Implications for coronal heating and magnetic field topology from coronal rain observations

by

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Submitted
in partial fulfillment of the requirements
for the degree of

Philosophiæ Doctor

Institute of Theoretical Astrophysics
Faculty of Mathematics and Natural Science
University of Oslo
Oslo, Norway
November, 2011

Series of dissertations submitted to the
Faculty of Mathematics and Natural Sciences, University of Oslo
No. 1176

ISSN 1501-7710

Cover: Inger Sandved Anfinsen.
Printed in Norway: AIT Oslo AS.

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Acknowledgements

This thesis has been crafted over many years of hard and constant work in many different places, starting from Japan and ending in Norway. The people at the Department of Astronomy of Kyoto University, and at the Institute of Theoretical Astrophysics of the University of Oslo, contributed greatly to my formation as a researcher in astronomy and particularly solar physics. I will always be impressed by, and grateful for, the deep physical intuition of my supervisors, Profs. Mats Carlsson and Viggo Hansteen, who have guided and inspired me more than they know. From the japanese side, much of what I learned I owe it especially to Prof. Kazunari Shibata, perhaps the busiest person I have ever met, and still a person with an open mind who is always ready for new challenges. Physical processes, as complicated as they may look, can always be understood from first principles (the only problem is to get those principles well rooted in the head!). I'm very grateful to have had the opportunity to work with Luc Rouppe van der Voort, whose observational experience and exceptional teaching abilities and kindness enriched greatly my formation. Furthermore, I would like to thank Erwin Verwichte and Gregal Vissers, for the many inspiring discussions and great collaborative work.

During all these years, but especially during my last years in the PhD at ITA, I learned the importance of group unity. Through coffee breaks, lunches, dinners, parties and great trips I was given a beautiful feeling of belonging. This is a feeling that will always linger within me despite leading a nomadic life at the moment. It is a pleasure to convey my gratitude to my office mates, Kosovare Olluri, Sandro Scodeller, Dan Sekse and Bhavna Rhatore, and to the people in the group, friends and colleagues who made my stay in Norway a joy, Lars Heggland, Nuno Rodrigues Guerreiro, Sven Wedemeyer, Juan Martinez Sykora, Eamon Scullion, Boris Gudiksen, Ada Ortiz, Wojciech Miloch, Kristin Mikkelsen, Asma Khedher, and Inger Egebakken.

Especially, I would like to thank my family, Gros Papa, Belle Maman, Nat and Pilou, who have always been there supporting me in spite of the distance. And to mi chiquita, Siew Fong, there are simply no words through which I can express my gratitude for being always there supporting and advising me throughout these years. Or perhaps yes: sayang.

To those who cross borders with their minds

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Part I

Introduction

Anybody can get captivated by solar images of the current telescopes. Anybody. No need to worry about mysterious wiggly lines to describe, or scatter plots of faint light sources barely above noise level to analyze. We can now see with amazing detail the various structure of the Sun's atmosphere. One such image speaks for itself. It is like this, that when seeing an image of the corona roughly 10 years ago (one of the culprits: Golub & Pasachoff 1997) I just could not refrain from gasping at the beauty and sizes of such structures (see for instance Fig. 1, a composite of 2 images taken by *SDO*/AIA in the filters 171 Å and 304 Å). I was immediately compelled to understand.

As some of you know, the amount of work and energy that I have invested to arrive to the present level of understanding may very well not be worth the effort. However, that brainless feeling is always a loyal companion. Anyways, in a subfield of a subfield of a subfield I may say I have a lot to say. The following work is then basically only for geeks, except perhaps for the images, which of course should captivate everybody!

In the following I will try to come up with an amazingly logical reason for why this thesis is composed of the addressed parts. However, one has generally only a faint idea at the beginning of how the big picture will end up looking like! Fortunately, in this case, I am tempted to say that it does not look so bad[1].

This thesis is (mostly) observational work. However, it started from modeling, namely, numerical simulations of coronal heating by Alfvén waves. In an attempt to predict observational signatures for coronal heating mechanisms I started a comparative study of two strong candidates for heating the solar corona: the Alfvén wave model and the nanoflare-reconnection model. While performing simulations of the later a funny event would sometimes occur: the hot corona would collapse (completely or only locally). I thought there was something wrong with my simulation, too little heating or little efficiency of the heating mechanism. However, when increasing the heating rate for those suspicious models the collapse of the corona would occur even more frequently. Fortunately, my supervisor at that time (Professor Shibata) pointed me in the correct direction by specifying that the observational consequence of that phenomenon could be coronal rain. Unfortunately, that mechanism (known as thermal non-equilibrium, or the catastrophic cooling mechanism) had already been discovered a long time ago (Goldsmith 1971; Hildner 1974)...

Coronal rain is a plasma with chromospheric properties. Thus, the study of the heating of the corona naturally led to the study of the chromosphere. But in the present case, I did not have to look down into lower atmospheric heights, but just look carefully enough in the corona itself. This is what

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[1] Unless it ends up published in New Inquisitor or some journal of the kind, which even then you would be able to read in the kitchen of our lovely institute, thanks to Line.

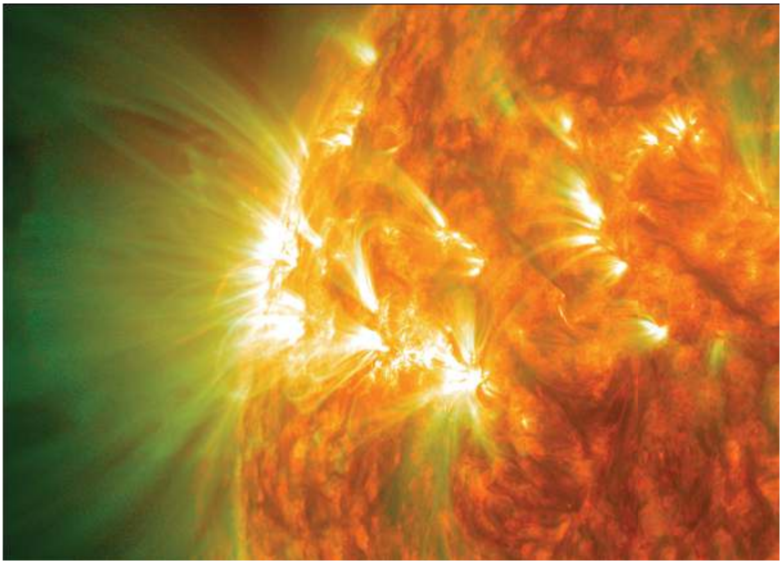

Figure 1: Active region loops observed by the *SDO* satellite with the AIA instrument on October 20, 2011. The figure is a composite of two images: one taken with the 171 Å channel (showing gas with temperatures around 1 million Kelvin), revealing the hot corona in green, and the other with the 304 Å channel (showing gas with temperatures around 80000 K), revealing the chromosphere in red (white color is the addition of the two). Loop structures at transition region - coronal temperatures seem to fill the solar corona. This picture was made with the JHelioviewer program (Müller et al. 2009).

coronal rain is all about. In this thesis I investigate the potential of this phenomenon in other fields of solar physics, such as coronal heating and coronal seismology.

This thesis is structured as follows. The first part consists of two chapters. A general introduction can be found first in chapter 1, which sets the historical context and defines the motivation of the thesis. In chapter 2 we present the structure of the thesis, the connection between the articles and the results. The second part presents the articles.

Chapter 1

The solar corona: hot and cold

The coronal heating problem constitutes a long standing problem not only in solar physics but in astrophysics, since it is addressed to all stars that possess a corona. The Sun, a middle aged main sequence star of class G2V, has been unveiling many mysteries to us in the last century, especially since the advent of the space era. More than 70 years ago a very hot temperature component in the corona was discovered, reaching temperatures as high as a few million degrees. Such a hot corona came as a surprise to astrophysicists, since it seemed to contradict the second law of thermodynamics being 200 times hotter than the underlying photosphere, the source of its energy. Since then the coronal heating problem has spawned a very active research community in solar physics that aims to unveil yet another mystery.

