Recent Insights into the Physics of the Sun and Heliosphere:
Highlights from SOHO and Other Space Missions
IAU Symposium, Vol. 203, 2001
P. Brekke, B. Fleck, and J. B. Gurman eds.

Coronal Heating and the Solar Wind Acceleration

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Abstract. We propose a coronal heating theory based on the magnetic twisting, which inevitably produces charge imbalance. The resulting electric field creates supra-thermal electron beams. Beams are then thermalized by classical collisions. The dissipation rate is enough to heat the corona and to accelerate the solar wind.

1. Introduction

Coronal heating and solar wind acceleration are basic unsolved problems in solar physics. Here we present a new scenario explaining both problems in a single mechanism [detail in Hirayama (2000, Paper I)]. It uses DC energy input as opposed to waves. The dissipation mechanism is the friction damping due to the classical collisions of supra-thermal electron beams as the bulk heating. This occurs without electric current due to the back streaming bulk electrons, so that it is not the Joule heating of any kinds.

2. Charge Generation due to the Twisting

We assume that the major energy flux density F_m responsible for the coronal heating is in the form of $F_m = \rho V_\theta^2 V_A$ (Wm^{-2}). Here ρ is the density (kgm^{-3}), V_θ is the rotating velocity of a thin flux tube of typically 25kms^{-1}, consistent to the observations, which is assumed to be applicable to any loop radii. The Alfvén velocty $V_A = 2200$kms^{-1} for $n_e = 10^{14}$m^{-3} $= 10^8$cm^{-3} and $B_z = 10^{-3}$T=10G.

If a slender coronal loop with a magnetic field strength B_z is rotated from below, an electric field $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$ is generated always directed to a radial direction, perpendicular to both twisting motion V_θ and B_z in cylindrical coordinates (r, θ, z) with $\partial/\partial\theta = 0$. Thus the radial-only $\boldsymbol{E}$ produces non-zero-divergence by definition, and electric charges $\sigma = \epsilon_0 \boldsymbol{div E}$.

The net charge in unit of the total charge density of protons is quite small: $\sigma_n \equiv (n_p - n_e)/n_p = \sigma/en_p \approx -2\epsilon_0 V_\theta B_z/(en_e R_c) = \pm 2.8 \times 10^{-10}$ ($e = 1.60 \times 10^{-19}$ C, $\epsilon_0 = 8.85 \times 10^{-12}$, and a typical loop radius $R_c \approx 100$km, see below). The net charge cannot be compensated unless the twisting is stopped, because $\sigma = 0$ means $\boldsymbol{div E} = B_z \partial V_\theta / r\partial r = 0$, and $V_\theta = 0$ is the only solution. Note that R_c in the quiet region may range from ≈ 10km to ≈ 1000km. The latter is from the observed facular radius of 80km [$= 10^3 \times \sqrt{10^{-3}T/0.15T}$km]. The former 10km comes from the elementary magnetic tube of ≈ 1km radius (with 0.15T

=1500G) inside a 0.2"-photospheric facula, below which no magnetic twisting is possible because the frozen condition is violated (Paper I).

3. Quasi-Static Electric Fields due to Charges

The electric field parallel to the magnetic field, E_z, arising from the above extremely small net charge is, however, rather large due to the integration along the tube. The electric potential $\Phi(\boldsymbol{r})$ and associated $\boldsymbol{E}(\boldsymbol{r}) = -\nabla\Phi(\boldsymbol{r})$ have been calculated as a static problem for given charge distributions from various twisting motions; $\Phi(\boldsymbol{r}) = \int \sigma(\boldsymbol{r}')|\boldsymbol{r} - \boldsymbol{r}'|^{-1}d\boldsymbol{r}'/4\pi\epsilon_0$. Then E_z becomes typically 20 times the Dreicer field E_D and is proportional to the tube radius/tube length= R_c/L. Here E_D is $e^3 n_e \ln\Lambda/4\pi\epsilon_o^2 kT = 6.05 \times 10^{-4} n_{14}/T_6$ [V m^{-1}] for 10^6K and $n_{14} \equiv n/10^{14}\mathrm{m}^{-3}$. Coulomb logarithm $\ln\Lambda$ of 20 is adopted. This numerically obtained $20E_D$ can be derived roughly as follows; the electric potential Φ is calculated from the delta-function behavior of $|\boldsymbol{r} - \boldsymbol{r}'|^{-1}$ in a very thin flux tube, and is given $\Phi \approx \sigma\pi R_c^2/4\pi\epsilon_o$ so that E_z equals $V_\theta B_z R_c/2L$ from $E_z \approx -\Phi/L$ and $\sigma \approx -2\epsilon_o V_\theta B_z/R_c$. Note that E_z was calculated as a small perturbation from a given $E_r = -V_\theta B_z \approx 4 \times 10^4 E_D$, and the result shows $E_z \ll E_r$ consistent with the assumed smallness.

