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Self-regulation of solar coronal heating via the collisionless reconnection condition

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Abstract. I present a novel view on the problem of solar coronal heating. In my picture, coronal heating should be viewed as a self-regulating process that works to keep the coronal plasma marginally collisionless. The self-regulating mechanism is based on the interplay between two effects: (1) Plasma density controls coronal energy release via the transition between the slow collisional Sweet-Parker regime and the fast collisionless reconnection regime; (2) In turn, coronal energy release through reconnection leads to an increase in the ambient plasma density via chromospheric evaporation, which temporarily shuts off any subsequent reconnection involving the newly-reconnected loops.

1. Introduction

I here discuss certain aspects of solar coronal heating (see Klimchuk 2006,for a recent review) in the context of the Parker (1988) nanoflare model. Since the main heating process in that model is magnetic reconnection, I will first discuss what we have learned about reconnection in the past 20 years. Even though we still don't have a complete picture of reconnection, there is now consensus about some of its fundamental aspects. My main goal is to use this emerging knowledge to shed some new light on the old coronal heating problem.

2. Transition to fast collisionless reconnection

First, I would like to emphasize the importance of a realization by Petschek (1964) that the main bottleneck in the classical Sweet–Parker (Sweet 1958; Parker 1957) reconnection model is the need to have a reconnection layer that is both thin enough for the resistivity to be important and thick enough for the plasma to be able to flow out. Furthermore, Petschek (1964) proposed that this can be resolved if the reconnection region has a certain special structure: the Petschek configuration, with four shocks attached to a central diffusion region. Then, there is an additional geometric factor that leads to faster reconnection. This idea is especially important in astrophysical systems, including the solar corona, irrespective of the actual microphysics inside the layer. This is because the system size L is much larger than any microscopic physical scale δ, e.g., the ion gyro-radius ρ_i, the ion collisionless skin-depth $d_i \equiv c/\omega_{pi}$, or the Sweet–Parker layer thickness $\delta_{\rm SP} = \sqrt{L\eta/V_A}$. Then, a simple Sweet–Parker-like analysis would give a reconnection rate $v_{\rm rec}/V_A$ scaling as $\delta/L \ll 1$, and hence would not be rapid enough to be of any practical interest. Thus, we come to **Conclusion I**: *Petschek's mechanism (or its variation) is necessary for sufficiently fast large-scale reconnection.*

However, several numerical and analytical studies (e.g., Biskamp 1986; Scholer 1989; Uzdensky & Kulsrud 2000; Kulsrud 2001; Malyshkin et al. 2005) and even laboratory experiments (Ji et al. 1998) have shown that in resistive MHD with a uniform (and, by implication, Spitzer) resistivity Petschek's mechanism does not work and the slow Sweet–Parker scaling applies instead. Thus, we come to **Conclusion II**: *In the collisional regime, when classical resistive MHD applies, one does not get Petschek reconnection.*

The natural question to ask now is whether fast reconnection possible in a collisionless plasma where resistive MHD doesn't apply. There is a growing consensus that the answer is YES. First, in space and solar physics there has long been a serious evidence for fast collisionless reconnection; recently it has also been confirmed in laboratory studies (Ji et al. 1998; Yamada et al. 2006). At the same time, several theoretical and numerical studies have recently indicated that fast reconnection, enhanced by the Petschek mechanism, does indeed take place in the collisionless regime. Moreover, it appears that there are even two physically-distinct mechanisms for fast collisionless reconnection: **(i)** *Hall effect* (e.g., Shay et al. 1998; Birn et al. 2001; Bhattacharjee et al. 2001; Cassak et al. 2005); and **(ii)** spatially-localized *anomalous resistivity* (e.g., Ugai & Tsuda 1977; Sato & Hayashi 1979; Scholer 1989; Kulsrud 2001; Biskamp & Schwarz 2001; Malyshkin et al. 2005). At present, we still don't know which of these two mechanisms operates under which circumstances and how they interact with each other. However, they both seem to work and both seem to involve an enhancement due to a Petschek-like configuration. Thus, we can draw **Conclusion III**: *a Petschek-enhanced fast reconnection does happen in the collisionless regime.*

To sum up, there are two regimes of magnetic reconnection: slow Sweet–Parker reconnection in resistive-MHD with classical collisional resistivity, and fast Petschek-like reconnection in collisionless plasmas.