Perhaps, what makes this problem very interesting is that it spans basically all areas of solar physics. Misleadingly, the coronal heating problem does not only involve the corona. The constituents of the solar atmosphere, the photosphere, the chromosphere, the transition region and the corona, are always interacting, and thus cannot and should not be treated separately. For instance, the coronal heating problem also involves a chromospheric heating problem, since the chromosphere requires 10 to 100 times more energy than the overlying corona. The source of energy resides in the lower (photospheric) layers, where convection (kinetic energy) continuously stresses the magnetic field (magnetic energy), which is the main transport agent of the energy throughout the solar atmosphere. How this magnetic energy is transformed into thermal energy, on which timescales, what spatial distribution does it have, are some of the main open questions to address.

1.1 Structure of the solar atmosphere

The structure of the solar atmosphere can be understood in terms of the local dominating physical processes that define, among others, the ionization state of the constituents of the gas. As the height increases from the solar surface (defined as the point at which the optical depth τ at 500 nm is 1) the density decreases roughly exponentially throughout the first few hundred kilometers, and then more slowly with height (more as a power law). A total of 9 orders of magnitude are spanned for the density from the photosphere to the corona. On the other hand the magnetic field decreases more slowly with height, thus defining a transition from 2 very different regimes: non-magnetic to magnetic-dominated plasma. The plasma-β parameter defined as the ratio of magnetic to gas pressure, $\beta = \frac{8\pi P}{B^2}$, is a first proxy for understanding the structuring of the solar atmosphere: the photosphere ($\beta \gg 1$), the chromosphere ($\beta \gtrsim 1$ to $\beta \lesssim 1$) and the corona ($\beta \ll 1$). The accordingly enormous change in the thermodynamic length and time scales of the physical processes throughout the solar atmosphere imposes a huge challenge for observing instruments and atmospheric modeling. For the latter, it requires simplifications based on approximations. Let us review the main characteristics of the structure of the solar atmosphere.

1.1.1 The photosphere

The photosphere in the Sun is a relatively small layer of about 500 km in height, and it is the region where the gas passes from being convectively dominated to being radiatively dominated. As the name states ('photos' and 'sphairos', respectively light and sphere) it is the region where most of the visible light is generated. In the deep photosphere, a photon travels a short distance before interacting with an atom or another particle. The continuous absorption and emission of photons assures continuous thermalization processes. The gas is in local thermodynamic equilibrium (LTE) and its constituents are mostly neutral (its spectrum approximates that of a black-body). At the outmost layer the temperature of the gas is roughly 5700 K and its number density is roughly 10^{17} cm^{-3}. Because of the exponentially decreasing density the photons produced at the top of the photosphere escape freely towards space without much interaction with matter. Opaque gas (optically thick in all wavelengths) becomes transparent (optically thin in most wavelengths, especially in the visible and near infrared parts). At short length scales rising hot gas adiabatically expands and cools, thus becoming more dense. The gravitational forces compete with the gas and magnetic pressure creating a granular structure with rising hot gas in the center and falling cool gas in the boundaries (called intergranular lanes). This granular pattern can be seen in the upper panel of Fig. 1.2, which is an image taken with the CRisp Imaging SpectroPolarimeter (CRISP; Scharmer

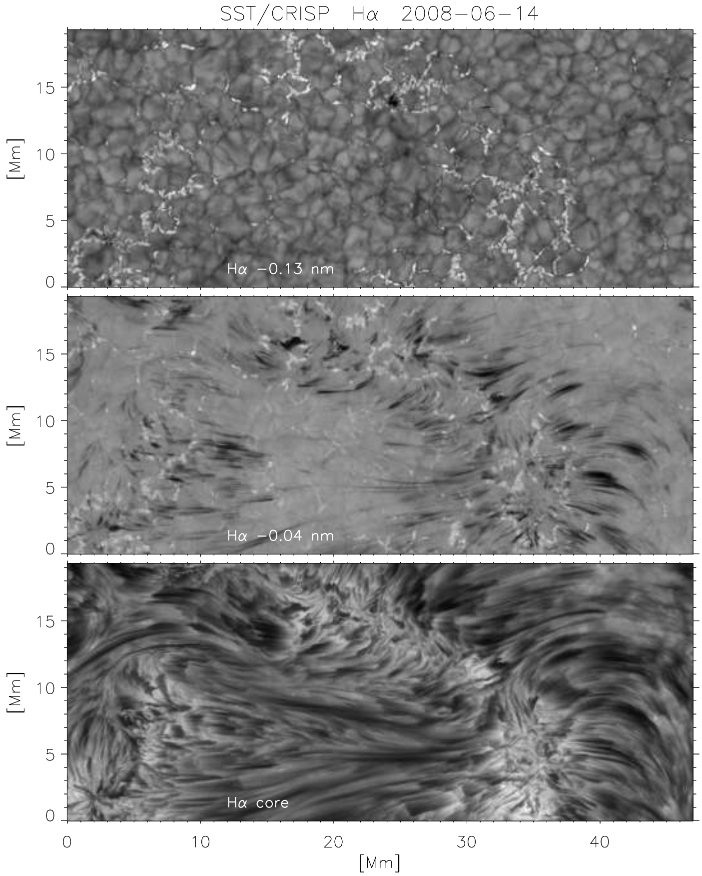

Figure 1.1: *SST*/CRISP observation of a decaying active region at disk center on June 14, 2008. Different offsets from Hα line center are shown: −0.13 nm. −0.04 nm and 0 nm (line core) from top to bottom, respectively. Sweeping the line from the wing towards line center different atmospheric layers can be observed. Here, the upper panel corresponds to an image of the photosphere (notice the granules as well as the bright points, bright network and pores of the active region), and the lower panel corresponds to an image of the chromosphere (notice the fibrillar structure revealing the magnetic field topology).

et al. 2008) at the Swedish 1-m Solar Telescope (SST; Scharmer et al. 2003) close to continuum (at an offset from Hα line center of 0.13 nm towards the blue wing). Each star has granules with a characteristic pattern depending on its gravitational force and magnetic field. In the Sun, the granules have an average size of 1 Mm and an average lifetime of 6 min (Schwarzschild 1959; Bahng & Schwarzschild 1961).

As the magnetic pressure is much smaller than the gas pressure in the photosphere ($\beta \gg 1$), the magnetic field lines are swept away by the granular flows, thus creating large concentrations of magnetic flux along intergranular lanes that seem to be ubiquitous in the Sun (Orozco Suárez et al. 2007; Ishikawa et al. 2008; Tsuneta et al. 2008a). These kG magnetic field concentrations appear as bright points in visible light. Due to hydrostatic equilibrium, the pressure outside (mainly gas) equals the inside pressure (mostly magnetic). The locally reduced density allows photons from deeper (and hotter) photospheric layers to reach the observer, thus appearing brighter due to the higher temperatures.

Active regions, regions with stronger magnetic field in the Sun, have a high concentration of bright points, and also areas where the magnetic field is strong enough to suppress convection (up to 3 kG). Depending on their size, such regions are defined as pores if small, or sunspots if large enough to develop a surrounding penumbra. Both of these regions appear as dips in the solar surface (termed the Wilson effect, after its discoverer back in 1769), and the lack of convection makes the gas inside about 1000 K to 3000 K lower than the surrounding photosphere, giving them their distinctive dark color. Active regions often comprise a bipolar region due to the emerging flux processes from which they form. The magnetic field ensuing from such regions fills significantly the overlying atmosphere, making the chromosphere and corona significantly different than in other regions of the Sun (quiet Sun regions or coronal holes).

