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A new mechanism for heating the solar corona

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Abstract. The heating of the solar corona to temperatures of the order of 10^6 K and more is one of the outstanding problems of solar physics. Beside the high temperatures, Soho/UVCS observations have shown that heavy ions in polar corona, like O^{5+} and Mg^{9+}, are heated more than protons, and that heavy ion heating is more than mass proportional; further, the perpendicular temperatures $T_\perp$ are much larger than parallel temperatures $T_\parallel$. Here we show that the heating of heavy ions can be explained by ion reflection off supercritical quasi-perpendicular collisionless shocks and the subsequent acceleration by the motional electric field $\mathbf{E} = -(1/c)\mathbf{V} \times \mathbf{B}$. The energization due to $\mathbf{E}$ is perpendicular to the magnetic field, and is more than mass proportional with respect to protons, because the heavy ion orbit is mostly upstream of the quasi-perpendicular shock foot.

Key words. Sun: corona — shock waves — collisionless plasmas

1. Introduction

The observed preferential heating of heavy ions in the polar solar corona represents a long standing puzzle, whose solution is crucial for understandin the coronal heating. Shock waves are considered to be common in the coronal holes and in the chromosphere/transition region (Yokoyama and Shibata 1995, 1996; Ryutova and Tarbell 2003; Aschwanden 2005). For instance, photospheric convection leads to the emergence of small magnetic loops, which are subject to magnetic reconnection with the ambient magnetic field. Small scale plasma jets are formed in the reconnection regions, and fast shocks can form when jets encounter the ambient plasma (Yokoyama and Shibata 1996). Indeed, recent X-ray Hinode and UV Stereo observations have shown that many more plasma jets are present in the polar corona than previously thought (Cirtain et al. 2007; Nisticò et al. 2009). Higher in the corona, magnetic reconnection happens when current sheets form because of the evolving coronal structures, while large scale shocks are associated with Type II radio bursts (Nelson and Melrose 1985; Aschwanden 2005). In the low β, nearly collisionless corona, a shock wave is formed when a superAlfvénic plasma flow having velocity $V_1 > V_A$ interacts with the ambient coronal plasma. Here, the plasma β is given by $\beta = 8\pi p/B^2$, where p is the total plasma pressure, B is the magnetic field magnitude, V_1 is the plasma velocity upstream of the shock, and $V_A = B/\sqrt{4\pi\rho}$ is the Alfvén velocity, with ρ the mass density. The Alfvénic Mach number is defined as $M_A = V_1/V_A$. It is well known both from laboratory (Paul et al. 1965; Phillips and Robson 1972) and from spacecraft experiments (Gosling and Robson 1985; Bale et al. 2005) that when $M_A > 2.7$ for low β perpendicular collisionless shocks (less than 2.7 if the shock is quasi-perpendicular), a fraction of ions, which grows with the Alfvénic Mach number (Phillips and Robson 1972; Quest 1986), is reflected off the shock, see Figure 1, leading to the so-called supercritical shocks. When the angle θ_{Bn} between the shock normal (pointing in the upstream direction) and the upstream magnetic field is larger (smaller) than about 45°, the reflected ions reenter (escape from) the shock after gyrating in the upstream magnetic field. Such shocks are termed quasi-perpendicular (quasi-parallel).

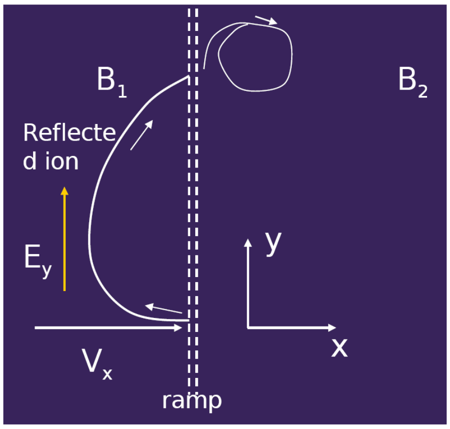

Fig. 1. Trajectory of a reflected ion upstream of the shock ramp. The motional electric field E_y and the coordinate system are indicated. B_1 (B_2) represents the magnetic field upstream (downstream) of the shock, with $B_2 > B_1$.

