DYNAMICAL MAGNETIC ENERGY RELEASE OF CURRENT LOOPS IN THE CORONA: EFFECTS OF TOROIDAL FORCES

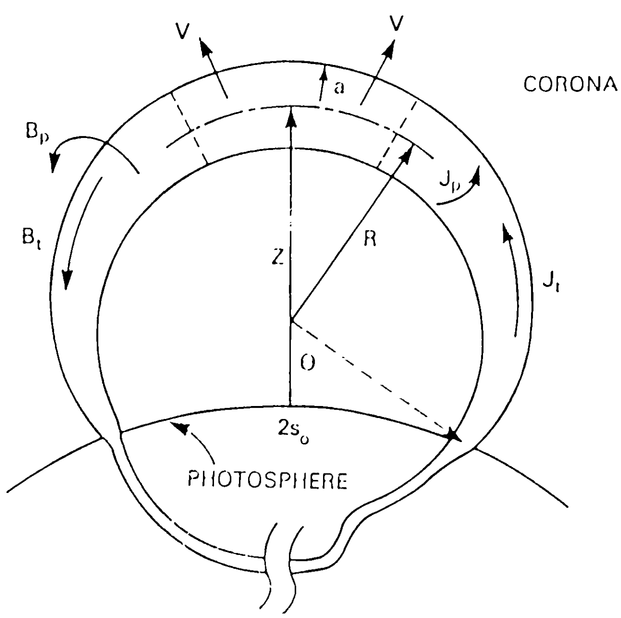
James Chen
U. S. Naval Research Laboratory
Washington, DC 20375, U.S.A.

Abstract

We discuss a mechanism whereby a current loop embedded in plasmas such as the solar and stellar coronae can dissipate magnetic energy without resistive effects or reconnection. This mechanism arises from the motion of magnetic/current structures driven by "toroidal forces". Using a simple model loop, we show that it can exhibit a wide range of motion with correspondingly wide range of magnetic energy dissipation rates. For example, a loop with ~20G can attain expansion velocities of ~1200km s^{-1} under solar coronal conditions, dissipating ~10^{32}erg in a few tens of minutes.

The solar corona consists of highly structured plasmas. It is almost certain that magnetic fields and currents play important roles in the dynamics of coronal plasmas. Among the possible configurations, loop structures have received considerable attention both for their simplicity and apparent prevalence. An important feature of a loop (and many other coronal structures) is that its footpoints are in the photosphere so that it necessarily has curvature. Figure 1 describes schematically an isolated loop which is initially in equilibrium, showing the components of the current density $\underline{J}$ and magnetic field $\underline{B}$. The subscripts "t" and "p" refer to the toroidal and poloidal directions, respectively. (We do not treat "dome-like" structures.) Such a current loop has "toroidicity", giving rise to "toroidal forces", a particular manifestation of $\underline{J} \times \underline{B}$ and $\underline{\nabla} p$ in a toroidal segment. By toroidal, we do not refer to a torus *per se* but to certain specific aspects arising in a plasma structure which may be approximated as a section of a torus. These forces are described in detail

Fig. 1



in Chen (1987), henceforth referred to as Paper 1. Because of the intrinsic curvature of many structures in the coronal plasma, we expect the toroidal forces to be present in a wide variety of systems. What do they do in various structures in the corona and under what circumstances are they important? As a start, we study the behavior of a simple structure depicted in Fig. 1 which, in addition to the significance in and of itself, may constitute elementary components of more complex systems. This paper will provide a brief description of the model which is presented in Paper 1 with a more comprehensive reference list.

In order to satisfy current conservation, we allow the current to close in or below the photosphere. The footpoint separation $2s_o$ remains constant because of the dense subphotospheric plasmas (ideal MHD line-tying is not invoked). No particular current structure will be specified below the photosphere. As a simplified geometry, we assume that the major radius R is related to the height of the apex Z by $R = (Z^2 + s_o^2)/2Z$. The force acting on plasma elements in the loop is given by $\underline{f} = (1/c)\underline{J} \times \underline{B} - \underline{\nabla}p$ with $\underline{J} = (c/4\pi)\underline{\nabla} \times \underline{B}$. Gravity proves to be unimportant for the examples discussed but is straightforward to include (Paper 1). The motion of the center of mass of a section of the loop, located on the dash-dot line in Fig. 1, is determined by the total force integrated over the given section:

$$F_R = \frac{I_t^2}{c^2 R}\left[\ln\left(\frac{8R}{a}\right) + \frac{1}{2}\beta_p - \frac{1}{2}\frac{B_t^2}{B_p^2} - 1 + \frac{\xi_i}{2}\right], \tag{1}$$

where $F_R = Md^2Z/dt^2$ with $M = \pi a^2 \bar{n} m_i$, $\beta_p = 8\pi(\bar{p} - p_a)/B_p^2$ and ξ_i is the internal inductance characterizing the minor radial distribution of the current. Here, F_R is the force per unit length of the loop in the major radial direction, $\bar{p}$ is the average pressure inside the loop, p_a is the ambient pressure and $B_p = B_p(a)$. The minor radius a(t) is also calculated using an integrated equation. In equilibrium, we demand that $F_R = 0$ and $d^2a/dt^2 = 0$, giving a geometrical constraint on physical quantities (Xue and Chen 1983). The above expression describes the case where the ambient magnetic field is zero. For the non-zero ambient field case, see Paper 1.

