

RICE UNIVERSITY

**Impacts of Two-fluid Effects on Emission from
Impulsively Heated Solar Coronal Loops**

by

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ABSTRACT

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The coronal heating problem has puzzled physicists and astronomers for nearly a century. While the origin of these surprisingly high temperatures in the upper solar atmosphere is most certainly magnetic,

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Chapter 1

Introduction

Intro to the first chapter Give a nice history of solar observations and discuss current observing efforts as well as modeling efforts, but briefly; quickly move into atmosphere, corona

The Sun is the most important celestial body to life on Earth. For the last five billion years, it has provided the light by which humans observe the world around them and the heat to save the planet from the frigid temperatures of interplanetary space. Because of its proximity, the Sun provides astronomers an exclusive and unique look into how stars behave. By observing and understanding the Sun, one can make conclusions about other types of stars in our galaxy and the universe.

Perhaps no other consistent celestial event has attracted as much attention as the solar eclipse. Solar eclipses have been observed and recorded for thousands of years, with some reports dating back to the fourteenth century BC (Golub & Pasachoff, 2010). The recordings of ancient eclipses have been heavily studied. Chinese rock drawings dating back to the Han dynasty (approximately 1900 years ago) appear to show the moon completely obscuring the Sun. Additionally, some have even suggested the Aubrey holes that surround the Stonehenge site were used to track and predict both solar and lunar eclipses (Golub & Pasachoff, 2010). Though some claims of



Figure 1.1 : Total eclipse as seen from Svalbard, Norway on March 20, 2015. Open and closed loops in the highly-structured solar corona are clearly visible. Photo courtesy of Miloslav Druckmüller.

ancient eclipse studies are controversial, it suffices to say that humans have long sought to study and explain the behavior of the nearest star to Earth.

In particular, solar eclipses have captured the attention of artists for centuries. Cosmas Damian Asam, a Bavarian painter and architect active in the early eighteenth century, used images of solar eclipses in many of his works, including several frescoes and an altarpiece. Olson & Pasachoff (2007) discuss how Asam, a deeply religious artist, was commissioned several times to depict the vision of St. Gregory the Great, a Benedictine monk, as described in his work *Dialogues*.

One of these depictions, an altarpiece at a Benedictine monastery in Kladruby, Czech Republic (see Fig. 7 of Olson & Pasachoff (2007)), shows “the visionary globe surrounded by a glowing halo of yellow light that more closely resembles the solar

corona” (Olson & Pasachoff, 2007). An additional altarpiece at another monastery in Weltenburg, Germany shows a perhaps even more pronounced depiction of the solar corona during a total solar eclipse. Olson & Pasachoff (2007) note that, given his detailed depictions, Asam must have observed several solar eclipses as well as the solar corona, with these astronomical events profoundly impacting his depictions of supernatural events in his works. This is but one example of how solar eclipses and their consequential insight into the highly structured solar atmosphere, have shaped scientific and artistic discourse throughout history. maybe here need some info on observing instruments, SDO/AIA, Hinode, Yohkoh, TRACE, IRIS, Hi-C; talk of early observations probably easily transitions into discussion of more modern observations, understanding of the Sun/corona need some sort of wrap-up for this section

1.1 Structure of the Solar Atmosphere

This section will discuss the structure of the solar atmosphere including the different layers of the Sun and how they are connected. This will help to introduce the solar corona

Though the Sun can be easily seen from Earth, its dynamic and highly structured atmosphere is not observable with the naked eye, with the one exception being brief glimpses of the corona during an eclipse. The interior of the Sun is of course very complex and constitutes a very different regime of physics than that seen in the solar atmosphere. Thus, this work will be primarily limited to the upper solar atmosphere

with some discussion of the lower layers.

The solar atmosphere is often divided up into four separate regions: the photosphere, the chromosphere, the transition region, and the corona. Fig. 1.2(a) shows a cartoon of the different layers while Fig. 1.2(b) shows the density and temperature profiles of the atmosphere with each region labeled. The *photosphere* is what we typically refer to as the solar surface, with the actual surface located where the optical depth, τ , is equal to 1. This region also contains the lowest temperature on the Sun, approximately 4400 K, located about 525 km above the surface (Carroll & Ostlie, 2007). The photosphere is where the majority of the visibly (with the naked eye) observable photons originate.