1.1.2 The chromosphere

A few hundred kilometers up from the solar surface the gas becomes partially ionized. Radiation from the photosphere, sound waves generated from convective motions and magnetically driven processes (leading to heating through ohmic and viscosity dissipation) contribute to this state. It is throughout this region where the famous Hα line in the red wing of the visible spectrum (6563 Å) is produced, corresponding to the transition from $n = 3$ to $n = 2$ of the neutral Hydrogen atom. Actually, the chromosphere owes its name to this line ('kroma' and 'sphairos', respectively color and sphere), since it appears reddish to the naked eye (as is observed during solar eclipses). Although the variations are large, characteristic ranges are, for temperature and number density: $4000 - 20000$ K and $10^{10} - 10^{13}$ cm^{-3}, respectively. In the chromosphere, the dissipated energy goes mostly towards

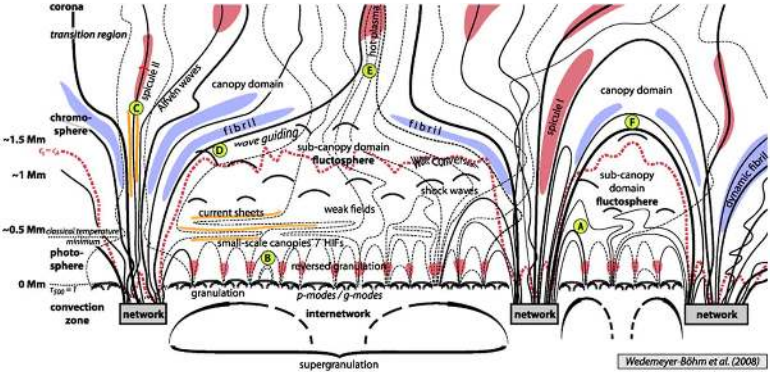

Figure 1.2: Schematic picture by Wedemeyer-Böhm et al. (2009) of the lower solar atmosphere (focusing on the quiet Sun), from the convection zone to the low corona, displaying roughly the locations in height for various processes. The solid thick lines and dotted lines extending from the network regions in the photosphere are magnetic field lines. As shown in red and blue patches, the gas is constrained to follow the magnetic field in the upper chromosphere and corona, creating fibrillar structure such as fibrils and spicules. Some MHD waves such as slow waves also follow the magnetic field lines, while fast waves can travel across field lines. Sound waves are ubiquitously produced by the constant granulation, and mostly heat the lower chromosphere due to their very fast dissipation with height. Dense structures such as loops define the region known as the 'magnetic canopy' and can serve as waveguides for MHD waves such as kink modes and sausage modes. The Alfvén wave travels along surfaces of constant magnetic field and are torsional (azimuthal) in dense structures. The red-dotted line in the figure denotes the hypothetical location for the $\beta = 1$ region (where linear mode conversion approximately takes place).

excitation of the elements, leaving the average temperature of the gas relatively constant with height. A photon in such a gas travels a long distance before interacting, making the radiative processes non-local (a state known as non-LTE). Furthermore, the transition from a $\beta > 1$ to a $\beta < 1$ gas implies an increasingly important role of the magnetic field in the (thermo-) dynamics of the gas, allowing wave conversion processes and hence energy conversion between magnetic, kinetic and thermal forms. The partial ionization state of the gas implies the coexistence of ions, electrons and neutrals, a situation which in some cases requires a multi-fluid approach and leads to more exotic (beyond MHD) phenomena such as Landau damping and ambipolar diffusion. In such cases electric fields become important (specially at small spatial scales), which creates current sheets that through anomalous resistivity can lead to significant ohmic dissipation via magnetic reconnection processes. The small spatial and temporal scales involved in all these physical processes complicates the problem substantially, making the chromosphere perhaps the most poorly understood layer in the solar surface. Even when assuming only MHD (a one fluid approach) correct numerical modeling of this region involves solving the population rate equations for the most important elements (H, He, Ca, Mg, Na) together with detailed non-LTE radiative transfer coupled with the 3D MHD equations of mass, momentum, energy and charge conservation, a task that only recently is being achieved (Gudiksen et al. 2011).

The importance of the magnetic field in the chromosphere can be clearly seen when comparing images obtained at different spectral offsets from the line core for a chromospheric line such as Hα. An example of this is shown in Fig. 1.1, where images at 3 different wavelengths from the wing to the core of Hα are displayed, taken with CRISP of *SST*. Different parts of the line are formed at different atmospheric heights, and by changing the wavelength position from the wing towards line center we observe higher atmospheric layers. In the figure, the upper panel corresponds to the photosphere, while the lower panel corresponds to the chromosphere. Notice the appearance of fibrillar structure as we go to upper layers, revealing the increasing dominance of the magnetic field on the gas dynamics. Solar physicists have defined a zoo of different observable structures, especially in the chromosphere. Fibrils, spicules, straws and swirls are some examples (Beckers 1972; Suematsu et al. 1995; Hansteen et al. 2006; Rutten 2006; De Pontieu et al. 2007a; Wedemeyer-Böhm & Rouppe van der Voort 2009; Rouppe van der Voort et al. 2009). Some of these structures and processes are sketched according to their average location in height in Fig. 1.2 (Wedemeyer-Böhm et al. 2009).

In the upper chromosphere the magnetic field has already expanded to fill most of the solar atmosphere. Both closed and 'open' (closing at 'infinity') magnetic field lines can be found, depending on the height (more closed field lines are found at lower heights), but also depending on the region in the Sun (coronal holes, as the name indicates, have more open magnetic field lines than quiet Sun regions or active regions). The expansion of the magnetic field and the increasing dominance over the gas pressure ($\beta < 1$ region) also defines what is called as the ‘magnetic canopy’, a region that has special relevance for wave heating mechanisms. Such regions are thought to define good waveguides due to the higher densities with respect to the ambient corona. A schematic picture of the location with height of diverse structure in the lower solar atmosphere is shown in Fig. 1.2.

1.1.3 The transition region and corona

Higher up, about 2 Mm from the solar surface, starts a region which is characterized by its very low density and very high temperature, with rough ranges between $10^8 - 10^9$ cm^{-3} and $1 - 5 \times 10^6$ K, respectively. This region is known as the corona, which means ‘crown’ in latin due to its shape when observed during solar eclipses. The drastic change of density and temperature as compared to the chromospheric values happens over a region known as the transition region, and corresponds to a very thin atmospheric layer of about 500 km in thickness. In these higher regions the gas is mostly magnetically dominated, a condition known as ‘frozen-in’ since it is not allowed to move freely in all directions but is constrained to the magnetic field structure ($\beta \ll 1$). In quiet Sun regions and active regions large structures known as coronal loops invade the atmosphere (spanning from 10 to several 100 Mm), a scenario that is shown in Fig. 1.

Apart from prominences and coronal rain (that we discuss below) most of the elements in the corona are completely ionized due to the high amounts of dissipated energy per particle. Considering that the gas in the corona is very tenuous (optically thin), the dominating excitation and de-excitation processes are, respectively, collision with thermal electrons and radiative decay. Radiative transfer in the corona is thus greatly simplified (known as the ‘coronal approximation’, this regime breaks down in solar flares, where very large energy dissipation takes place leading to temperatures above 10^7 K and electron number densities exceeding 10^{10} cm^{-3}). After most of the elements become fully ionized the excess energy cannot be radiated away, leading to an abrupt increase of the temperature and subsequent decrease in density and pressure, thus creating the transition region. The main mechanism through which the dissipation is achieved, its spatial and temporal characteristics, is currently unknown, and constitutes the famous coronal heating problem that is discussed in section 1.2.

1.1.4 Coronal rain and prominences

But not everything in the corona is hot. The structures observed at all heights in the solar atmosphere are very dynamic. A significant number of

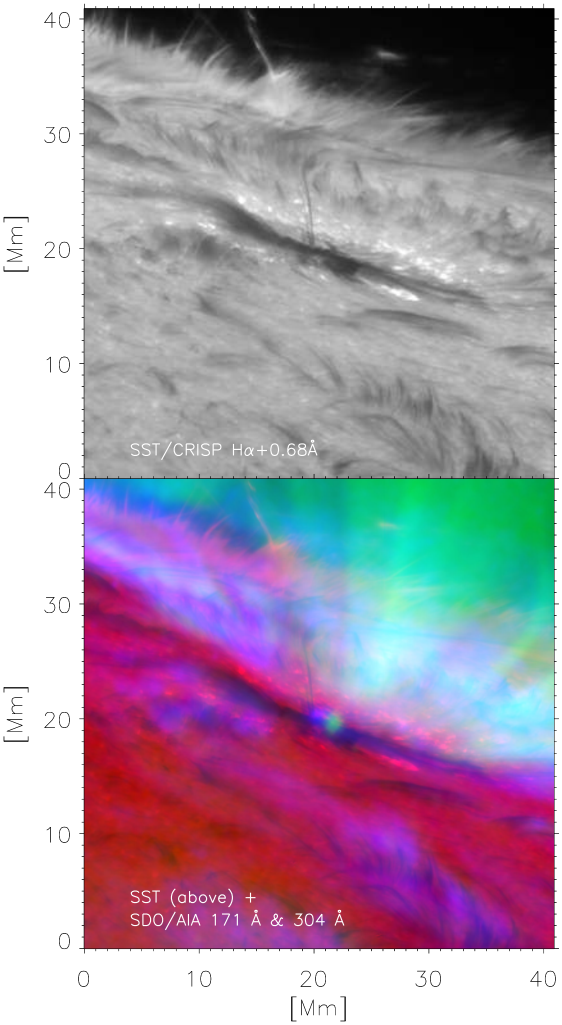

Figure 1.3: *Upper panel*: *SST*/CRISP observation of an active region at the east limb of the Sun on June 26, 2010. The image corresponds to an offset from Hα of 0.68 Å towards the red wing. Coronal rain can be observed as an elongated structure falling towards the sunspot along a loop-like path (bright in emission above the limb, and dark in absorption against the bright background). *Lower panel*: Composite color image obtained by co-aligning simultaneous observations by *SST* and *SDO*. Two images by *SDO*/AIA in the 171 Å (green) and 304 Å (blue) channels are added to the *SST* image above (red).