2. Theory

For the solar corona, we consider a quasi-perpendicular supercritical collisionless shock, and we assume a simple one dimensional shock structure. The upstream quantities are indicated by the subscript 1, and the downstream quantities by the subscript 2. We adopt the Normal Incidence Frame (NIF) of reference, in which the shock is at rest, the upstream plasma velocity is along the x axis and perpendicular to the shock surface, $\mathbf{V}_1 = (V_{x1}, 0, 0)$, the upstream magnetic field lays in the xz plane, $\mathbf{B}_1 = (B_{x1}, 0, B_{z1})$, so that the motional electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$ is in the y direction, $E_y = V_{x1}B_{z1}/c$. We further assume that $B_{z1} \gg B_{x1}$ ($\theta_{Bn} \simeq 90°$), in order to simplify the discussion. A characteristic feature of quasi-perpendicular collisionless shocks is the formation of a "foot" in the magnetic field profile in front of the main magnetic ramp (Phillips and Robson 1972). The foot is due to the population of reflected and gyrating protons, which causes an increase in the plasma density, and, because of the magnetized electrons, in the magnetic field strength (Phillips and Robson 1972). We define $B_{\rm foot} = (1 + b)B_{z1}$, with b depending on the ion reflection rate; b can be estimated to be of the order 0.5–1 for $M_A \simeq 3$–5. Direct observations in space show that very strong fluctuation levels are found in association with collisionless shocks. However, in what follows we will neglect fluctuations and we will consider only the average quantities, in order to set the stage. We assume the magnetic field to be along the z axis, and set the origin of coordinates at the point of ion reflection, with $t = 0$; then the equations of the particle motion are:

$$x(t) = -\frac{v_\perp}{\Omega}\sin(\Omega t) + \frac{cE_y}{B}t \tag{1}$$

$$y(t) = \frac{v_\perp}{\Omega}[1 - \cos(\Omega t)] \tag{2}$$

where $\Omega = q_i B/m_i c$, and B is the local magnetic field. The corresponding particle velocity is

$$v_x(t) = -v_\perp \cos(\Omega t) + \frac{cE_y}{B} \tag{3}$$

$$v_y(t) = v_\perp \sin(\Omega t). \tag{4}$$

Specular ion reflection implies that at $t = 0$ the ion velocity v_x is opposite to the incoming plasma velocity, $v_x(t = 0) = -V_{x1}$, so that

$$v_\perp = V_{x1} + \frac{cE_y}{B_{\rm foot}} = V_{x1}\frac{2 + b}{1 + b} \tag{5}$$

The reflected ions meet again the shock surface, at $x = 0$, at a later time $t_1 > 0$, corresponding to

$$\frac{v_\perp}{\Omega}\sin(\Omega t_1) = \frac{cE_y}{B}t_1 \quad (6)$$

Upon inserting the values of $v_\perp$ and of E_y in the above equation we obtain

$$\sin(\Omega t_1) = \frac{\Omega t_1}{2+b}, \quad (7)$$

whose numerical inversion yields $\Omega t_1 = 2.27885$ for $b = 1$, $\Omega t_1 = 2.1253$ for $b = 0.5$, and $\Omega t_1 = 1.8955$ for $b = 0$. At the time t_1 the particle will have moved in the y direction by an amount given by

$$\Delta y(t_1) = \frac{m_i V_{x1} c}{q_i B_{z1}}[1 - \cos(\Omega t_1)]\frac{2+b}{(1+b)^2}. \quad (8)$$

This displacement in the y direction determines the energy $W = q_i E_y \Delta y$ gained by reflected ions during the gyromotion in the field E_y:

$$W = m_i V_{x1}^2 [1 - \cos(\Omega t_1)]\frac{2+b}{(1+b)^2} \quad (9)$$

Taking into account the fact that protons move in the foot magnetic field B_{foot}, we can assume that $b \simeq 1$, as would be the case for $M_A \simeq 5$. In such a case, $1 - \cos(\Omega t_1) = 1.65035$ for $b = 1$ (or 1.52652 for $b = 0.5$), so that

$$W_p \simeq \frac{3}{2} \times 1.65035 \times \left(\frac{1}{2}m_p V_{x1}^2\right). \quad (10)$$