As a result of this field aligned quasi-static field, the electrons are accelerated and start to runaway. The important point is that the kinetic energy of runaway electrons is limited by the input energy flux, and in fact close to it as shown below. Thus the situation is much different from the classical electron runaways, where the input energy is implicitly supposed to be infinite. Hence we better call our case 'potential runaways'. If the energy flux density of $\rho V_\theta^2 V_A$ is introduced from one end of a loop for duration of Δt, the increase of the total kinetic energy of accelerated electrons cannot exceed the input energy, namely $\rho V_\theta^2 V_A \Delta t \geq \Delta(\frac{1}{2} m_e n_b V_b^2 L) \approx \frac{1}{2} m_e n_b V_b^2 L(\mathrm{Jm}^{-2})$. Here n_b is the number density of beam electrons, V_b their average velocity, and L the loop length. We find $\Delta t \geq 0.24L/V_A \approx$ 5s$-$100s,to reach $n_b/n_e = 10^{-3}$ and $V_b/V_T = 3$, where V_T is the electron thermal speed of $5500\sqrt{T_6}\mathrm{kms}^{-1}$. This is extremely slow as compared to the electron acceleration time of $\Delta t = m_e \Delta V/eE < 10^{-2}$s e.g. for $\Delta V = V_T$ and $E = 20E_D$. The two time scales of a large difference mean that all the available energy is being given to the supra-thermal electrons instantaneously. This is to say, even if $E_z \gg E_D$, we should expect that n_b and V_b are nearly constant in time (not in z). The energy flux density is roughly given as $\frac{1}{2} m_e n_b |V_b^3| = \rho V_\theta^2 V_A$.

When a small number of beam electrons are created, bulk electrons (n_0) immediately start moving in the opposite direction to supra-thermal beams to keep the plasma neutral. That is, $n_b V_b + n_0 V_0 = 0$, maintaining $n_b + n_0 = n_e$ in any volume element. Namely beam and bulk electrons are co-spatial. Here $n_0 \approx n_e$ and $|V_0| = 16\mathrm{kms}^{-1} = 10^{-3} V_T$, a very small speed.

In our case the field aligned electric field is not constant along the tube, but follows closely to $E_z = -\partial\Phi/\partial z \approx \frac{1}{2} R_c B_z \partial V_\theta/\partial z$. Therefore under the usual cases of varying V_θ, we must expect that the electron acceleration differs at different z. Hence $n_b V_b + n_0 V_0 = 0$ at any z and r is the only possibility.

4. Heating by Electron Beams due to Coulomb Collisions and Solar Wind Acce lerations

These beam electrons give away their kinetic energy by Coulomb collisions with protons and bulk electrons as the heating. The heating rate is given as the rate of momentum change $m_e n_b V_b \nu_b$ times V_b.

$$H_b = m_e n_b V_b^2 \nu_b = 3 \times 10^{-5} (n_b/n_e)_{-3} (3V_T/V_b) \mathrm{Wm}^{-3} \tag{1}$$

Here ν_b is the collision frequency of the beam electrons; $\nu_b = 3\nu_0 (V_T/V_b)^3$ with $\nu_0 = eE_D/2m_e V_T = 9.66 n_{14} T_6^{-1.5} \mathrm{s}^{-1}$. This value of H_b is sufficient to heat the corona to 10^6K. Energetically all process can be expressed as

$$\rho V_\theta^2 V_A =< m_e n_b V_b^2 \nu_b > L_D = \int [\text{radiation loss}] dz. \tag{2}$$

Here L_D is the damping length of the energy flux density and is taken to be roughly $V_b/2\nu_b$, which is the thermalizing length of the beams. We claim that this is the basic mechanism of coronal heating. At the present level of our study it is necessary to adopt V_b/V_T as a parameter, e.g. from 1.5 to 5 or so.

The heating rate given in equation(1) is $H_b \propto n_e^2 T^{-1/2}$, and if this is equated to the heat conduction loss [$\propto d(T^{5/2} dT/dz) dz \propto T^{7/2}/L^2$] for the loop length L, we immediately obtain the RTV scaling law $T \propto (PL)^{1/3}$. Further refinement in Paper I confirmed this. For isothermal corona, we find that the twist velocity increases with height for $V_b > 3.6V_T$. For $V_b < 3.6V_T$ we find a decreasing velocity in the corona. In fact non-thermal velocities in both directions have been reported.

The important parameter in the solar wind is the damping length L_D of the mechanical energy flux. We give $L_D = V_b/2\nu_b$ as before, and this is inversely proportional to the pressure (for near constant temperature) in agreement with Withbroe (1988). To match with the Withbroe's modeling of $L_D \approx 0.4R_\odot$, we find $V_b \approx 2V_T$ at around 2 solar radii, which is a reasonable value. Hence our heating scenario is in agreement with the modeling, which in turn is in accord with observations. We expect a substantial direct heating of protons in the solar wind, because ν_b only for bulk protons amounts to $1 \times \nu_o(\nu_T/\nu_b)^3$. Cyclotron waves may be excited from the electron and ion beams (ions are subject to the runaway conditions too).

Returning to the closed loop, we suppose that the same mechanical flux comes to the coronal base for a given B_z as in the open field. Then the closed loop structure will have excess dispensable energy as compared to the open field, because of no loss to the solar wind. The result may be that the enhanced heating causes repeated evaporations and cooled denser downdrafts so that the observed red shift averaged over emission measure may result.

I thank Prof. E.N.Parker for useful comments.

References

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