loops (as those observed in Fig. 1 in green), called coronal loops due to their big sizes, seem to be out of hydrostatic equilibrium (Aschwanden et al. 2001; Aschwanden 2001; Winebarger et al. 2003) and exhibit heating and cooling processes continuously, especially in active regions (Kjeldseth-Moe & Brekke 1998; Ugarte-Urra et al. 2006; Warren et al. 2007; Ugarte-Urra et al. 2009; Landi et al. 2009). Cool downflows along the legs of these loops are often reported in EUV lines (Foukal 1976, 1978; Schrijver 2001; O'Shea et al. 2007; Tripathi et al. 2009). When observing in cooler lines in active regions, such as with the *SDO*/AIA 304 Å channel (in red in Fig. 1, corresponding to an approximate temperature of 8×10^5 K) or even cooler chromospheric lines (around 10^4 K or lower), such as Hα, cooling events rapidly appear (in a timescale of minutes) as blob-like matter falling down from coronal heights along loop structures, a phenomenon known as coronal rain, which is the main focus of this thesis.

Coronal rain corresponds to matter and not flows (De Groof et al. 2004; de Groof et al. 2005), which catastrophically cools down following a local thermal instability in the corona (Mendoza-Briceño et al. 2005; Müller et al. 2003, 2004). The partially ionized material becomes dense due to a local pressure loss, thus appearing in chromospheric lines with an emission or absorption profile, depending on the brightness of the background (Schrijver 2001). In the upper panel of Fig. 1.3 an example of coronal rain in Hα observed with CRISP of the *SST* is shown. Here, coronal rain appears as an elongated and very fine structure (below 1 Mm in width) falling along a loop-like path rooted in the penumbra of the sunspot. In the lower panel, an alignment with *SDO* has been performed. Simultaneous observations with the AIA instrument in the 171 Å (shown in green) and 304 Å (blue) channels are plotted over the CRISP-Hα image (red). The green regions show the hot coronal plasma (coronal loops in the figure), blue regions show the upper chromosphere / lower transition region plasma, and the red regions show the chromospheric plasma. Although observed for more than 40 years (Kawaguchi 1970; Leroy 1972), coronal rain has so far been treated as a rather peculiar and sporadic phenomenon of active regions, attached to prominences (discussed below), and thus has not received particular attention. The advent of high resolution telescopes such as *Hinode*/SOT, *SST*/CRISP and *SDO*/AIA is revealing a scenario in which coronal rain seems to be more frequent than previously thought and has a more ubiquitous character, in agreement with the recurrent findings in EUV lines. In this thesis we show the large potential that this phenomenon beholds in the understanding of the coronal magnetic field and coronal heating.

Coronal loops are closed magnetic field lines filed with hot plasma that follow roughly a bipolar topology of the magnetic field. However, the magnetic field topology is far more complex than that of a magnet. As observed in Fig. 1, twisted, sheared, and inclined coronal loops can be observed. The magnetic field can also present more complicated shapes, for instance, they can present dips and helical structures which are thought to be responsible for sustaining dense clumps of matter over long periods of time (Kippenhahn & Schlüter 1957; Low & Hundhausen 1995). Such phenomena are called prominences (or filaments if observed on disc), and can exist both in active regions and in quiet Sun regions (with, however, different properties) over periods of days or even weeks. Apart from providing support against gravity through the Lorentz force, the magnetic field can also act as a thermal insulator, due to the very low cross-field transport coefficients. The partially ionized prominence material can thus be very cool (below 10^4 K) and long lived, and cross-field diffusion of neutrals may happen, possibly leading to ambipolar diffusion. Another scenario of prominences has also been proposed, in which the matter is continuously replaced through flows and thermal instabilities locally in the corona (Priest & Smith 1979; Tandberg-Hanssen 1995; Zirker et al. 1998; Karpen et al. 2001, 2005).

Both coronal rain and prominences are part of a phenomenon of thermal instability in plasmas (Field 1965). First applied to prominences (Parker 1953; Kleczek 1957), this phenomenon has also been suggested for being responsible of observed structure at larger scales: planetary nebulae (Zanstra 1955), spiral arms condensing out from the galactic halo (Spitzer 1956), condensation of interstellar clouds (Field 1962), filamentary structure in interstellar medium (Cox 1972). Numerical simulations in the last 30 years have largely contributed to the understanding of this phenomenon (Goldsmith 1971; Hildner 1974; Mok et al. 1990; Antiochos & Klimchuk 1991; Dahlburg et al. 1998; Antiochos et al. 1999; Mok et al. 2008). The thermal instability occurs when radiative cooling dominates over heating in some region. This can happen following a density perturbation (anything leading to an increase of the density, such as a shock wave) since the cooling increases faster than linearly with density. As a consequence, temperature and pressure drop in the perturbed region, accreting gas from the surroundings and forming an increasingly larger condensation. This cascading effect proceeds until heating and cooling balance again at some lower temperatures and higher densities (and when pressure balance is regained).

In the case of the solar corona, this thermal instability is known as ‘thermal non-equilibrium’ or also ‘catastrophic cooling’. High densities necessary for the instability onset are thought to be achieved through footpoint heating. The latter consists on having the heating concentrated towards the footpoints of coronal loops. In such a scenario, chromospheric evaporation together with direct mass injection into the corona from the heating events ensure a dense corona. Thermal conduction results insufficient in transporting enough energy to the dense corona, whose temperature is consequently reduced over time. At some point a critical state is reached in which any density perturbation (for instance, any shock wave traveling along the loop) is enough for triggering the thermal instability. The catastrophic cooling and condensation that ensues implies recombination of elements. The partially ionized clumps form and become visible in cool lines. Depending on the existing forces (gravity, magnetic and gas pressure gradients), the clumps either fall (coronal rain), or stay (prominences). Since the material can remain over long periods of time in the corona supported by the magnetic field, the element population can differ significantly between coronal rain and prominences, as well as the thermodynamics. It is thus important to distinguish both phenomena.

Solar flares also exhibit a phenomenon that is similar in appearance to coronal rain. Following the large energy release in the corona through magnetic reconnection, thermal conduction together with the energetic contribution through collisions of the accelerated non-thermal particles, the footpoints of post-flare loops are considerably heated. The chromospheric evaporation that follows creates high enough densities along the loops, a situation that is ideal for the onsetting of thermal instabilities in the corona (Parker 1953). Post-flare loops often exhibit catastrophic cooling and subsequent cool downflows observed in chromospheric lines, agreeing with the thermal instability scenario (Foukal 1978; Schmieder et al. 1995; Shimojo et al. 2002; Hara et al. 2006).

As one of the main problems in solar physics, and because of its importance in this thesis, it is interesting and instructive to know how the coronal heating problem came to be. Let us briefly review its history.