In analyzing the dynamics of the system, we take advantage of the fact that the integrated major radial force F_R depends only on integrated quantities (e.g., $\bar{p}$ and ξ_i). We evolve these quantities using the following global conditions; conservation of toroidal and poloidal fluxes and adiabatic gas law for the loop interior. The results give a behavior which is consistent with these physical constraints but do not give detailed information concerning the minor radial distribution. However, this is not a serious disadvantage since observation often gives "averaged" quantities so that the present approach, applied to specific systems, can produce testable predictions regarding the dynamics of current loops.

We now perturb the major radius R (equivalently Z) of an equilibrium loop. The toroidal flux conservation gives $B_t a^2$ = constant and the poloidal flux conservation leads to $\Phi_T \equiv L_T I_t$ = constant, where Φ_T is the total poloidal flux and L_T is the total self-inductance of the the current distribution including the subphotospheric structure. Let us define the inductance L_p associated with the poloidal flux Φ_p above the photosphere so that $L_p = \Phi_p/I_t$. Then, we can define

$$\varepsilon \equiv \frac{\Phi_p}{\Phi_T} = \frac{L_p}{L_T}. \tag{2}$$

This quantity is a measure of the relative size of the loop above the photosphere and the entire current structure (see Paper 1 for more detail). For a given loop in the corona, ε parametrizes the subphotospheric structure in terms of the relative flux. For the loop interior, we assume that the plasma obeys $\bar{p}V^{\gamma}$ = constant where V is the volume of the loop and γ is the adiabatic index.

The linear behavior of the loop with respect to a perturbation δZ has been calculated analytically (Paper 1). It is shown that a loop can be unstable to expansion (increasing Z, R and a) and that there exists a quantity ε_{cr}, determined only by physical paramters of the loop above the photosphere, such that (1) the loop is stable for $\varepsilon > \varepsilon_{cr}$ and (2) the loop is unstable for $\varepsilon < \varepsilon_{cr}$. The loop is marginally stable if $\varepsilon = \varepsilon_{cr}$. This is a "global" MHD instability of the loop. An unstable current loop initially in equilibrium with no ambient magnetic field is found to have slow (subsonic) expansion velocities, typically ~100km s^{-1}. If a loop carries a relatively strong current and magnetic field, then rapid expansion can occur. Such a current may exceed the equilibrium limit in the zero-ambient field limit but may result from loss of initial equilibrium with non-zero ambient fields.

The nonlinear behavior of the model loop including the minor radial dynamics has been obtained numerically for several examples compatible with the solar environment (Paper 1). Figure 2(a) shows the velocity profile of a loop which has, at t = 0, Z = s_o = 10^5km, a = 2×10^4km, I_t = 4.5×10^{10}A,

