processed image obtained at 8h 50m. U.T.
B. Sketch made from the 3 selected images at exactly the same scale to emphasize the dynamics of this event.

The first two images were taken at 8h 23m. U.T. and 8h 50m. U.T. without any neutral radial filter, so that the low corona is completely overexposed and all details are lost. Accordingly, we concentrated on more details of the intermediate corona and especially the outermost corona. The sketch of Fig.3 gives the proper motion velocities as deduced from the analysis of pictures separated by ten

![Graph showing typical velocities measured over different parts of the February 15, 1990 CME event.](image)

through thirty minutes, assuming that the velocities are constant for each identified feature, and Fig.4 shows the position of the two legs of the CME.

Figure 4  Legs of the CME as seen after processing (by Madmax algorithm) of the original picture of J. Durst at 10h 10m. U.T. Note the apparent position of the two legs of the CME as shown by arrows.

3. Possible scenario of CMEs.

The Figures presented above suggest the following scenario of a CME with twisted legs. We assume that large-scale magnetic loops interconnecting monopolar active regions can be twisted by long-lived photospheric vortical motions, leading to the production of a secondary loop, or knotted field lines as a result of a kink-instability ("tennis racket" configuration) (see Fig.5). The possibility of such a magnetic configuration has been shown numerically by Finn et al (Ref.11). They show that the twisted loop can be unstable with respect to a kink instability, spontaneously forming the X-line associated with a plasmoid (or a region of closed flux surfaces surrounded by a separatrix and not connected to the photosphere) reconnection, if the angle exceeds roughly 1 turn, or $\varphi \geq 2 \pi$. Such a plasmoid can be produced as a result of loss of equilibrium associated with a tearing-like stability involving fast reconnection process (Ref.11, 12). In this case, formation of a CME should be associated with the production of accelerated particles and, therefore, non-thermal hard X-ray radiation. In some cases X-ray emission associated with CMEs was observed (Ref. 10).

A closed magnetic field configuration has two components: $B_\phi$ is the azimuthal component of the magnetic field formed as a result of the $B_z$ component of the bottom loop, and $B_z$ is the azimuthal component of the closed configuration, representing the azimuthal field of the bottom loop. Let’s consider the case of toroidal geometry. Then, $B_\phi$ should be larger than $B_z$, and the tension force ($\sim B_\phi^2/R$, where $R$ is the curvature radius of the closed magnetic configuration) is directed toward the center of symmetry of the magnetic torus. We have shown on the basis of 2D MHD time-dependent simulations, that if the $B_\phi$ is much larger than $B_z$ and the plasma pressure inside the torus is much smaller than outside the magnetic field ($\leq 0.01$), a closed magnetic configuration is unstable with respect to convergence to the axis of symmetry, producing hot and dense plasma at the axis due to the Z-pinch (Ref. 14). But, if the
plasma pressure inside a closed magnetic field is not negligible compared to the plasma pressure outside, then slight convergence of the torus to the axis of symmetry due to the azimuthal current will cause expansion of the plasmoid (since $B_z \propto r^{-2}$, while $B_\phi \propto r^{-1}$). Thus, the closed magnetic field will be unstable with respect to the expansion (when $B_z \geq B_\phi$). A magnetic torus will expand preferentially in the radial direction in the solar corona (initially with sub-Alfvénic, but supersonic velocity) forming less dense and cool plasma inside the magnetic field. The latter can represent a cavity that forms due to adiabatic expansion ($T \sim n^{2/3}$, where $T$ is the plasma temperature and $n$ is the plasma density inside a closed magnetic field) (see Fig. 5).

![Reconnection](image)

**Figure 5** Sketch, illustrating a possible scenario of evolution of a coronal loop twisted by large-scale, long-lived photospheric vortex.

It is worth mentioning that recent observations of CMEs by the SPARTAN satellite in the $\text{H}_\alpha$ line (Ref.15) show that the temperature in a cavity is lower than in an ambient coronal plasma, $\sim 5 \times 10^6$K. These first observations support the idea that a cavity represents an expanding, and therefore cooling, plasma.

From the above scenario for CMEs, we can estimate the total energy flux per unit time available in the magnetic field (due to twisting of magnetic loop by a photospheric vortex), which is given by:

$$F_{\text{tw}} = \frac{1}{4\pi} v_\phi B_\phi B_z \text{ (erg cm}^{-2} \text{ s}^{-1}),$$

where $v_\phi$ is the characteristic velocity of a photospheric vortex, which is taken as 1 km/s (Ref.4), $B_z$ is the magnetic field at the photosphere level $\sim 1$ kG, and $B_\phi$ is the azimuthal component of the magnetic field $\approx 0.1$ B$_z$. Assuming, according to the observations, that the lifetime of large-scale vortical flows on the scale of a supergranule is about several hours, or $3 \times 10^4$ s at the characteristic area $3 \times 10^{18}$ cm$^2$, we find that the total free magnetic energy available in the corona is about $10^{32}$ erg, which is sufficient to reproduce large energy events such as coronal mass ejections.

4. Conclusion

Large-scale photospheric vortices are considered here as a possible energy source for coronal mass ejections, sometimes causing solar flares and filament eruptions before the CMEs. We qualitatively discuss a possible scenario of CME formation as a result of a kink instability, and find that estimates of available energies are sufficient to produce observed CME events.

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References