The temperature minimum defines the top of the photosphere above which lies the *chromosphere*. As can be seen from Fig. 1.2(b), the density in the chromosphere is many orders of magnitude less than that of the photosphere and the temperature has increased from the minimum up to about 1×10^4 K. Though not visible with the naked eye, the chromosphere is highly structured. Structures such as spicules, tall columns of gas that extend high into the solar atmosphere thought to heavily impact the behavior of plasma in the corona (De Pontieu et al., 2011), originate in the photosphere as well as filaments, essentially spicules observed on-disk and plage, bright regions surrounding sunspots.

Next is the *transition region*, so called because of the steep temperature and density gradients (see Fig. 1.2(b)) that mark the transition between the chromo-

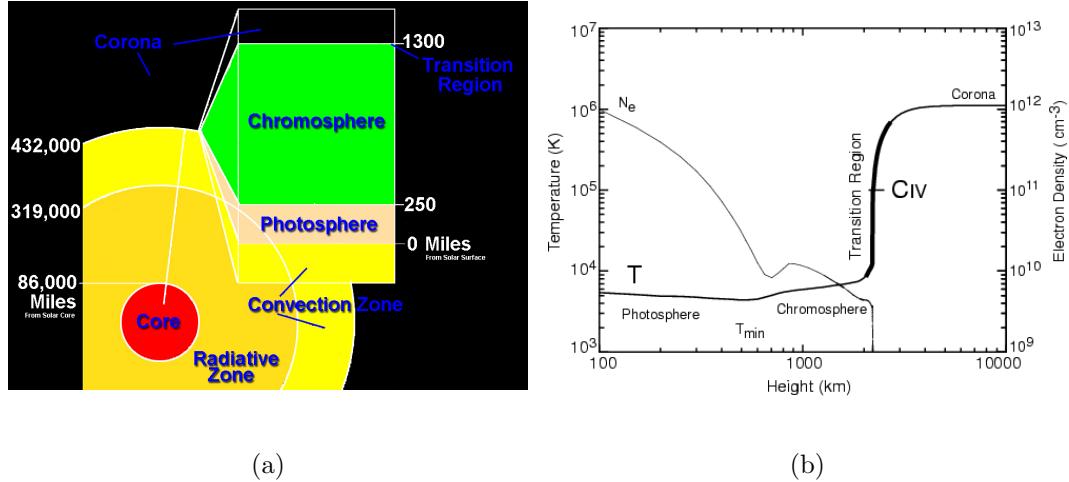


Figure 1.2 : Layers of the solar atmosphere (a)Courtesy of NASA (b) Taken from Gary et al. (2007)

sphere and the corona. The transition region is extremely thin, only a few hundred kilometers as compared to the chromosphere which extends over many thousands of kilometers. However, in this very short change in altitude, the temperature in the solar atmosphere jumps from $\approx 1 \times 10^4$ K to temperatures exceeding 1×10^5 K.

Finally, the solar *corona*, or “crown”, is the highly-dynamic uppermost layer of the Sun’s atmosphere. Visible with the naked eye only during a total solar eclipse (see Fig. 1.1), the corona is highly-structured and diffuse. Here, the temperature continues to increase, with typical coronal temperatures exceeding 1×10^6 K. Particularly high temperatures ($\approx 1 \times 10^7$ K) have also been observed in *active regions*, sites of intense magnetic activity associated with sunspots. These active regions can contain plasma as cool as 1×10^4 K as well and represent some of the most dynamic portions of the solar corona.

The work presented here will focus primarily on the plasma dynamics in the corona, in particular, in the cores of active regions where the intense magnetic field drives the motion of the plasma. In the following sections, we will discuss the origin of the solar magnetic field, its topology, how it impacts plasma in the solar corona, and finally how it connects to the anomalously high temperatures seen in the upper solar atmosphere.

