# EXPULSION OF MAGNETIZED PLASMAS FROM CORONAE

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Abstract. A theory of the white light transient phenomena in the solar corona is given, based on recent analytic treatments of magnetohydrodynamics.

## I. INTRODUCTION

When the solar corona is observed in electron-scattered white light, large-scale structures are found to undergo reconfiguration on average about twice a day, often involving an outward ejection of matter estimated to be of the order of $10^{15}$ gm. This new awareness of an active corona came largely as the result of data obtained in the past decade with the use of space-born coronagraphs (MacQueen 1980). Some progress has been made in treating analytically the magnetohydrodynamics (MHD) of stellar atmospheres. We present a physical picture, suggested by the theoretical MHD results obtained, to explain how and why magnetized plasma is sporadically expelled out of the gravitational bound of the Sun. Conceivably, the same physical process takes place in coronae other than that of the Sun.

## II. THE ERUPTION OF CORONAL MAGNETIC FIELDS

An essential effect of solar activity is the introduction of fresh magnetic flux into the corona from below. The magnetic field at first evolves slowly, driven by gradual changes of boundary conditions due to the transport of magnetic flux along and across the coronal base. Slow changes also result from fluctuation in the ambient heating and energy transport taking place in the corona everywhere. On the very large scale, say $10^5$km, the electrical conductivity may be regarded to be infinite. Consequently, free energy can be stored in the form of electric currents as a magnetic field is gradually

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distorted during its evolution. In the low corona, pressure gradients and gravity have important roles to play. One situation in which this is the case, is the formation of prominence filaments supported by Lorentz force against gravity. It is well-known from eclipse pictures that these filaments are encased in cavities of low density (Newkirk 1967). Such cavities do not collapse presumably because of an internal magnetic field (Low 1980). In the stratified atmosphere, the cavity is buoyant but the "magnetic" buoyancy (Parker 1955) is countered by the tension force of the field lines anchored to the photosphere. As the magnetic footpoints evolve apart, the tension force eventually fails to hold the cavity in equilibrium. Then, the cavity rises indefinitely as the prominence erupts (Low 1981, Wolfson 1982). The point to stress is that the corona is an active system capable of storing free energy to erupt. The eruption can take place in association with a prominence as we just described. It can also take place, more impulsively, in association with a flare in the low corona (Munro et al. 1979). In both types of events, the flare, prominence and coronal re-configuration need not have a simple cause-effect relationship with one another but are all consequences of a global loss of equilibrium.

Preliminary results on the coronal transients in its early development below $2.2R_\odot$, observed with HAO's ground-based coronagraph at Mauna Loa, showed that two main classes of events can be discerned (MacQueen and Fisher 1982). Those that are flare-associated, moving at speeds of 500 km/s or more and characterized by bright loops and those that are associated with eruptive prominences, slowly moving at speeds typically below 200 km/s and characterized by a moving void. It seems natural to identify the latter "dark" transients with a prominence cavity that has broken away, and the case can be supported with a comparison between theoretical models and observation (Fisher, Garcia and Seagraves 1981 and Low, Munro and Fisher 1982). A dark transient may start to move before the associated prominence erupts. This, as well as its characteristic low speed, is consistent with a spontaneous loss of equilibrium. Since the motion is driven internally by the hydromagnetic system, drawing upon the stored free energy, the transition is not impulsive and the speed of the plasma can, at most, be accelerated to the order of the signal speeds at which the fluid system communicates between its different parts. The sound speed at the coronal temperature of $1.5 \times 10^6$ K is about 120 km/sec. For a plasma beta in the neighborhood of unity, applicable to the prominence environment, the hydromagnetic signal speeds are perhaps not more than a factor of two larger. Many of the dark transients are, in fact, observed to have speeds of less than 100 km/sec. The dark transients develop bright loops as they travel above 2.2 $R_\odot$, the typical field of view of orbiting coronagraphs. Except for their low speeds, the appearances of these transients in this field of view are similar to the flare-associated ones that developed bright loops during their early stages.