1.2 History of the coronal heating problem

Spectroscopic observations by Grotrian of the solar corona in the late 1930s revealed unusual absorption lines in the visible spectrum (Grotrian 1934). The mysterious transition lines were interpreted as belonging to an unknown element at the time which was then called ‘coronium’. Later, in the 1940s, the correct interpretation of the spectral lines discovered by Grotrian was put forward by Edlén showing that they corresponded to transitions of highly ionized iron (Edlén 1945), namely, Fe X and Fe XI. Rapidly, the discovery of further spectral lines of highly ionized elements followed (see Alfvén 1941, for an early review of the accumulating observational evidence). It was then realized that in order to reach such levels of ionization the gas in the corona had to be in a very hot permanent state, with temperatures above one million degrees Kelvin. However, the temperature of the underlying photosphere was known to be several hundred times lower, close to 6000 K. The huge discrepancy in temperatures came thus as a surprise in astronomy, giving birth to the coronal heating problem.

The corona is composed of a very tenuous gas (with a mean particle density of 10^8 cm^{-3}), and the energetic requirement for heating and maintaining the corona to the high million degree temperatures is estimated to be 10^5 erg cm^{-2} s^{-1} for quiet Sun regions and 10^6 erg cm^{-2} s^{-1} for active regions (Withbroe & Noyes 1977). This requirement is dwarfed by the radiative energy flux of the Sun ($\sim 5.4 \times 10^{10}$ erg cm^{-2} s^{-1}). Hence the energy reservoir is more than enough for our purposes. However, since the corona is so tenuous (optically thin plasma), after traveling through the photosphere and chromosphere most of the photons escape without interacting with the gas of the corona.

The problem then consists in finding a suitable mechanism which can carry enough energy through the lower layers of the solar atmosphere (photosphere and chromosphere) and dissipate it in the appropriate length and time scales in the corona. The dissipated energy must be enough to balance the energy losses in the corona, namely, optically thin radiation and thermal conduction (which acts as an energy redistribution mechanism taking energy out from the hot corona and pouring it into the cooler chromosphere along the magnetic field lines). The most important point, however, is that any proposed coronal heating mechanism must predict observational features that match observations (for a review of these facts see for instance Klimchuk 2006; Aschwanden et al. 2007).

For the last 70 years many heating mechanisms have been put forward in order to explain this fascinating problem. First theories were based on acoustic heating (Biermann 1946; Schwarzschild 1948), where acoustic waves are generated by convection. This mechanism was attractive since acoustic waves are easily generated by the solar granulation. Also, due to the high stratification in density of the solar atmosphere it was realized that waves would rapidly increase in amplitude, convert into shocks and heat the plasma. The acoustic wave energy fluxes were estimated at first to be sufficient to heat the chromosphere or atmosphere of non-magnetic stars (Stein & Nordlund 1991; Narain & Ulmschneider 1996; Fawzy et al. 2002). However, in the case of the Sun, it was soon realized that the energy budget from these waves was only enough for the lower chromosphere. Indeed, Athay & White (Athay & White 1978) pointed out that the observed broadening of lines in the chromospheric spectrum gave an upper limit to the amplitudes, and therefore to the energy flux of the waves available there, and this upper limit was below the energetic requirement for heating the upper chromosphere or the corona.

Around the same time of the theory of heating by acoustic waves a magnetic heating mechanism was proposed by Alfvén (1947). It was proposed that magnetic modes would carry the required energy to heat the corona. The propagation of such waves was then studied extensively (Ferraro 1954; Ferraro & Plumpton 1958; Osterbrock 1961), and was generally found that the energy flux from these waves was enough to supply the estimated heating. However the easy reflection and refraction of the fast magnetohydrodynamic (MHD) mode posed a problem for it to be accounted as a viable coronal heating agent. The slow MHD mode, being essentially the counterpart of the acoustic waves when traveling along magnetic fields, faced the same problems as for the non-magnetic counterpart. Focus was then put into the third MHD mode, the Alfvén mode, which was found to carry the required amounts of energy into the corona and not to suffer from reflection nor refraction. Alfvén wave heating rapidly became one of the leading candidates for heating the solar corona. Alfvén wave heating is further discussed in section 1.3.1.

The important role played by the magnetic field in the heating of the solar corona became apparent with the advent of high resolution solar telescopes since the days of the Skylab mission (1970s). Any simultaneous magnetogram and X-ray image of the Sun could then reveal the correlation between the strong magnetic field regions and high temperature regions in the solar atmosphere, suggesting a magnetic origin for the coronal heating mechanism. For the wave heating scenario this meant further support for MHD waves. Later, it was realized that the magnetic field topology of the solar corona was essentially closed (composed mostly of coronal loops, closed magnetic field structures). Arguing on the restricted cross-field transport coefficients (as compared to the field aligned direction) researchers concentrated mostly on the heating of loops as separate entities (one-dimensional loop modeling). Also, due to the different physical characteristics between the regions in the Sun (quiet Sun, active regions and coronal holes) the possibility of equally important but different heating mechanisms acting in each region was considered.

In his seminal paper, Parker (1988) suggested the other strong candidate of coronal heating. Due to the constant shuffling of the magnetic field from convective motions, the resulting build-up of magnetic stresses as non-potential free magnetic energy in the corona was suggested to be dissipated in discrete events uniformly distributed over the corona. These events are thought to be magnetic reconnection events in which the bulk of the dissipation takes place either through anomalously high resistivity (sweet-Parker model, Sweet 1958; Parker 1957) or through slow shocks in the reconnection region (Petschek model, Petschek 1964). Parker estimated the energy release in such event to be roughly 10^{24} erg, that is, 10^9 times smaller than that of a solar flare, thus giving rise to the 'nanoflare' concept. Since waves have also been shown to reproduce the bursty intensity profile characteristic of observed nanoflares in X-ray or EUV lines (Katsukawa & Tsuneta 2001; Krucker & Benz 1998; Parnell & Jupp 2000), this heating model is sometimes referred to as the nanoflare-reconnection model (Moriyasu et al. 2004; Antolin et al. 2008).

The heating mechanisms have been divided into two categories regarding the timescales in which they perturb the magnetic structures in which they act. On one hand we have AC heating mechanisms, in which the perturbation of the magnetic field is faster than the relaxation time of the structure $t_A = L/v_A$, where L is the size of the structure (a coronal loop for example) and v_A is the Alfvén velocity. Waves enter in this category (with appropriate dissipation mechanisms such as are resonant absorption, phase mixing, mode conversion, parametric decay or also through turbulence). On the other hand we have DC heating mechanisms, or stressing models, in which the perturbations caused on the magnetic structures are slow compared to the relaxation time t_A. In this case the coronal magnetic field lines become twisted, braided, shuffled around, or sheared and build up nonpotential free magnetic energy, which eventually becomes unstable and released by a magnetic reconnection process.

Recent 3D-MHD simulations with proper radiative transfer treatment are producing an impressively realistic model of the solar atmosphere (Gudiksen et al. 2011). Called Bifrost, the code is adapted to model a large section of the solar atmosphere, from a convective layer to the corona (the simulation box has a few tens of Mm in each direction). As initial condition a previously determined magnetic field is set (which can be potential), and after a few convective turn-over times the dissipation of magnetic field stresses through joule heating produces a large enough energy per particle that satisfactorily produce a chromosphere, transition region and corona. The obtained spatial and temporal line profiles for the most important elements seem to agree well with observations. 3D models such as Bifrost underline the fact that it is impossible to avoid the creation of a corona, due to the large magnetic field dissipation. However, it is not yet known how the dissipation occurs, on which spatial and time scales. While the heating seems to fall exponentially with height with a scale length similar to that of the magnetic field (in close resemblance to a footpoint heating scenario), more detailed spatial and temporal characteristics of the heating await. The knowledge of such would allow an assessment of the roles of AC and DC heating mechanisms.

1.3 Some heated debates in the solar physics community

1.3.1 On the look for Alfvén waves

New observations from polarimetric, spectroscopic and imaging instruments are revealing a corona permeated with waves. Compressive modes such as the slow and fast MHD modes have a long chapter in observational history (see reviews by Nakariakov & Verwichte 2005; Banerjee et al. 2007; Ruderman & Erdélyi 2009; Taroyan & Erdélyi 2009). Having magnetic tension as its restoring force, the 3rd MHD mode, the Alfvén wave, is less affected by the large transition region gradients with respect to the other modes. Also, when traveling along thin magnetic flux tubes they are cut-off free since they are not coupled to gravity (Musielak et al. 2007; Verth et al. 2010). Alfvén waves generated in the photosphere are thus able to carry sufficient energy into the corona to compensate the losses due to radiation and conduction, and, if given a suitable dissipation mechanism, heat the plasma to the high million degree coronal temperatures (Uchida & Kaburaki 1974; Wentzel 1974; Hollweg et al. 1982; Poedts et al. 1989; Ruderman et al. 1997; Kudoh & Shibata 1999) and power the solar wind (Suzuki & Inutsuka 2006; Cranmer et al. 2007; Matsumoto & Suzuki 2011).