How can one quantify the transition between the two regimes? Consider for simplicity the case with no guide field $B_{\rm guide} = 0$, (If $B_{\rm guide} \neq 0$, some of the arguments and results presented below may be modified, but they will remain conceptually similar). Then, the condition for fast collisionless reconnection can be formulated [e.g., Kulsrud (2001); Uzdensky (2003); Cassak et al. (2005); Yamada et al. (2006)] roughly as

$$\delta_{\rm SP} < d_i, . \tag{1}$$

Expressing resistivity in terms of the Coulomb-collision electron mean-free path $\lambda_{e,\rm mfp}$, one can write (Yamada et al. 2006):

$$\frac{\delta_{\rm SP}}{d_i} \sim \left(\frac{L}{\lambda_{e,\rm mfp}}\right)^{1/2} \left(\frac{m_e}{m_i}\right)^{1/4}. \tag{2}$$

where I have neglected numerical factors of order 1 and used the condition of force balance between the plasma pressure ($2n_eT_e$) inside and the reconnecting field pressure ($B_0^2/8\pi$) outside the layer. Then, the above fast reconnection condition becomes

$$L < L_c \equiv \sqrt{m_i/m_e}\, \lambda_{e,\rm mfp} \simeq 40\, \lambda_{e,\rm mfp} \tag{3}$$

The mean-free path is given by $\lambda_{e,\rm mfp} \simeq 7 \cdot 10^7 {\rm cm}\, n_{10}^{-1}\, T_7^2$, where we set $\log\Lambda \simeq 20$ and where n_{10} and T_7 are the central layer density n_e and temperature T_e in units of 10^{10} cm^{-3} and 10^7 K, respectively. Then equation refeq-3 becomes: $L < L_c(n,T) \simeq 3 \cdot 10^9 {\rm cm}\, n_{10}^{-1}\, T_7^2$. The strong temperature dependence indicates that knowing T_e at the center of a Sweet–Parker layer is crucial. If there is no guide field, T_e follows readily from the cross-layer pressure balance: $T_e \simeq 1.4 \cdot 10^7\,{\rm K}\, B_{1.5}^2\, n_{10}^{-1}$ [here $B_{1.5} \equiv B_0/(30\,{\rm G})$]. Moreover, even if $B_{\rm guide} \neq 0$, one can show that this estimate still approximately holds. As a result, the collisionless reconnection condition becomes (Uzdensky 2006)

$$L < L_c(n, B_0) \simeq 6 \cdot 10^9\ {\rm cm}\ n_{10}^{-3}\, B_{1.5}^4 \tag{4}$$

3. Self-regulation of solar coronal heating

Let us now discuss the implications of these results for the solar corona. I propose that *coronal heating is a self-regulating process keeping* *the corona marginally collisionless* in the sense of equations (3)-(4) (see Uzdensky 2006).

As long as flux emergence and the braiding of coronal loops by photospheric footpoint motions keep producing current sheets in the corona, magnetic dissipation in these current sheets results in intermittent coronal heating (Rosner et al. 1978; Parker 1988). Typical values of L and B_0 of these current sheets are determined by the emerging magnetic structures and by the footpoint motions. Therefore, here I will regard L and B_0 as known and ask what determines the coronal density and temperature.

Resolving (4) with respect to n_e, we get a critical density, n_c, below which reconnection switches from the slow collisional regime to the fast collisionless regime:

$$n_c \sim 2 \cdot 10^{10}\,\mathrm{cm}^{-3}\,B_{1.5}^{4/3}\,L_9^{-1/3}\,. \tag{5}$$

(Here $L_9 = L/10^9\,\mathrm{cm}$.) This value is close to that observed in active solar corona. I suggest that this is not a coincidence.

As an example, consider a coronal current sheet with some L and B_0. If initially the ambient density n_e is higher than $n_c(L, B_0)$, the current layer is collisional and reconnection is in the slow mode. Energy dissipation is weak; the plasma gradually cools radiatively and precipitates to the surface. The density drops and at some point becomes lower than n_c. Then, the system switches to the fast collisionless regime and the rate of magnetic dissipation jumps. Next, there is an important positive feedback between coronal energy release and the density. A part of the released energy is conducted to the surface and deposited in a dense photospheric plasma. This leads to chromospheric evaporation along the post-reconnected magnetic loops. As a result, these loops become filled with a dense and hot plasma. The density rises and may now exceed n_c. This will shut off any further reconnection (and hence heating) involving these loops until they again cool down, which occurs on a longer, radiative timescale.

Thus we see that, although highly intermittent and inhomogeneous, the corona is working to keep itself roughly at the height-dependent critical density given by equation (5). In this sense, coronal heating is a self-regulating process (Uzdensky 2006).

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