1.2 The Solar Magnetic Field

touch on field origin (dynamo theory), discuss how the field gets tangled, formation of loops, drives behavior of the atmosphere, lead into discussion of coronal heating, low beta versus high beta

Because of the high temperatures that characterize both the solar atmosphere and interior, much of the gas that makes up the Sun is ionized; that is, each atom has been stripped of at least one of its electrons. This means that the Sun is filled by a sea of charged particles, or plasma. In the corona where temperatures are often higher than 1×10^6 K, even heavy elements such as Mg, Ca, and Fe are stripped of their electrons. Because these particles are charged, their motion is strongly dictated by both the electric and magnetic fields via the Lorentz force law. Thus, to understand the dynamics of the coronal plasma, one must first try to understand the magnetic field that ultimately controls it.

1.2.1 The Solar Dynamo and Flux Emergence

The Sun, like the Earth, possesses an intrinsic magnetic field, though its origin and dynamics constitute a largely unsolved problem. Additionally, unlike Earth, the solar magnetic field is highly dynamic and comparatively quite strong (up to 1000 G in sunspots as compared to the < 1 G field on Earth) (Aschwanden, 2006). From the earliest studies of magnetism, it has been known that a conductor moving through a magnetic field produces a current. This current then in turn produces an additional magnetic field. Treating the convection zone (below the photosphere) plasma as the conductor and assuming some preexisting, but small magnetic field leads to what is commonly known as *dynamo theory* (Golub & Pasachoff, 2010).

Dynamo theory seeks to show self-consistently how the interaction between the Sun's hot plasma and some small initial field leads to the observed complicated topologies and field strengths. Modeling such a system is no easy task as the interactions between the field and the plasma are highly non-linear, meaning solving the so-called “dynamo equations” requires a significant amount of computational effort. But how does this field affect the plasma dynamics of the corona? The solar magnetic field is said to be *frozen in* to the solar plasma; that is, the field moves with the plasma. Since the Sun is not solid, it undergoes *differential rotation*, meaning that different latitudes are spinning at different rates. Since the field follows the motion of the plasma, this causes the normally dipolar (north-south aligned) field to have an east-west component. This amplified and twisted field is then carried up to the pho-

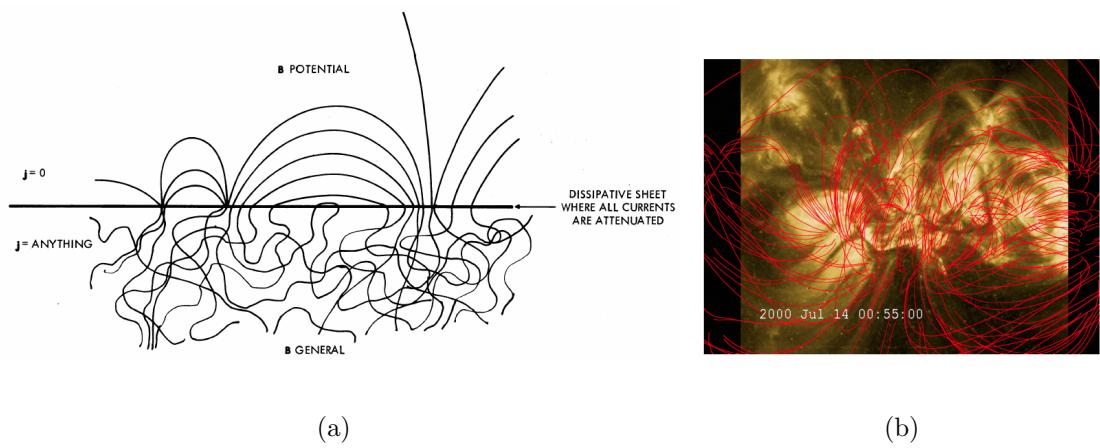


Figure 1.3 : (a) Flux emergence from twisted and tangled field below the photosphere yields loop structures that stretch high into the solar atmosphere. Taken from Gold (1964). (b) The coronal magnetic field topology is extremely complex, making determinations of coronal plasma dynamics difficult. Shown here is a magnetic field extrapolation constructed from an optical magnetogram. An image from the TRACE satellite is superimposed to show the loop structures. Taken from Reale (2010).