Despite its importance in coronal heating, only recently, through the development of high resolution instruments, strong evidence for the existence of the Alfvén wave in the solar atmosphere is being obtained. However, in the majority of the observational reports of Alfvén waves ambiguity exists and clear distinction from other modes is difficult (De Pontieu et al. 2007b; Erdélyi & Fedun 2007). Using the Coronal Multi-Channel Polarimeter (*CoMP*) Tomczyk et al. (2007) analyzed properties of infrared coronal emission line Fe XIII (1074.7 nm) across a large field of view with short integration times. Waves propagating along magnetic field lines with ubiquitous quasi-periodic fluctuations in velocity with periods between 200 s and 400 s (power peak at 5-min) and negligible intensity variations were reported. Wavelengths and phase speeds were estimated to be higher than 250 Mm and 1 Mm s^{-1} respectively. In this work it was suggested that these waves were Alfvén waves probably being generated in the chromospheric network from mode conversion of p-modes propagating from the photosphere (hence explaining the peak in the power spectrum of the waves). On the other hand Van Doorsselaere et al. (2008) argued that an interpretation in terms of fast kink waves was more appropriate due mainly to the observed collective behavior which should be absent in the case of Alfvén waves. Being compressible waves it was argued that kink waves would appear however incompressible in the corona for an instrument such as *CoMP* due to the very small variation in intensity they produce.

The difficulty in detecting the Alfvén wave is due in part to its incompressible nature. Being only a transverse disturbance in the magnetic field, it is practically invisible to imaging instruments, unless the structure of propagation is displaced periodically from the line of sight (Williams 2004). Also, due to the large wavelengths (a few megameters) and short periods (a few minutes) that may be involved in the corona, a large field of view, short integration time and proper resolution are needed for their detection in the corona. With polarimeters and spectrographs, however, Alfvén waves are more easily detected. In the presence of a stable waveguide, these waves propagate as torsional disturbances of the magnetic field along iso-surfaces of the field (known as torsional Alfvén waves), causing a periodic and spatially dependent spectral line broadening (Zaqarashvili 2003). Using the Solar Optical Universal Polarimeter (SOUP) of the *SST*, Jess et al. (2009) report the detection of such waves.

As first described by Alfvén (Alfvén 1947), this wave holds its nature in the presence of an homogeneous medium. It is being argued that such ideal conditions do not exist in the corona and, although the restoring force would remain the magnetic tension, a coupling with other modes is inevitable. The pure Alfvén mode is thus expected to share its energy with other modes, such as the longitudinal slow and fast modes (Moriyasu et al. 2004; Antolin et al. 2008; Antolin & Shibata 2010) and also transverse 'trapped' MHD modes such as the kink mode (Pascoe et al. 2011), which would explain the historical ambiguity in the interpretation of such waves. Due to the mixed properties of the resulting wave, a new nomenclature has been suggested for its description. Termed 'Alfvénic', McIntosh et al. (2011) have reported their detection with the *SDO*/AIA instrument. Found to permeate the transition region and corona, these waves present enough energy to heat the quiet Sun corona and accelerate the fast solar wind.

The main problem faced by Alfvén wave heating is to find a suitable dissipation mechanism. Being basically an incompressible wave it must rely on a mechanism by which to convert the magnetic energy into heat. Several dissipation mechanisms have been proposed, such as parametric decay (Goldstein 1978; Terasawa et al. 1986), mode conversion (Hollweg et al. 1982; Kudoh & Shibata 1999; Moriyasu et al. 2004), phase mixing (Heyvaerts & Priest 1983; Ofman & Aschwanden 2002), or resonant absorption (Ionson 1978; Hollweg 1984; Poedts et al. 1989; Erdelyi & Goossens 1995). The main difficulty lies in dissipating sufficient amounts of energy in the correct time and space scales. For more discussion regarding this issue the reader can consult for instance Klimchuk (2006); Erdélyi & Ballai (2007) and Aschwanden (2004).

Due to the high densities (and therefore higher intensity contrast with respect to the surroundings), as is the case for spicules in the chromosphere, coronal rain and prominences offer easier direct wave detection possibilities in the corona. An example for transverse MHD waves in the case of prominences is provided by Okamoto et al. (2007) and Terradas et al. (2008). In this thesis it is shown that coronal seismology can be further performed with coronal rain (paper II). We also show that Alfvén waves can have a definite effect on thermal non-equilibrium, thus regulating the presence/absence of coronal rain (paper I).

1.3.2 Footpoint heating vs. uniformly distributed heating

Uniform heating in the corona is only achieved when energy losses, due to radiative cooling and thermal conduction, are balanced efficiently by the energy input. Famous analytical work by Rosner et al. (1978) showed that quasi-steady loops with this characteristic have their thermodynamic properties linked to their geometry by means of scaling laws (RTV scaling laws). This work further presented significant observational support for coronal loops being mostly uniformly heated along their lengths. Probably based on this and subsequent work, Parker (1988) suggested a corona heated by nanoflares uniformly distributed along braided and twisted coronal loops.

However, in the last 10 years, observational evidence not only for uniform heating (Priest et al. 1998) but also for footpoint heating (Aschwanden 2001) has been found, thus generating a debate in the solar physics community.

Footpoint heating in active region loops has received significant observational support in recent years. As stated previously, a significant number of loops is observed to be out of hydrostatic equilibrium (Aschwanden et al. 2001; Aschwanden 2001; Winebarger et al. 2003; Schmieder et al. 2004; Aschwanden et al. 2009), a state that is generally explained through footpoint heating. Similar interpretations have been made from findings of upflows that often appear correlated with nonthermal velocities at the footpoints of some active region loops (Doschek et al. 2007; Hara et al. 2008; Nishizuka & Hara 2011). Furthermore, Hansteen et al. (2010) and De Pontieu et al. (2011) have shown that a considerable part of the hot coronal plasma could be heated at low spicular heights, thus explaining the fading character of the ubiquitous type II spicules (Rutten 2006; De Pontieu et al. 2007a; Rouppe van der Voort et al. 2009). But perhaps one of the clearest evidences for footpoint heating is put forward by the presence of cool structures in the active region coronae, such as filaments/prominences and coronal rain, as explained in section 1.1.4.

A solution to this debate seems to lie on the fact that different families of coronal loops may exist in the Sun, as supported by recent studies of coronal loops (see for instance Ugarte-Urra et al. 2009). For instance, loops that are out of hydrostatic equilibrium seem to have in general temperatures below $2-3\times10^6$ K, and are thus denoted as warm loops. These show significant changes over relatively short timescales as compared to hotter loops, which, on the other hand appear to be uniformly heated. Cool loops, with transition region temperatures, define a third branch of loops. Different lifetimes, dynamics and thermodynamics properties define each of these groups (see the extensive review by Reale 2010).

It is not known, however, how much is footpoint heating important (and therefore the phenomenon of thermal non-equilibrium). On one hand, through one dimensional simulations of loops, considering both monolithic and multi-stranded scenarios (see section 1.3.3), Klimchuk et al. (2010) have shown that thermal non-equilibrium produces observables that do not seem to match observations (for instance, monolithic models end up with far too much intensity structure, while multi-strand models are either too structured or too long-lived). On the other hand, 3D-MHD models of an active region with a footpoint heating function leading to thermal non-equilibrium have provided satisfactory results (Mok et al. 2008). The resulting evolution of the light-curves, the variation of temperature along the loops, the density profile, and the absence of small scale structures in the intensity profiles are all compatible with real loops, thus supporting the thermal non-equilibrium scenario (Lionello et al. 2010).

