# Global Estimate of Coronal Heating due to Magnetic Reconnection based on SDO Observations

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## Introduction

Ever since it was discovered that the solar corona has a temperature of the order of $10^6 K$, the problem of how the corona is heated has received a great deal of attention. Two mechanisms have been proposed as the most likely to deliver nonthermal energy to the upper solar atmosphere. In both cases the energy in the convection region is the source that feeds the corona with the required thermal energy, and the presence of the magnetic fields is required for the mechanisms to operate. One possibility is that the subphotospheric motions generate MHD waves which propagate upwards along the magnetic field lines, and when they reach the corona the waves are dissipated, producing heat. It is not known if Alfvén waves can carry enough energy nor how it is dissipated. The second mechanism arises as the photospheric foot-points of the magnetic field lines slowly move and produce the magnetic field in the corona to get distorted, thus accumulating energy in different magnetic structures such as tangential discontinuities (due to magnetic braiding) or current sheets. This magnetic energy can then be released by magnetic reconnection at the sites where the field becomes more stressed. This process should be taking place at multiple scale lengths, and the number of events at each scale should increase as the small scales are approached, while the energy decreases. Thus energy releasing events with energies billionths of times weaker that the energy in an ordinary solar flare could be so numerous that can provide most of the energy to heat the corona. These are the nanoflare events postulated by Parker[1] to dissipate the accumulated magnetic stresses.

In this work we consider nanoflares as the source of coronal heating and make an estimate of the energy flux they can input into the corona based on the a reconnection model and on the observations of the coronal emissions from the Solar Dynamic Observatory (SDO). This is compared to the required value to explain the observed temperature and find that the order of magnitude is of the correct order but the difference can be accounted by the contribution from scales below the resolution limit in the pictures, which can be also estimated using the inferred energy spectrum. Our working hypothesis is that the radiation emission from the upper atmosphere is related to the occurrence of some reconnection events that release energy accumulated by magnetic flux rope braiding or any other one that produces magnetic null points.

**Reconnection model.** To estimate the power released in a reconnection event we developed a model that starts with a magnetic X-point and a perpendicular guiding field: $\mathbf{B} = \hat{z} \times \nabla \psi(x,y,t)\hat{z} + B_z(x,y,t)\hat{z}$ with the initial flux function $\psi_0 = B'_\perp xy$. This allows for certain 3D contribution which occurs in general for braided flux tubes. The plasma enters towards the X-point driving the reconnection in the xy plane. The equations solved correspond to a plasma which can have resistive or collisionless reconnection and have been described in [2]. All quantities are normalized to the characteristic values in the reconnection region, thus the same model serves for all scales. The input parameters are the plasma input velocity $v_0$, the resistive diffusion and the collisionless scales. Depending on the plasma parameters (giving a mean free path $\lambda_c$) and the reconnection scale $L$, the plasma is determined to be either collisional ($\lambda_c < L$) or collisionless ($\lambda_c > L$). The reconnection code gives the normalized reconnected flux $\hat{\psi}$ and the reconnection rate $\dot{\hat{\psi}}$ for both regimes. This is used for the heating model developed later. For the appropriate parameters, using for $v_0$ the velocity of the foot-points ($\approx 10^5 cm/s$), the rates found for collisional and non-collisional regimes are, $\dot{\hat{\psi}}_c = 1.1 \times 10^{-3}$ and $\dot{\hat{\psi}}_{nc} = 6 \times 10^{-4}$.

**SDO data.** The information about the distribution of events is obtained from the high resolution pictures of the AIA instrument in the SDO, having 4096×4096 pixels. Each pixel amounts to about 0.6 arcsec or 440 km. The wavelengths chosen are 335$\AA$ and 171$\AA$ corresponding to the active and quiet corona / transition region, respectively. The images used are from 12/25/2010, shown in Fig.1 for 171$\AA$. Magnetic fields are obtained from the magnetogram given by the HMI instrument, with the same resolution. Since these correspond to photospheric fields they have to be extrapolated up to the corona, for which we use the dipolar model [3] which gives the variation shown in Fig.2. From here, the reduction factor for coronal fields we use is 0.44.

