THE ROLE OF MODELING AND OBSERVATIONS FOR A COMPLETE EXPLANATION OF CORONAL HEATING

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RESUMEN

El problema de cómo la corona solar se encuentra cientos de veces más caliente que la fotósfera subyacente continúa siendo objeto de intenso estudio e interés para la comunidad de física solar. Uno de los desafíos que aún persisten es que los procesos fundamentales ocurren en escalas espaciales que están más allá del poder de resolución de los instrumentos actuales. Por lo tanto, una fuerte interacción entre modelos y observaciones es necesaria. Por parte de los modelos, la diversidad de escalas espaciales, desde el radio de giro de las partículas individuales (de cm a decenas de m) a la estructura de los arcos magnéticos coronales (decenas a centenas de Mm), hace imposible incluir todas ellas en un mismo escenario numérico, demandando en su lugar diferentes aproximaciones y formalismos físicos para regímenes en distintas escalas. Respecto de las observaciones, es necesario poner bajo un mismo marco fenomenológico diversos conjuntos de datos obtenidos en longitudes de onda desde radio hasta rayos X. Aquí repasaremos los aspectos principales del problema, su estado presente y algunos de los avances recientes en la comprensión de los procesos fundamentales.

ABSTRACT

The problem of how the solar corona is hundreds of times hotter than the underlying photosphere continues to be a subject of intense study and interest for the solar physics community. One of the main persisting challenges is that fundamental processes occur on spatial scales that are beyond the resolution power of instruments presently available. Therefore, a strong interaction between models and observations is necessary. From the side of modeling, the highly diverse spatial scales, from single particle gyroradii (cm to tens of m) to the structure of coronal magnetic loops (tens to hundreds of Mm), make it impossible to include all of them in single numerical simulations, demanding instead the use of different approaches and physical formalisms for different spatial scale regimes. Regarding observations, it is necessary to put under the same phenomenological frame diverse sets of data obtained in wavelengths spanning from radio to X-rays. Here, we review the main aspects of the problem, its present state and some of the recent advances in understanding the underlying processes.

Key Words: sun: atmosphere — sun: corona — sun: magnetic fields — sun: activity

1. INTRODUCTION

In the second half of the nineteenth century, when astronomers began to use spectrographs to observe the solar corona during total solar eclipses, they found spectral emission lines associated to known elements such as H and Ca, but they also found previously unidentified lines that they associated to unknown elements, such as He, found on Earth in the first decade of the twentiest century, and a suspected new element called "Coronium". It wasn't until the 1940s that it was found that the "Coronium" line corresponded in fact to Fe in a high state of ionization (FeXIV, Edlén 1943), indicating that the solar corona must be at a temperature of more than 1 MK. Thanks to radiative transfer modeling and observations, nowadays we count with a reconstruction of the coronal thermal structure consisting of a photosphere (the main radiant surface of the Sun, whose spectrum is mostly in the visible range) at 5800 K, a chromosphere extending up to 5 Mm with temperatures ranging from 4500 to 20000 K, and a narrow transition region (TR) of a few hundred km width where temperatures vary from a few tens of thousands of K to more than 1 MK in the solar corona (Foukal 2004). The density suffers similarly dramatic changes from 10^{17} cm^{-3} in the photosphere to 10^{12} cm^{-3} in the chromosphere to 10^{9} cm^{-3} in the corona. It was shown that the energy fluxes needed to keep the corona at those temperatures are of the order of 10^{7} erg cm^{-2} s^{-1} on active regions and 3×10^{5} erg cm^{-2} s^{-1} in the quiet-Sun (Withbroe & Noyes 1977). It has been demonstrated that the only

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way to store and release those amounts of energy in the solar corona is by means of the magnetic field. The Poynting flux injected by convective motions, acting on magnetic field lines rooted on the photosphere, provides the required energy budget (Priest 2014).

The solar atmosphere is strongly dominated and structured by the magnetic field. Due to the low magnetic resistivity, leading to the "frozen-in" condition of the plasma and the magnetic field, and the force free condition due to the low plasma β (the ratio between the gas and magnetic pressures) in the low corona, both heat conduction and plasma motions are confined along magnetic field lines (Reale 2014). For this reason, the coronal plasma, particularly in active regions, is observed to be structured in the form of magnetic flux tubes or loops. These can be considered the building blocks of the coronal structure. Any model proposed to explain coronal heating must be consistent with the observed characteristics and evolution of these loops (Klimchuk 2015).