Coronal rain, being a direct manifestation of thermal non-equilibrium (and therefore of footpoint heating), can help estimate the importance of this mechanism in the solar corona. Based on *TRACE* observations, Schrijver (2001) estimated the occurrence time of coronal rain in a coronal active region loop to be at most once every two days suggesting a sporadic character of coronal rain, and thus suggesting that thermal non-equilibrium may not play a significant role in coronal heating. However, these observations are constrained by the resolution of *TRACE* (1 arcsec at most), and thus can only show the tip of the iceberg. Observations of coronal rain with instruments such as the Solar Optical Telescope (SOT, Kosugi et al. 2007) on board of *Hinode* (Tsuneta et al. 2008b) or CRISP of the *SST*, which provide much higher spatial resolution (down to $0\farcs2$ arcsecs or below), can drastically change the statistics of coronal rain, as is shown in this thesis (paper III).

1.3.3 Multi-stranded vs. monolithic loops

Images of the corona obtained with *TRACE* or *SDO*/AIA (such as that of Fig. 1) show a corona permeated by loop-like structures. Since the field-aligned transport coefficients (such as the conductivity coefficient) are much larger than their cross-field counterparts, these coronal loops are often treated as separate entities with a specific magnetic flux and thermodynamic state, different from the surroundings. However, since the intensity is dependent on the density squared, only a small density difference is needed in order for these structures to appear as single isolated structures in the images. Furthermore, since the channels of such coronal instruments normally have very narrow temperature coverage, a multi-temperature loop would appear only partially in one channel. These facts can make the concept of coronal loops ill-defined. As discussed in the previous section, the concept of a loop as a waveguide can be controversial also because of the relatively short lifetimes of warm loops and fast apparent changes in their internal structure.

Due to the limiting spatial resolution of current coronal instruments (achieving a maximum resolution of roughly 1 arcsec), the internal structure of these entities is still under debate. Depending on the thermodynamic variables and magnetic field gradients such loops are either considered to be monolithic (if homogeneous across the main magnetic field axis) or multi-stranded (if heterogeneous), where the concept of a strand is defined as a single magnetic flux entity with no internal change in the cross-field direction). Since the magnetic field topology is especially essential for understanding the upper (low-β) solar atmosphere, the multi-strand vs. monolithic problem is then not only relevant for the wave community, but to all of solar physics.

On the other hand, chromospheric instruments such as *Hinode*/SOT or CRISP of the *SST* provide much higher spatial resolution. Since coronal rain is a chromospheric phenomenon occurring in the corona (and it is matter where the neutrals are strongly coupled to the ions, and therefore follow the magnetic field lines), its observation provides a unique insight into the coronal magnetic field structuring. This is one of the ideas exploited in this thesis (papers I, II and III).

Chapter 2

Results from the thesis

In this chapter a summary of the results of the thesis is provided. This is divided into 3 sections, where each section corresponds to a paper (in order). As explained in section 1.3, the subject of this thesis is to show the potential that coronal rain beholds in the understanding of the coronal magnetic field and the coronal heating problem.

2.1 List of included publications

- *Coronal rain as a marker for coronal heating mechanisms*
  Antolin, P., Shibata, K., Vissers, G.
  ApJ, 716, 154 (2010)

- *Transverse oscillations of loops with coronal rain observed by Hinode/Solar Optical Telescope*
  Antolin, P., Verwichte, E.
  ApJ, 736, 121 (2011)

- *Observing the fine structure of loops through high resolution spectroscopic observations of coronal rain with the CRISP instrument at the Swedish Solar Telescope*
  Antolin, P., Rouppe van der Voort, L.
  ApJ, 745, 152 (2012).

2.2 A marker for coronal heating mechanisms. Effects of Alfvén waves on the thermal stability of loops

In this paper we start by reporting very high resolution limb observations of coronal rain with *Hinode*/SOT in the Ca II H line. At this resolution coronal rain is observed to separate and elongate as it falls into strand-like structures. Statistics of the dynamics are obtained in which accelerations are in average lower than the effective gravity along loops, confirming earlier finds by De Groof et al. (2004); de Groof et al. (2005); Schrijver (2001) with coarser instruments. This implies that the structure and dynamics of the condensations are far more sensitive to the internal pressure changes in loops than to gravity.

We perform 1.5-D MHD numerical simulations including thermal conduction and radiative cooling (with an optically thick approximation for the lower atmosphere) of a loop where Alfvén waves are generated through random azimuthal motions at the footpoints, in close resemblance to convective processes (Matsumoto & Shibata 2010). The waves mode convert non-linearly to longitudinal modes (through wave-to-wave interaction, density fluctuations and deformation of the wave shape during propagation), that subsequently dissipate their energy in the corona through shock heating. The ensuing Alfvén wave heating has a characteristic uniformity in the corona, as has been shown previously (Moriyasu et al. 2004; Antolin et al. 2008). For instance, the resulting Alfvén wave heated coronae follow closely the RTV scaling law (Rosner et al. 1978, see section 1.3.2). The loop is also subject to small-scale discrete heating events artificially added at the footpoints of the loops (simulating for instance nanoflare-reconnection heating, see section 1.2), which easily trigger thermal non-equilibrium.

It is found that if a loop is predominantly heated from Alfvén waves, thermal non-equilibrium is inhibited due to the characteristic uniform heating they produce. Hence, coronal rain would not be generated in such loops. Coronal rain may then not only point to the spatial distribution of the heating in coronal loops but also to the agent of the heating itself. We thus propose coronal rain as a marker for coronal heating mechanisms.

2.3 A tool for coronal seismology of loops. Observations with *Hinode*/SOT

Observations of coronal rain at the limb in the Ca II H line with *Hinode*/SOT are performed. As coronal rain falls, the condensations separate and elongate, delineating the loop-like structure of a loop whose axis appears to be roughly aligned along the line of sight. By tracking down the rain several fine strand-like structures are observed, which exhibit in-phase transverse oscillations (with respect to the main loop axis) with periods between 100 s and 200 s, similar to those normally observed in prominences (Okamoto et al. 2007; Terradas et al. 2008). The amplitudes of the oscillations have ranges between 250 km and 500 km, and are observed to vary significantly with respect to the position along the loop, having a maximum at roughly halfway through one leg and minimums at both the apex and toward the footpoint of the leg. We interpret this result as a signature of a first harmonic of a standing transverse MHD wave in the loop, although an upward propagating wave is also a possible, but less likely, scenario. This interpretation implies a wavelength equal to the loops length, 80 ± 15 Mm.

Since this active region loop exhibits a catastrophic cooling event we expect the internal density to be significantly higher than that of the external corona for an interval of time long enough to create a waveguide along the loop. The obtained phase speeds of the waves are between 400 km s^{-1} and 1000 km s^{-1}, implying either a fast (horizontal) kink mode or a torsional Alfvén mode. The wide distribution of speeds found may be due to the possible uncertainties in the measurements, given the short time in which the loop can be observed. On the other hand, if the distribution in the phase speeds is real, it implies a loss of collective behavior which can be explained in terms of phase-mixing, present both in a scenario in which each strand has its own kink mode and in the scenario of a torsional Alfvén wave. The average coronal magnetic field inside the loop is estimated to be between 8 ± 2 G and 22 ± 7 G, in agreement with other estimates of coronal magnetic fields in active region loops through coronal seismology techniques (Nakariakov & Ofman 2001).

As the condensations fall they exhibit large distributions of velocities but rather concentrated accelerations around a much lower value than that of the average effective solar gravity along the loop, thus implying the presence of a different force. An estimate of the force imparted by the transverse MHD wave into the plasma gives values in accordance with the observed deceleration. Also, a rough estimate indicates an average plasma-β parameter of 0.1 in the condensation due to the high densities and strong shocks that are normally created by the thermal non-equilibrium mechanism. This would explain the often observed initial separation of the condensations, and can also be linked to the deceleration of the plasma.

2.4 A probe for the internal structure and local thermodynamic conditions in loops. Observations with *SST*/CRISP

In this work we present spectropolarimetric observations in Hα with CRISP of the *SST* of coronal rain above an active region at the limb of the Sun. The excellent quality of the data (close to the theoretical diffraction limit for the *SST* at the wavelength of Hα: $\lambda/D \simeq 0\overset{''}{.}14$) provides a unique picture of coronal rain in which it literally invades the entire field of view. On-disc blobs dark in absorption are also observed and shown to have the same dynamical, morphological and thermodynamical properties as the off-limb blobs, from which we conclude that it corresponds to the same phenomenon.