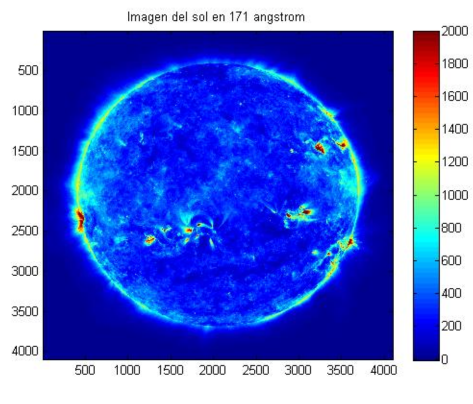


Figure 1: SDO image for 17.1 nm.

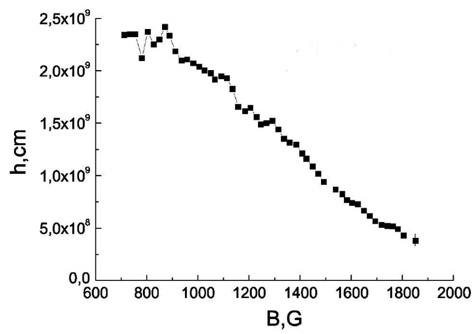


Figure 2: Magnetic field variation with height from dipolar model [3].

To analyze the data we select the emissions according to the scale length and the intensity, in realtion to the corresponding magnetic field. To minimize projection effects we consider only the central section of the disk (of radius $r = 0.5R_{\odot}$). The criterion to select a region as a reconnection event is that the emission at some scale must have a corresponding B field larger than the average value at the same scale-length. This is done for both wavelengths and the resulting distribution of events, $N(l,I)$, is shown in Fig.3. They are quite similar as we would expect.

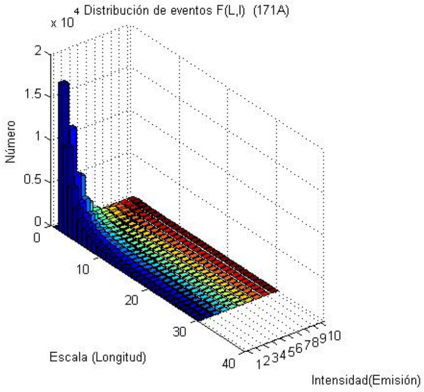


Figure 3: Histogram of reconnection events for 17.1 nm.

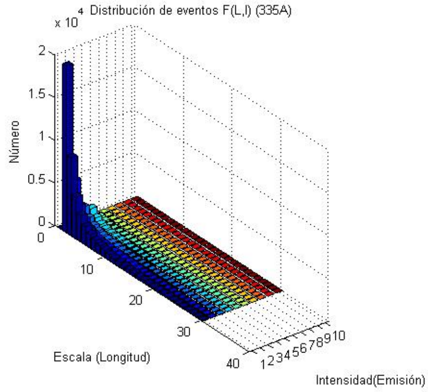


Figure 4: Histogram of reconnection events for 33.5 nm.

**Heating estimate.** Using the observational data and the reconnection rates we construct a model to estimate the energy released to the corona. The first approximation is to assume that all the magnetic energy contained in the fields of a given region is converted into free energy. This will give an upper limit for the heating power. For a region of size $l \times l$ and depth on one pixel ($l_p$ =the minimum available length), $V = l^2 \cdot l_p$. The reconnection time is $t = \tau_A / \dot{\psi}_c$. Writing $l = l_p n_l$ where $n_l$ varies from 1 to 30 (pixels), and the emission intensity as $I$, the magnetic field is $B = B(n_l, I)$. In terms of the magnetic energy, $E_l$, at a given scale, the average power is then, $P_l = E_l/t = [B^3/(8\pi) \cdot V \dot{\psi}]/(l\sqrt{4\pi\rho}) = 1.46 \times 10^{19} \dot{\psi} B^3(l,I) n_l$. The total power released to the whole corona is obtained from the weighted sum over events,

$$P_B = 3.57 \times 10^{-3} \dot{\psi} \sum_{n_l=2}^{30} \sum_{I} B^3(l,I) N(l,I) n_l \frac{erg}{cm^2 seg} \tag{1}$$