On the other hand, for heavy ions like O^{5+} most of the trajectory is upstream of the foot, in the unperturbed plasma where $B \simeq B_{z1}$. Then we can set $b = 0$ with good approximation, and obtain $1 - \cos(\Omega t_1) = 1.319$, so that

$$W_{\text{heavy}} \simeq 4 \times 1.319 \times \left(\frac{1}{2}m_i V_{x1}^2\right). \quad (11)$$

Here we can see that, with respect to protons, heating is more than mass proportional, in agreement with observations by Soho/UVCS (Kohl et al. 1997, 1998; Esser et al. 1999). For $b = 1$, the ratio between the heavy ion energy gain and the proton energy gain is $W_{\text{heavy}}/W_p \simeq 2.13 \times m_i/m_p$ (if $b = 0.5$ is assumed, we find $W_{\text{heavy}}/W_p \simeq 1.55 \times m_i/m_p$). Also, heating is essentially perpendicular, since it is due to the motional electric field E_y which is perpendicular to the magnetic field by definition. This allows to understand the observed strong temperature anisotropy with $T_\perp \gg T_\parallel$. In addition, a single shock encounter is required to accelerate the ions, so that the heating mechanism is very fast, as required by the observations reported by Esser et al. (1999).

If we consider that about 25% of protons are reflected at the shock (Leroy et al. 1982), the average proton energy gain is, from Eq. (10), $\langle W_p \rangle \simeq 0.62 \times \frac{1}{2}m_p V_{x1}^2$. We can define the sonic Mach number as $M_s = V_{x1}/v_{th}$, and estimate the energy gain as a function of the upstream thermal energy $\frac{1}{2}m_p v_{th}^2$. In the low β corona, the thermal speed is much less than the Alfvén speed, so that $M_s \gg M_A$. Therefore, even if $M_A \sim 2$, we can have easily have $M_s \sim 10$. Assuming such a sonic Mach number, we obtain $\langle W_p \rangle \simeq 62 \times \frac{1}{2}m_p v_{th}^2$. In other words, the crossing of a couple of shocks is enough to bring the chromospheric plasma from temperatures of the order of 10^4 K to coronal temperatures of the order of 10^6 K.

Our model leads to the prediction that a non negligible fraction of heavy ions is also reflected at quasi-perpendicular shocks. In collisionless shocks, an electrostatic potential barrier $e\Delta\phi \simeq \frac{1}{2}m_p(V_{x1}^2 - V_2^2)$ arises, which slows down the incoming ions (Phillips and Robson 1972; Leroy et al. 1982; Bale and Mozer 2007). Ions are expected to undergo specular reflection if their kinetic energy is less than the potential barrier: however, for heavy ions this is not usually found. Nevertheless, experimental evidence of α particle reflection at Earth's quasi-perpendicular bow shock has been reported by in Scholer et al. (1981), while evidence of α particle specular reflection off the quasi-parallel bow shock was reported by Fuselier et al. (1995). On the other hand, laboratory experiments show that increasing M_A the number of reflected ions increases, while the potential jump *decreases* (Phillips and Robson 1972), contrary to expectations if the potential jump would be the only cause of ion reflection. This shows that ions are not simply reflected by the average potential jump across the shock, and that also the magnetic foot and the fluctuating electric and magnetic overshoots play a role in ion reflection.

3. Conclusions

In conclusion, we have considered the heavy ion energization due to the ion reflection off quasi-perpendicular shocks. Our model can explain both coronal heating and the more than mass proportional heavy ion heating observed by Soho/UVCS. This heating mechanism is strictly perpendicular to the magnetic field and is very fast. In addition, the strongly anisotropic heating with $T_\perp \gg T_\parallel$ can give rise to efficient ion cyclotron emission, which later on can heat locally the solar wind by cyclotron resonance dissipation.

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