From the projected (on the plane of the sky) and Doppler velocities we are able to measure absolute velocities and accelerations, which, as in the previous studies, show values that are, respectively, significantly lower than free fall speeds and the effective gravity along loops. In some cases the condensations show strong decelerations near the footpoints, which is expected due to the higher atmospheric densities at chromospheric heights. The condensations present small but elongated cores of a few 100 km in width and lengths (along the path) of 700 km or so, stressing the need of high spatial (and temporal) resolution to fully observe coronal rain. The shapes are however non constant during their fall, but continuously change along the trajectories. The blobs further present average temperatures of 7000 K, and possibly even lower if turbulence and the Stark effect are important. Some evidence of progressive cooling over time was found, as suggested from previous work (de Groof et al. 2005; Schrijver 2001).

Through orders of magnitude estimates we show that the coronal rain observed in Hα is expected to come from a neutral Hydrogen population strongly coupled to the protons. At least on length scales on the order of the blob sizes (a few hundred km) no diffusion across the magnetic field is expected. Coronal rain can thus be considered as a tracer of the coronal magnetic field. Combining the projected (on the plane of the sky) and Doppler velocities we show that it is possible to retrieve the angles of fall of the blobs, allowing a reconstruction of the coronal magnetic field. No evidence for twisting or braiding of strands in loops is found, but we do not discard their existence at lower length scales (under 100 km), where turbulence may also be important. The tracing of strands by the blobs further suggest a constant area cross-section in the corona for these loops with no significant expansion down to chromospheric heights. The expected flux tube expansion may happen at lower (photospheric?) heights.

We further find that coronal rain occurs frequently in neighboring strands in a simultaneous way, forming groups of condensations which, if close enough together, are seen as large clumps. We term these sporadic events as ‘showers’, and they can have widths up to a few Mm. This is probably what has been observed in the past with instruments of lower spatial resolution such as *TRACE* and *SOHO*/EIT. Co-temporal *Hinode*/EIS observation in EUV lines of the same region does not show any trace of coronal rain, from which we suspect that loops with coronal rain are multi-thermal, as suggested previously by Schrijver (2001).

Our observations support the multi-stranded loop scenario and suggest that a significant fraction of strands in a loop do not have an independent thermodynamic evolution. Indeed, neighboring strands often display a coherent cooling (in the form of coronal rain) of a significant number of strands in a loop, suggesting a heating mechanism which acts in roughly the same way on neighboring strands. A footpoint heating mechanism imparting a similar heating scale height over all or part of the strands in a loop is a simple scenario that can explain the observations. Since we expect an expansion of the loops at low (possibly photospheric) heights spatially small heating events may suffice for such purpose.

The presented observations suggest that coronal rain may not be a sporadic phenomenon of active regions as previously thought, but a rather common phenomenon deeply linked to the heating mechanisms of coronal loops. We estimate the fraction of coronal volume with coronal rain to be between 7 % and 30 %. This is however strongly dependent on the magnetic field filling factor and on the projection effects. We further estimate the occurrence time of this phenomenon in a loop to be between 5 and 20 hours. Longer datasets with larger fields of view are needed to clearly answer the question on how common coronal rain is. The obtained mass drain rate in the form of coronal rain is roughly 5×10^9 g s^{-1} taking a mass density of 10^{-13} g cm^{-3} for the condensations. This number is on the same order of magnitude as the estimated mass flux into the corona from spicules (Beckers 1972), reinforcing the idea that coronal rain is an important phenomenon. This suggests a scenario in which the hot spicular material injected into the corona falls back cool, ‘raining’ down.

2.5 Other publications, conferences, workshops and schools

Refereed Journals

- *Predicting observational signatures of coronal heating by Alfvén waves and nanoflares* P. Antolin, K. Shibata, T. Kudoh, D. Shiota, D. Brooks, The Astrophysical Journal, Volume 688, 669-682 (2008)

- *The Role Of Torsional Alfvén Waves in Coronal Heating* P. Antolin, K. Shibata, The Astrophysical Journal, Volume 712, 494-510 (2010)

Proceedings

- *Predicting observational signatures of coronal heating by Alfvén waves and nanoflares* P. Antolin, K. Shibata, T. Kudoh, D. Shiota, D. Brooks, Proceedings of the International Astronomical Union, IAU Symposium, Volume 247, 279-287, ”Waves & Oscillations in the Solar Atmosphere: Heating and Magneto-Seismology” (2008).

- *Alfvén Wave and Nanoflare Reconnection Heating: How to Distinguish Them Observationally?* P. Antolin, K. Shibata, T. Kudoh, D. Shiota, D. Brooks, Proceedings of the Astronomical Society of the Pacific, ASP Conference Series, Volume 415, 247, "The Second Hinode Science Meeting: Beyond Discovery-Toward Understanding" (2009).

- *Signatures of Coronal Heating Mechanisms* P. Antolin, K. Shibata, T. Kudoh, D. Shiota, D. Brooks, Astrophysics and Space Science Proceedings, ISSN 1570-6591 (Print), pp. 277-280, "Magnetic Coupling between the Interior and Atmosphere of the Sun" (2010).
- *Implications for coronal heating from coronal rain* P. Antolin, K. Shibata, M. Carlsson, L. Rouppe van der Voort, G. Vissers, V. Hansteen. Scheduled for publication in ASP Conference Series, "The 3rd Hinode Science Meeting". (editors: Takashi Sekii, Tetsuya Watanabe and Takashi Sakurai).
- *A Sharp Look on Coronal Rain with Hinode/SOT and CRISP of SST* P. Antolin, M. Carlsson, L. Rouppe van der Voort, E. Verwichte, G. Vissers. Scheduled for publication in ASP Conference Series, "Hinode-4: Unsolved Problems and Recent Insights". (editors: L.R. Bellot Rubio, F. Reale, and M. Carlsson).

Conferences, Workshops and Schools
(O): Oral presentation
(P): Poster presentation

- *Some problems related to coronal heating.* P. Antolin, K. Shibata. Summer School in "Radiative Transfer and Numerical Magnetohydrodynamics", Institute of Theoretical Astrophysics, University of Oslo, Oslo - Norway, 19-29 June 2007. (O)
- *On the Frequency Distribution of Heating Events in Coronal Loops, simulating Observations with Hinode/XRT*, P. Antolin, K. Shibata, D. Shiota, D. Brooks, International Astronomical Union Symposium 247 "Waves & Oscillations in the Solar Atmosphere: Heating and Magneto-Seismology", Caracas - Venezuela, 17-22 September 2007. (O)
- *Coronal Rain as an Indicator of Coronal Heating Mechanisms*, P. Antolin, K. Shibata, International CAWSES Symposium, Kyoto - Japan, 23-27 October 2007. (P)
- *Some indicators of coronal heating mechanisms: power law indexes and coronal rain.* P. Antolin, K. Shibata. Hinode Informal Workshop, Kyoto - Japan, 13 November 2007. (O)

- *An introduction to MULTI - a radiative transfer code-*, MULTI Workshop, National Astronomical Observatory of Japan, Mitaka - Japan, 27-28 February 2008. (O)
- Hinode data analysis - EIS -. P. Antolin, S. Kamio, S. Park, K. Lee, Y. Kim. Asian Solar Physics Winter School, National Astronomical Observatory of Japan, Mitaka - Japan, 4-7 March 2008. (O)
- *Predicting observational signatures of coronal heating by Alfvén waves and nanoflares*, P. Antolin, K. Shibata, T. Kudoh, D. Shiota, D. Brooks, Solar research from Hinode and outlook on Solar-C Science, Symposium, National Observatory of Japan, Mitaka - Japan, 17-18 March 2008. (P)
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Part II

Articles

Paper I

Coronal rain as a marker for coronal heating mechanisms
Antolin, P., Shibata, K., Vissers, G.
ApJ, 716, 154 (2010)

Paper II

Transverse oscillations of loops with coronal rain observed by Hinode/Solar Optical Telescope
Antolin, P., Verwichte, E.
ApJ, 736, 121 (2011)

Paper III

Observing the fine structure of loops through high resolution spectroscopic observations of coronal rain with the CRISP instrument at the Swedish Solar Telescope

Antolin, P., Rouppe van der Voort, L.

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