For the case of collisional reconnection, the results for the two wavelengths are $P_{B_{171}} = 2.83 \times 10^5 \, erg \, cm^{-2} \, seg^{-1}$ and $P_{B_{335}} = 3.31 \times 10^5 \, erg \, cm^{-2} \, seg^{-1}$.

An improved estimate is obtained considering the energy generated by the electric field induced during reconnection $E = -\partial\psi/\partial t$. Assuming the current sheet has width $\delta \ll l$, the total released power is found to be, for collisional reconnection,

$$P_{Tot} = \left(\frac{\delta}{l}\right)^2 \sum_I \sum_l \frac{(\dot{\psi}_c)^2}{c} \frac{e B^3 N(l,I)}{4\pi m_H} (20.8 \, cm^{-1}) n_l^2. \tag{2}$$

The values for the two wavelengths are functions of the ratio $\delta/l$ and are: $P_{171} = (\delta/l)^2 \cdot (5.10 \times 10^8)\, erg\, cm^{-2}\, seg^{-1}$ and $P_{335} = (\delta/l)^2 \cdot (5.99 \times 10^8)\, erg\, cm^{-2}\, seg^{-1}$. Using the fact that these values have to be smaller than those found before, one can get an upper bound for the current sheet length ratio, which is $\delta/l \leq 0.024$.

These estimates were for the collisional plasma, but actually for small scales the plasma is collisionless. Thus a better estimate of heating rate is found doing a separation of scales using the corresponding reconnection rate for each one. The transition scale length is 7 pixels. The resulting powers using the limit value of $\delta/l$ just found are: $P'_{171} = 1.82 \times 10^5 \frac{erg}{cm^2\, seg}$ and $P'_{335} = 2.13 \times 10^5 \frac{erg}{cm^2\, seg}$. These have to be compared with the required power, established as $P = 3 \times 10^5 erg/cm^2 seg$. Since our values are somewhat smaller than this, it is the possible that there is a missing contribution which can come from smaller scales and intensities than those provided by SDO. These are contributions from nanoflares below the resolution limit. In order to take these into account we first obtain the scaling of $N(I,l)$ from observations and then extrapolate to lower scales. Assuming a power law dependence $N(n_l, I) = K n_l^{\alpha} I^{\beta}$, we found $\alpha = -1.78, \beta = -3.92$ for 171$\AA$ and $\alpha = -1.6, \beta = -3.05$ for 335 $\AA$. With this scaling we can use the same expressions for the power and integrate over the smaller intensities and length scales. This can be used to determine whether or not the small scales can contribute to account for the needed energy flux and if so, down to what scale one has to include.

From the calculations we find that the exponent of $n_l$ is not steep enough to increment the power substantially, while the contribution from $I$ is more important so that the very numerous low emitting regions can provide enough power. For 171 $\AA$ the minimum intensity needed is $I = 12$ counts, whereas for 335 $\AA$ the minimum intensity has to be close to zero (0.03), thus practically all existing events are required. This also implies energy release from emission at 17.1 nm is more efficient.

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## References

[1] Parker, E., *Astrophys. J.* **330**, 474 (1988)

[2] Martinell, J.J., *Rad. Effects Defec. Solids* **165**, 114 (2010)

[3] Bogod, B.M., Yasnov, L.Y., *Universal Heliophysical Processes. IAU*, Gopalswami & Webb eds., pp.349 (2008)