ARE CORONAL MASS EJECTIONS CAUSED BY MAGNETIC PUMPING?

JAN KUIJPERS
Sterrekundig Instituut, Utrecht University, 3508 TA Utrecht, The Netherlands; HEFIN, University of Nijmegen, Toernooiveld 1, 6525 ED Nijmegen; and CHEAF, 1009 DB Amsterdam, The Netherlands

LYNDSAY FLETCHER
ESA Space Science Department, ESTEC, 2200 AG Noordwijk, The Netherlands

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(Dedicated to Cornelis de Jager)

Abstract. Magnetic pumping in the solar corona is revisited. We derive conditions under which magnetic pumping can be the cause of heating of loops rather than of particle acceleration. Candidate sources for such a process are coronal mass ejections (CMEs). Large loops are susceptible to heating primarily of protons by magnetic compressions with periods between 50 and 5000 s, the observed spectrum of the photospheric driver. Efficient heating by pumping occurs since in these large loops the density is low enough that the proton-proton collision time is comparable to the periods of the external compressions. We suggest that CMEs may be pressure-driven explosions of large-beta loops caused by magnetic pumping, in contrast to current-driven ‘flares’ in low-beta environments.

1. Introduction

Particle acceleration in the solar corona is largely attributed to magnetic reconnection in a low-β plasma, where $β = \frac{p_{\text{gas}}}{p_{\text{mag}}}$ is the ratio between gas and magnetic pressures (Giovanelli, 1946; Sweet, 1958; Sakai and de Jager, 1996). This does allow, however, for different acceleration processes – by direct electric fields, or large-amplitude MHD waves and shock waves, or plasma turbulence – during different phases of solar flares. Heating of the corona may occur partially by reconnection in (nano) flares, but resonant heating of coronal loops by Alfvén waves excited by convective motions at the photosphere can definitely not be neglected (Kuperus, Ionson and Spicer, 1981; Goedbloed and Halberstadt, 1994; Goossens, 1994; Poedts and Boynton, 1996). Here we assess the importance of magnetic pumping for the heating of magnetic loops in the solar corona. The sources of the large-amplitude low-frequency MHD waves required for magnetic pumping to operate, are both convective motions at the photosphere and reconnection events of magnetic fields in the solar corona.

After a brief description of the physics of magnetic pumping in Section 2, we consider its role in the explanation of CMEs in Section 3, and look ahead in Section 4.
2. Magnetic Pumping

Magnetic pumping, sometimes termed betatron acceleration, is an acceleration or heating process operating in temporally changing magnetic fields in the presence of particle scattering. Briefly, when the magnetic field strength $B$ changes on a time scale long compared to the gyration period of the particle $2\pi/\omega_{cij}$ in its guiding centre frame, the quantity

$$\frac{p_{\perp}^2}{B} = \frac{p_{\perp}^2(0)}{B(0)}$$  \hspace{1cm} (1)$$

is an invariant of the particle motion, the so-called first adiabatic invariant. When the field changes in a periodic fashion with period $t_{osc}$ the transverse particle momentum $p_{\perp}$ varies adiabatically in accordance with Equation (1) in the absence of scattering. However, if the particles are scattered in pitch angle with respect to the magnetic field direction on a time scale $t_{scat}$, the particle distribution always moves towards isotropy. The changes in transverse momentum are then partially transferred to particle momentum along the field direction and this component remains unaffected by field changes. As a result there is a systematic increase in particle momentum when averaged over all particles, which is second-order in the field amplitude $\Delta B/B$ (at least as long as this ratio is small). This implies that this acceleration-heating process is of a stochastic nature.

Here the frequency of gyration of a charged particle (charge $q_j$, rest mass $m_j$, Lorentz factor $\gamma$) with perpendicular velocity component $v_{\perp}$ ($\beta_{\perp} = v_{\perp}/c$) in a magnetic field of strength $B$ is given by its cyclotron frequency

$$\omega_{cij} = \frac{|q_j|B}{\gamma m_j} = 1.76 \times 10^{11} \frac{B}{\gamma m_j} \text{ rad s}^{-1},$$  \hspace{1cm} (2)$$

and its cyclotron radius by

$$r_{cij} = \frac{v_{\perp}}{\omega_{cij}} = 1.7 \times 10^{-3} \frac{\gamma \beta_{\perp} m_j}{B m_e} \text{ m}.$$  \hspace{1cm} (3)$$

This acceleration process was first developed in the context of particle acceleration under astrophysical conditions (Swann, 1933; Fermi, 1954; Alfvén, 1954; Schlüter, 1957; Kulsrud and Ferrari, 1971; Melrose, 1980) and later for plasma heating (Berger et al., 1958; Spitzer, 1962; Stix, 1992). Obviously, the process bears a strong resemblance to second-order Fermi acceleration (Fermi, 1954) of a particle moving in magnetic fields with spatial variations on a large scale ($r_{cij} \ll L_B$). In fact the spatial case can be transformed into the temporal case by a coordinate transformation to the guiding centre frame of the particle.

