Energy budget in the magnetic loops of the quiet Sun

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Abstract / The $\gtrsim 1$ MK characteristic temperature of the solar corona is $\sim 200$ hotter than that of the photosphere. The causes for such heating are of a magnetic nature and several possible mechanisms have been proposed. Most studies on coronal heating focus on active regions, but the so called quiet sun, or diffuse corona, is also subject to heating phenomena. By combining differential emission measure tomography applied to EUV (Extreme Ultraviolet) images time series, with potential extrapolations of the coronal magnetic field, it is possible to estimate the radiative loss energy along coronal loops of the diffuse corona, and the energy flux at their footpoints that is required to maintain thermodynamically stable structures. In this work we show the first results of this technique.

Keywords / Sun: corona — Sun: activity — Sun: magnetic fields

1. Introduction and methodology

While most coronal heating studies focus on active regions (ARs), the quiet diffuse corona is also subject to heating phenomena. Bright loops in ARs are directly seen in EUV images, revealing the shape of the magnetic flux tubes, that can be described by means of force free magnetic models. Opposite to that, in the global quiet corona no individual bright loops can be seen although its whole volume is, of course, threaded by magnetic fields.

To study the thermodynamics of the global diffuse corona, differential emission measure tomography (DEMT) can be applied. DEMT uses time series of EUV images in different bands, covering a full solar rotation, to determine the three-dimensional (3D) distribution of the so called local differential emission measure (LDEM). In DEMT the corona is discretized in a spherical computational grid, and the LDEM describes the thermal distribution of the electron plasma contained in each individual tomographic grid voxel. For a detailed description of the DEMT technique the reader should consult Frazin et al. (2009). For a recent review on all published work based on DEMT we refer the reader to the work by Vásquez (2015).

By taking moments of the LDEM, the final product of the DEMT are 3D maps of the coronal electron density and temperature. In this work, we analyze Carrington rotation (CR) 2081 (March 2009), which corresponds to one of the most quiet periods of the last solar minimum. To feed the DEMT codes we used data taken by the Extreme UltraViolet Imager (EUVI) telescope on board the Solar TERrestrial RElations Observatory (STEREO) mission.

To model the global corona magnetic field, on the other hand, we apply the potential field source surface (PFSS) model developed by Tóth et al. (2011) to the synoptic magnetogram of the same period taken by Michelson Doppler Imager (MDI) on board the SOlar and Heliospheric Observatory (SOHO) mission.

Once the DEMT 3D maps of electron density and temperature are obtained, and the magnetic field model is computed, the tomographic electron density and temperature can be traced along individual magnetic field lines of the PFSS model. Using this approach we can then study the energy budget along individual magnetic loops, as described in detail in the next Section.

2. Magnetic loop model and energy balance

We will consider a simple model for a stationary steady state coronal magnetic flux tube (or loop). In the mag-
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From Eq. (1) we then obtain,
\[ \phi_h = \phi_r + \phi_c, \]  
\[ \phi_r = \int_0^L \frac{E_r(s)}{B(s)} \left( \frac{B_0B_L}{B_0 + B_L} \right) ds, \]  
\[ \phi_c = \frac{B_0F_c(L) - B_LF_c(0)}{B_0 + B_L}. \]

where \( B_0 \) and \( B_L \) denote the magnetic field strength at both footpoints of the magnetic loop, and the magnetic null divergence condition along the flux tube, \( A(s)B(s) = \text{constant} \), has been used. Note that, by defining flux quantities we are freed from the basal area quantities and the resulting Eqs. (5)–(7) hold for each individual magnetic field line, rather than magnetic flux tubes.

All terms in Eqs. (6)–(7) can be numerically computed by tracing the results of the DEMT technique along the magnetic field lines of the PFSS model. The reader is referred to Huang et al. (2012) and Nuevo et al. (2013) to see details on how this is done. In particular, the radiative power is computed from the LDEM as \( E_r = \int dT \text{LDEM}(T) \Lambda(T) \), where the radiative loss function \( \Lambda(T) \) is in turn computed with the CHIANTI atomic database and emission model (Dere et al., 1997).

3. Results

Using the DEMT results for CR-2081, in combination with the PFSS model based on the MDI/SOHO synoptic magnetogram of the same rotation, we have computed all quantities in Eq. (5) for a large number of magnetic field lines.

For the analysis below we discriminate the data between magnetic loops with footpoints on low latitudes (< 30°) of the Sun and those on middle latitudes. The reason for this is that Carrington maps of the electron temperature show distinct thermodynamical states in the two regions (Nuevo et al., 2013). Figs. 2 and 3 show the results for closed magnetic field lines with footpoints at low and middle latitudes, respectively.

In the top panels of both Figs. 2 and 3, the violet/red dots correspond to magnetic loops with apex within/outside the tomographic computational volume. In the case of loops with apex located outside the tomographic volume, the radiative loss power was extrapolated to larger heights by means of an exponential decay fit.

It can be noted that, while the radiative \((\phi_r)\) and heating \((\phi_h)\) energy fluxes are always positive, the conductive flux \((\phi_c)\) is dominated by positive values at mid latitudes. Low latitudes show both positive and negative values, being the former the dominating population. In magnetic loops for which \( \phi_c > 0 \) the temperature increases with height, while the opposite holds when the temperature decreases with height. The structures for which the temperature increases/decreases with height have been dubbed as up/down loops by Huang et al. (2012) and Nuevo et al. (2013). Our results concerning energy budget calculations are consistent with those previously published results.

For a few field lines, the histograms of the heating energy flux show \( \phi_h < 0 \), which is an unphysical re-
result. One possible reason for this is that, in computing the radiative loss term in Eq. (5), we take into account the thermal plasma emission detected by the three EUV bands of EUVI, used as the input to DEMT. Even if that should account in principle the bulk emission of the diffuse corona, extra emission outside the sensitivity range of the data could explain the values $\phi_h < 0$.

4. Conclusions

A new DEMT tool was developed that allows calculation of the heating energy flux $\phi_h$ required at the coronal base of magnetic loops of the quiet sun to sustain thermodynamically stable structures.

The characteristic values we obtain are consistent with estimates for quiet corona (Withbroe & Noyes, 1977), and have different characteristics in different sub-regions of the equatorial streamer, related to the presence of different types of thermodynamic structures (Huang et al., 2012; Nuevo et al., 2013).

Using an enthalpy based model of the thermal evolution of loops (Klimchuk et al., 2008) we have also confirmed that the heating fluxes obtained are consistent with the observed temperatures and densities. Details of this comparison are deferred to a future expanded publication.

In a next step, we will apply the new tool to data taken by the Atmospheric Imaging Assembly (AIA) telescope on board the Solar Dynamics Observatory (SDO) mission. We anticipate that the extended sensitivity range provided by AIA could increase the radiative loss calculations by about 15% (Nuevo et al., 2015) and potentially eliminate negative values of $\phi_h$.

This new tool is able to provide a semi-empirical constraint to global coronal heating models. We plan to use it as a validation tool on predictions of the energy flow in the coronal base of the 3D MHD upper-chromosphere/coronal model component of the Space Weather Modeling Framework (SWMF) developed by van der Holst et al. (2014).

References

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