The physical mechanism by which free magnetic energy accumulated in the field is released in the form of plasma heating, is still the subject of intense study and discussion. The proposed processes can be broadly divided in three main families: 1) the release of magnetic stress by reconnection (see, e.g., Parker 1988; Priest 2011; López Fuentes & Klimchuk 2010) or Ohmic dissipation (Gudiksen & Nordlund 2005), 2) magnetohydrodynamic waves dissipation by resonant absorption (O'Neill & Li 2005) or phase mixing (Heyvaerts & Priest 1983), and 3) turbulent regimes (Dmitruk & Gómez 1997). As we thoroughly describe in the following sections, in this report we focus on results obtained with the first type of models, in particular, the so called nanoflare heating model, originally proposed by Parker (1988).

2. LOOP MODELING AND OBSERVATIONS

In order to test the predictions of the models described in Section 1, it is necessary to convert the heating rates provided by them in emission outputs susceptible to be compared with observations. To do this, it is first necessary to compute the response of the plasma to the heating, in terms of the evolution of its temperature, density and velocity. As we described in Section 1, the coronal plasma, particularly in active regions and in the low corona in general, is structured in the direction of the magnetic field, forming coronal loops. It is therefore possible to model the evolution of the plasma in the loops using a one-dimensional hydrodynamic approach. This consists in solving the equations of mass, moment and energy conservation, plus an equation of state (see e. g., Reale 2014), to obtain the temporal evolution of the spatial distribution of temperature, density and velocity of the plasma along the loops. The hydrodynamic modeling output can be further modeled to simulate synthetic observations to be eventually compared with actual observations. Alternatively, diagnostic techniques can be applied directly to observations to infer temperatures, densities and velocities that can be compared with hydrodynamic modeling outputs.

Among the usual procedures to obtain temperatures and densities from observations, one of the simplest is the so-called filter ratio technique. Considering the emission in two different instrumental bands, in the isothermal case it can be shown that the ratio of the intensities is a function only of temperature. The temperature can then be obtained from the instrumental response in both bands, $I_a/I_b = S_a(T)/S_b(T) = R(T)$, and the density is obtained from the emission measure in any of those bands (see, e. g., López Fuentes et al. 2007). A more sophisticated procedure, useful to characterize multithermal plasmas, is to obtain the differential emission measure distribution, DEM. Expressing the emitted intensity as an integral in temperature (instead of as a spatial integral), $I = \int DEM(T)\ S(T)dT$, the method consists in testing different parametrizations of the DEM, choosing the one that better fits simultaneous observations in different bands or spectral lines (see e. g., Schmelz & Pathak 2012; Warren et al. 2012; Nuevo et al. 2020).

3. HEATING REGIMES

According to the wavelength in which they are observed, coronal loops can be classified in two broad classes: 1) hot loops, mostly observed in soft X-rays in active region cores, with temperatures above 2 MK and densities of the order of 10^8 cm^{-3}, and 2) "warm" loops, observed in the Extreme Ultraviolet (EUV) in the periphery of active regions, with temperatures of around 1.5 MK and densities of more than 10^9 cm^{-3}. One of the first studies dedicated to characterize the thermal state of loops was done by Rosner et al. (1978). They assumed that loops were in a state of equilibrium, or evolving in quasi-static equilibrium, such that a slowly varying heating source was instantaneously balanced by thermal conductive and radiative losses. Later research showed that although hot loops observed with the Soft X-ray Telescope (SXT, Tsuneta et al. 1991) on board Hinode, were consistent with this kind of scenario (Porter & Klimchuk 1995), warm loops observed with the Transition Region and Coronal Explorer (TRACE, Handy et al. 1999) had densities and scale heights that were too high to be consistent with equilibrium solutions (Aschwanden et al. 2001; Winebarger et al. 2003). Instead, it was demonstrated that the high densities and broad temperature distributions observed in warm loops could only be explained by impulsive heating (see, e. g., Warren et al. 2002).

In a recent paper, Nuevo et al. (2020) studied 13 loops of the warm class observed with Atmospheric Imaging Assembly (AIA, Lemen et al. 2012) on board the Solar Dynamics Observatory. They modeled the analyzed loops using two alternative scenarios: 1) constant heating assuming loops in equilibrium, and 2) heating by impulsive events or nanoflares. Their results showed that the loops were overdense with respect to loops in quasi-static equilibrium and that impulsive heating correctly reproduced the observed densities and temperatures. They also found that the width of the temperature distribution was consistent with loops formed by multiple strands.