Usually a distinction is made between two kinds of magnetic pumping: transit-time and ‘collisional’ magnetic pumping (Stix, 1992; Berger et al., 1958; Schlüter,
1957). In both cases a confining magnetic field is being modulated at frequency $f$ (assumed to be small in comparison with the particle cyclotron frequencies) over a distance $d$. Transit-time pumping occurs when the bounce time of the particles is approximately equal to the modulation frequency: $f \approx d / v$. In ‘collisional’ pumping particles are scattered in pitch angle by an independent process, sometimes but not necessarily by particle collisions.

On average the increase in energy ($= \gamma - 1$ in units of the rest-mass energy $mc^2$) by pumping of angular frequency $\omega$ is given by

$$\dot{\gamma}_{\text{acc}} = \frac{\alpha \omega}{4\pi} \left( \frac{\Delta B}{B} \right)^2 \frac{1}{1 + \Delta B / B} \left( \frac{\gamma^2 - 1}{\gamma} \right),$$

where $\alpha$ is a small coefficient and the field varies periodically between the values $B$ and $B + \Delta B$. The value $\dot{\gamma}_{\text{acc}}$ is the average increase in the particle population energy with time due to the magnetic pumping process; $\alpha$ depends primarily on the ratio of field oscillation time to pitch-angle scattering time scale. Whereas in a few illustrative cases (e.g., Alfvén and Fälthammar, 1963; Melrose, 1980) $\alpha$ can be estimated from heuristic considerations, we have calculated its value exactly in a stochastic simulation: $\alpha = 0.40$ at optimum when the scattering time equals the oscillation period (Kuijpers et al., 1996).

If we restrict our considerations to the non-relativistic regime, Equation (4) becomes

$$\dot{E} = \frac{\alpha \omega}{2\pi} \left( \frac{B}{B} \right)^2 \frac{E}{1 + \Delta B / B}.$$

Of course, particles only gain energy when the increase from pumping exceeds energy losses. Here we shall consider the case where the gain is continuously redistributed over the entire thermal particle population by Coulomb collisions. The increase in temperature is moderated by thermal contact with dense regions at the footpoints which acts as a thermostat and leads to a density increase in the loop by ‘evaporation’. For electrons in a thermal plasma the deflection or pitch angle scattering time is determined by Coulomb collisions with other electrons and is given by (Spitzer, 1962)

$$t_{\text{col}}^e = \frac{m_e^{0.5} (3k_B T)^{1.5} (4\pi e_0)^2}{4\pi n e^4 \Lambda},$$

where $\Lambda$ is the Coulomb logarithm, $n$ the background electron density, and $T$ the temperature. This time is also the time on which a Maxwellian distribution is established amongst particles of the same species. For protons in a hydrogen plasma again these time scales coincide but are a factor $(m_p / m_e)^{0.5}$ larger:

$$t_{\text{col}}^p = t_{\text{col}}^e \left( \frac{m_p}{m_e} \right)^{0.5}.$$
3. Coronal Mass Ejections

CMEs are apparently not driven by flares in the lower corona (Harrison, 1995; Gopalswamy and Kundu, 1995). As they are primarily eruptions of mass the cause of the eruption then is likely to be related to the very fact that they are overdense structures to start with. The suggestion that CMEs are just caused by large-scale reconnections of magnetic structures linking the (solar) northern and southern hemispheres (Low, 1996) does not answer the question how the extra mass has been transported into the structure. There is therefore good reason to pursue the line of thought that perhaps CMEs are reconnecting structures driven primarily not by large electric currents but rather by high gas pressure. In other words, are CMEs unstable high-$\beta$ structures in contrast to the common low-$\beta$ flares? Relatively large coronal densities at high altitudes imply large heating rates. Of course, this heating rate might still come from many small reconnection events. But then it is puzzling that similarly to the missing nanoflares, the required multitude of such small-scale reconnections has not been observed at radio frequencies (Benz, 1995). Benz concluded that heating by waves, separately from flares, is probably required to an amount of $10^{20}$ W to maintain the corona.

What are the requirements for magnetic pumping to produce heating? First, to be effective the oscillation time should be equal to the scattering time, which has an upper limit in the collisional deflection time: $t_{osc} \approx t_{scat} \leq t_{col}$. Next, to cause heating instead of particle acceleration the pumping time scale should be larger than or equal to the minimum of intraspecies energy collision time and conductive time scale to the dense footpoints of the loop where evaporation takes place: $t_{acc} \geq \min\{t_{cond}, t_{col}\}$. Note that conduction is not a real loss of energy but simply partitions of the available energy over more particles by evaporation. Putting $\Delta B/B = 0.25$ in Equation (5) to obtain the pumping or acceleration time scale $t_{acc} = E/\dot{E}$ these conditions can be combined into