For the fully developed coronal transients, the time-dependent MHD equations provide the lowest order description. For a $\gamma=4/3$ polytrope, the atmosphere can expand radially outward in a self-similar flow (Low 1982a, b, 1983). Explicit solutions can be constructed. An essential feature is that solar gravity is included and the expelled plasma can travel outward at speeds less than the local escape speed. From these self-similar solutions, two implications are noteworthy.

For a polytropic magnetostatic atmosphere in a $1/r^2$ gravity, the total energy is given by $E=-(3\gamma-4)U$, where U is the internal energy and various singularities at r=0 have been appropriately re-normalized. The polytrope $\gamma=4/3$ is the marginal case between gravitationally bound ($E<0$) and unbound ($E>0$) states. That the self-similar MHD solutions exist for $\gamma=4/3$ is a manifestation of the fact that the static atmosphere for $\gamma\leq4/3$ is gravitationally unstable. It follows that the outward expansion of a coronal transient could be interpreted in general terms to be the result of a hydromagnetic system that has gained sufficient energy to become gravitationally unbound. The transition to an unbound state may be gradual, such as through the introduction of new magnetic flux and ambient heating, or, in the case of a flare-related event, through the enhanced heating as part of the flare build-up. The transition may be impulsive such as through a sudden input of energy released by a flare. The flare with its rapid rise time is effectively an external driver, being able to impart speeds much in excess of the characteristic speeds of the coronal medium above it. Transient speeds of the order of 1000 km/sec are sometimes observed.

We interpret the coronal transient to be the outflow of a gravitationally unbound, pre-existing hydromagnetic structure in the corona. The observed white-light density structure is a part of this moving pre-existing structure. This contrasts with the physical picture of some numerical MHD models (e.g., Dryer et al. 1979), in which the observed transient density structure is interpreted to be a wave-like response in the ambient atmosphere due to an impulsive input at the coronal base. In our picture, the ambient atmosphere is swept upward and sideways by a large-scale outflow.

## III. CONCLUSION

If there is no magnetic field, the corona expands outward in a spherically symmetric solar wind, the impossibility of a gravitationally bound state being the consequence of heating and the absence of adequate confining pressures in the interstellar medium (Parker 1963). Magnetic fields anchored at their footpoints can trap pockets of coronal matter, first in gravitationally bound local systems and then through subsequent heating and evolution, transit into an outward moving unbound state. This, we believe, is the origin of coronal transients.

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## DISCUSSION

SPRUIT: Can your self-similar solutions have the form of observed loops?

LOW: Yes, and that is easy to see. In the self-similar space, explicit time dependence has been removed, and one has a problem very much like that of magnetostatic equilibrium. Loop solutions occur naturally. Transformed into real space-time, the loop solutions become expanding loop structures.

CAMPOS: Your self-similarity solution depends on the ratio of specific heats, $\gamma = 4/3$. For a fully ionized gas, with monoatomic molecules, $\gamma = 5/3$, and you say that the difference is due to heating. The value $\gamma = 4/3$, however, is the classical ratio of specific heats for a polyatomic gas, with three-dimensional molecules, and 6 degrees of freedom. Why do you need a value of $\gamma$ for polyatomic molecules when the coronal gas is monoatomic? Is it a coincidence that heating accounts exactly for the difference between $\gamma = 4/3$ and $\gamma = 5/3$?

LOW: In my analysis I do not regard $\gamma$ to refer directly to the degrees of freedom of the constituent gas. The polytropic relation is a mathematical device to close the equations of motion. The interesting properties of the $\gamma = 4/3$ polytrope, namely, those properties arising from a marginally bound state, are applied to the corona in the very crude approximation that a $\gamma < 5/3$ polytrope simulates a $\gamma = 5/3$ gas subject to heating.

MARTENS: Do I understand that by taking $\gamma = 4/3$, you simulate or solve for the coronal heating problem?

LOW: One does not solve the coronal heating problem by taking $\gamma < 5/3$. The idea is that a $\gamma < 5/3$ for an expanding gas implies a pressure going down with density more slowly than the 5/3 power, and in this sense simulates some heating during the expansion.