4. NANOFLARE MODEL

Proposed by Parker (1988), the nanoflare model is based on the idea that loops are made of elementary subresolution magnetic strands that are shuffled and tangled by photospheric convective motions. This, in turn, produces field discontinuities and current sheets leading to reconnection heating events called nanoflares. The evolution of observed loops would be, then, due the summed contribution of a number of these strands evolving independently. López Fuentes & Klimchuk (2015) developed a model based on the interaction and reconnection between strands using a cellular automata scheme. The evolution of the plasma on each indifvidual strand was modeled using the Enthalpy Based Thermal Evolution of Loops (EBTEL, Cargill et al. 2012) code. In a later work (López Fuentes & Klimchuk 2016) they showed that synthetic lightcurves constructed by adding the contribution of the evolution of a number of strands from the model, using typical solar parameters, reproduced the main statistical properties, such as the mean, standard deviation and skewness, of real observed lightcurves. They also showed that the model reproduced DEM distributions consistent with other authors observations (Schmelz & Pathak 2012; Warren et al. 2012). Analyzing cross correlation factors between the emission in different SDO/AIA bands, Viall & Klimchuk (2012) found time lags that are consistent with the presence of impulsive heating and cooling processes, confirming the plausibility of the nanoflare model.

5. PLASMA FLOWS

An important prediction of the nanoflare model is the ubiquitous presence of plasma flows. Doppler shifts and non-thermal broadenings of spectral emission lines associated with upflows and downflows are frequently observed in coronal observations (Tripathi et al. 2012; Winebarger et al. 2013). The density changes associated with the nanoflare model are accompanied by flows from and into the chromosphere and corona. López Fuentes & Klimchuk (2022) analyzed the effect of plasma flows from the nanoflare model on EUV synthetic spectral lines. The lines were obtained integrating the contribution of model strands along typical observation times. They considered a set of 11 lines of ions with temperature formations ranging from 0.5 to 7.8 MK. Lines were integrated along 30 s samplings, as it is customary for spectrometers like the EUV Imaging Spectromenter (EIS) on board Hinode, taken from the modeled strand evolutions. The obtained synthetic lines were then analyzed with usual diagnostic techniques based in the computation of the moments of the line profiles, that provide Doppler shifts and non-thermal widths. The results are generally consistent with observations for the temperature range below 3 MK (Brooks & Warren 2016; Testa et al. 2016). For the hotter temperature range (above 5 MK) there are still very few observational reports to compare with. This is the kind of observations expected from a new generation of instruments dedicated to explore that temperature range in the near future (see, e. g., De Pontieu et al. 2022).

6. QUIET-SUN LOOPS

In the quiet-Sun corona, loops are usually not directly observable as they are in active regions, mainly because the contrast with their environment is very low. Using the DEM tomographic technique described by Vásquez (2016), Mac Cormack et al. (2017) reconstructed the mean coronal plasma properties along a solar rotation. The technique provides the 3D distribution of the mean temperature and density in a spherical grid between 1.025 and 1.25 $R_\odot$. Combining the obtained distributions with potential models of the coronal magnetic field (PFSS) they reconstructed and characterized physical parameters along integrated loops. Mac Cormack et al. (2023, in preparation) used the tomographic reconstruction of Carrington rotation 2082

(April 2009) to statistically analyze mean thermal properties of reconstructed loops. Using a superposed epoch analysis procedure they compared these reconstructions with loops modeled with a 1D hydrodynamic code (HYDRAD, Bradshaw & Cargill 2013) for constant and impulsive heating. Their results showed a good consistence with impulsive heating localized near the base of the loops.

7. CONCLUSIONS

We analyzed some of the problems and methods associated with the study of coronal heating. We saw that due to the fact that most fundamental mechanisms lie beyond present instrumental capabilities, the interaction between models and observations is crucial for a complete explanation of the problem. We introduced the nanoflare model and we showed that it is able to explain much of the sometimes confusing observational evidence, making it one of the main candidates to explain coronal heating (at least in active regions and the lower corona). The investigations reported here suggest that the statistical characteristics of quiet-Sun loops may be also consistent with impulsive heating. Among things that still need to be confirmed is the presence of high velocity upflows at temperatures above 5 MK. It is expected that new space and ground observatories (Parker Solar Probe, Solar Orbiter, MUSE, Solar-C, DKIST) and novel methods of analysis would soon provide long awaited answers and newer questions for future study.

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