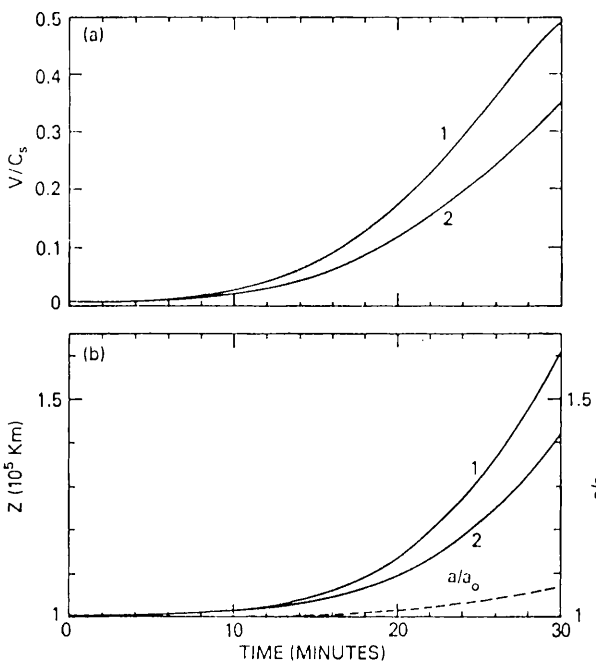


Fig. 2

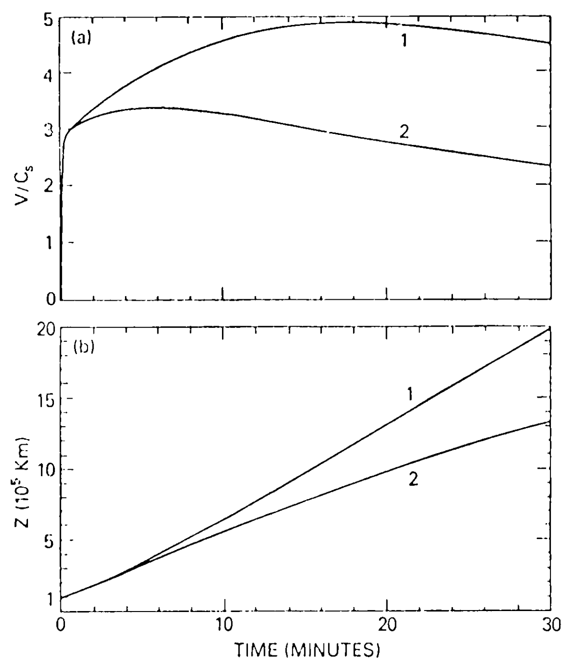


Fig. 3

B_p = 4.5G and B_t = 8.1G. The velocity is normalized to the sound speed C_s = $(\gamma kT/m_i)^{1/2}$ which is ~230km s^{-1} for γ = 5/3 and $T_{e,i}$ = 2×10^6K, where T = $T_e + T_i$. For this example, ε_{cr} = 0.28. In this and all other figures, Curves 1 and 2 correspond to ε = 0.01 and and ε = 0.05, respectively. In Fig. 2(b), we show the height of the loop for this example. The time dependence of velocity V and height is exponential, implying that the acceleration is also exponential. This seems compatible with the power law fit for acceleration reported by Kahler et al. (1988) in connection with filament eruptions and the impulsive phase of solar flares. (The observed time scales may be somewhat shorter than those in this example but the duration of observation is limited.) However, the time scale is generally shorter for less massive loop or for greater current I_t. Paper 1 gives an example of a smaller loop with a shorter time scale (~2 - 4 minutes). In this respect, note that the observed examples reported by Kahler et al. are somewhat smaller (10^3 - 10^4km) than the example of Fig. 2 (10^5km). Figure 3(a) shows the velocity profile for a loop of the same size but with I_t = 10^{11}A, B_p = 20G and B_t = 21G. We see that a loop can be driven supersonically by the toroidal forces. Figure 3(b) shows the height of the apex. The rise time is much shorter than that of the example of Fig. 2.

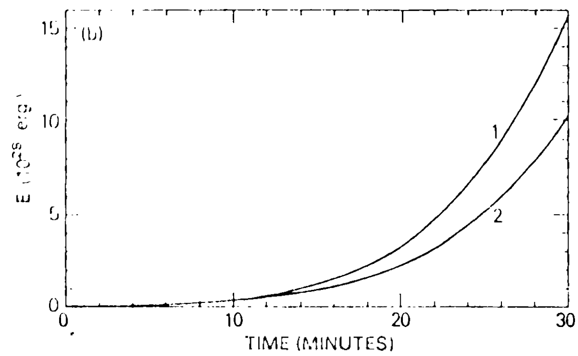


Fig. 4

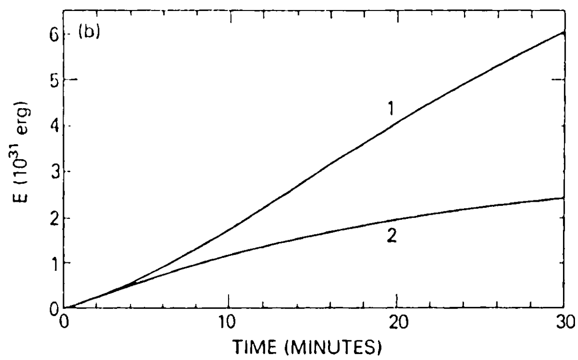


Fig. 5

The loop material is driven by the Lorentz force and the loop kinetic energy is dissipated by drag heating of the ambient plasma. The rate of energy release is proportional to V^3 where V is the apex velocity, having similar profile as the velocity [Figs. 2(a) and 3(a)]. In particular, for the example of Fig. 3, the energy release rate attains ~2×10^{28}erg s^{-1} after a short rise time for both curves. For Curve 1, it increases to ~4×10^{28}erg s^{-1} at ~14 minutes. For Curve 2, the rate stays nearly constant for ~6min and decreases to ~10^{28}erg s^{-1} in ~20 minutes. The sharp rise in energy release rate may appear as an "impulsive" heating of plasma. Figures 4 and 5 show the time-integrated magnetic energy release profiles for the examples of Fig. 2 and Fig. 3, respectively. It is clear that current loops can exhibit a wide range of motion and energy release under the action of toroidal forces. The characteristic time scales of motion and energy release appear to be minutes to tens of minutes. In addition, a loop can undergo quasi-equilibrium evolution with slowly changing parameters such as I_t and $\bar{p}$ (Paper 1). Slowly moving loops, if numerous enough, may contribute to the overall heating of the corona. An equilibrium loop can make transition from stability to instability as a result of changes below the photosphere. For example, topological changes in the subphotospheric flux/current structure can result in an increase in Φ_T and thus a decrease in ε, causing ε to become less than ε_{cr}. Thus, motion and energy release of an equilibrium loop can be triggered with no apparent coronal events.

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