$$t_{osc} \leq t_{col} \leq 50 \, t_{osc} \tag{8}$$

for both electrons and protons where it is understood that $t_{col}$ is the collision time within the same species (see Equation (6) and Equation (7)). The constraint (8) for efficient heating can now be written as (putting $\Lambda = 20$)

$$1.93 \times 10^{11} T_6^{1.5} t_{osc}^{-1} \, m^{-3} \leq n \leq 9.65 \times 10^{12} T_6^{1.5} t_{osc}^{-1} \, m^{-3} \text{ for } e^- \tag{9}$$

$$8.27 \times 10^{12} T_6^{1.5} t_{osc}^{-1} \, m^{-3} \leq n \leq 4.15 \times 10^{14} T_6^{1.5} t_{osc}^{-1} \, m^{-3} \text{ for } p^+ \tag{10}$$

where $T_6$ is the temperature in units of $10^6$ K. Substituting the observed range of periods in the power spectrum in photospheric flows, $50 \, s \leq t_{osc} \leq 5000 \, s$ (Tarbell et al., 1990), for the oscillation periods in Equations (9) and (10)
and putting $T_k = 2$ we expect pumping to occur in loops with densities between $1.1 \times 10^8 \text{ m}^{-3} \leq n \leq 2.3 \times 10^{13} \text{ m}^{-3}$. The lower bound is for heating of electrons, the upper bound for protons. These are low-density and therefore large loops (note that the collision time is $50 \text{ s} \leq t_{col}^e \leq 5000 \text{ s}$).

As long as the conductive time scale towards the footpoints remains smaller than the radiative loss-time, $t_{cond} \leq t_{rad}$, the density in the loop will increase (of course within the limits posed by Equations (9) and (10)). The optimum is reached when $t_{acc} \approx t_{cond}$. Writing $t_{cond} \approx L/v_{lj}$, where $v_{lj} = (3k_B T/m_j)^{0.5}$ is the characteristic thermal speed of particles of species $j$, we find for such an optimum situation loop half-lengths with a lower limit $L \approx 50t_{osc} v_{lj} \geq 5.6 \times 10^8 \text{ m (0.8 } R_\odot)$, surprisingly similar to the spatial dimensions of CMEs. Note that such a static structure is compatible with the density scale height in an isothermal hydrogen plasma, $L_n = 2k_B TR^2(GM_\odot m_p)^{-1} = 0.7 R_\odot$ at a temperature $T = 2 \times 10^6 \text{ K}$ and distance $R = 2 R_\odot$ from the centre of the Sun.

The total mass in a volume of $1 R_\odot^3$ can go up to $M \approx 1.3 \times 10^{13} \text{ kg}$ for proton pumping and to a value a factor 43 times smaller for electron pumping. The observed mass in a CME can go up to $10^{13} \text{ kg}$ (Jackson and Froehling, 1995; Harrison, 1995).

The total thermal energy in the gas for proton pumping at a temperature of $2 \times 10^6 \text{ K}$ in a volume of $3 \times 3 \times 1 R_\odot^3$ can go up to $W_{\text{gas}} \approx 3 \times 10^{24} \text{ J}$, compared to observed values of $10^{24} - 10^{25} \text{ J}$ (Low, 1996).

At the maximum density $n_p = 2.3 \times 10^{13} \text{ m}^{-3}$ (at a temperature $T = 2 \times 10^6 \text{ K}$ and $t_{osc} = 50 \text{ s}$) the radiative loss-time (Raymond, Cox, and Smith, 1976) is still much larger than the acceleration time, $t_{rad} > t_{acc}$, as is required for continued evaporation.

We therefore conclude that the energetics, spatial scale, mass, temperature, density, and the observed evolution of CMEs (such as observed with SOHO) are consistent with magnetic pumping of protons (but not of electrons) preferentially heated by MHD oscillations at the dominant periods of the photospheric motions. If this is true the CME eruption is primarily pressure driven, i.e., takes place in a high-$\beta$ plasma in contrast to the low-$\beta$ flare eruptions in the low corona. Note that a magnetic structure must open up when its gas pressure becomes comparable to the magnetic pressure at its weakest part (at the top). A corollary of our proposal is that the characteristic magnetic field strength at the top of the proto-CME has the equipartition value, of order $B_{\text{top}} \approx (2\mu_0 3nk_B T)^{0.5} = 7 \times 10^{-5} \text{ Tesla (0.7 G)}$.

4. Prospects

Observational determination of the plasma-$\beta$ at the top of a starting CMA can disprove or confirm our proposal that CMEs are pressure driven reconnecting field structures. Further, if CMEs do indeed occur in relatively weak magnetic fields, large amplitude $(\Delta B/B)$ MHD waves rising upward from the photosphere...
can be expected because of conservation of wave flux. Obviously our proposal requires detailed modelling, a code for which is available (developed by one of us, Fletcher, 1995). Finally, if this process works on the Sun it will also be operating in magnetized coronae of other stars and accretion disks, and it could form a generic mechanism to produce dense high-β plasmoids and their expulsion.

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