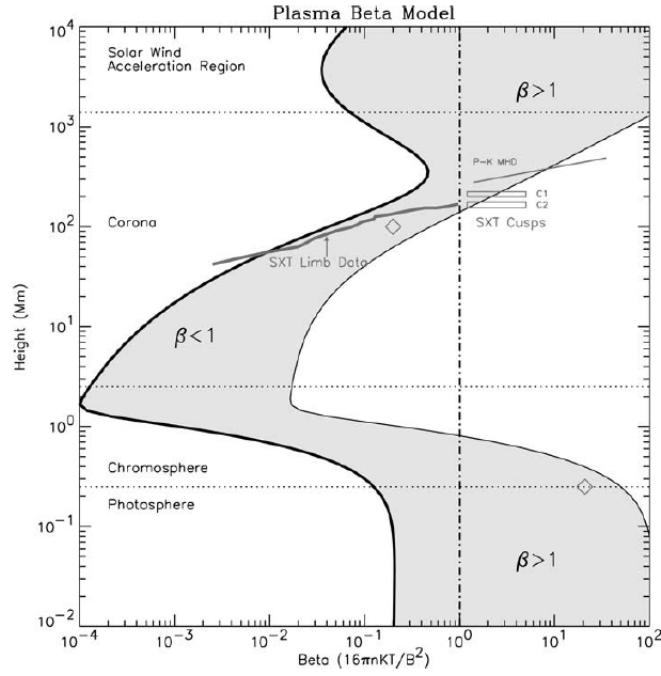


Figure 1.4 : Taken from Gary (2001).

tosphere by magnetic buoyancy, an idea first proposed by (Parker, 1955), resulting in dipolar loop-like structures poking through the solar atmosphere (see Fig. 1.3(a)). This phenomenon, commonly referred to as magnetic flux emergence, is by no means a solved problem and is a continuing topic of research (see Cheung & Isobe, 2014). Finding out how the solar magnetic field is generated and how it makes its way to the upper atmosphere will undoubtedly help to explain much of the observed plasma dynamics in the corona.

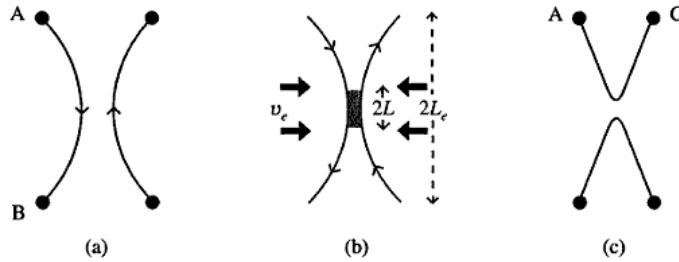


Figure 1.5 : Cartoon showing basics of reconnection process. Image taken from Priest & Forbes (2000).

1.2.2 Magnetic Reconnection

After the magnetic field is forced into the solar atmosphere by the buoyant motion of the convective zone, it remains rooted in the photosphere, whether it is an *open* (flux tube extends radially outward, possibly connecting with the interplanetary magnetic field) or *closed* (both ends attached to the solar surface) field line. Because the field is *line-tied*, or frozen into the photospheric plasma, the turbulent motion of the photosphere deforms and stresses the overlying field, leading to the storage of magnetic energy. This motion can eventually lead to a topological restructuring of the magnetic field as it relaxes from a stressed to an equilibrium state, a process popularly known as *magnetic reconnection*.

Magnetic reconnection is thought to be a dominant process in a variety of space and astrophysical plasma environments, including Earth's magnetosphere, solar flares, and accretion disks. Additionally, reconnection has also been observed in laboratory settings such as the tokamak and the reversed field pinch (Priest & Forbes, 2000). It is

also thought to be the primary driver of several proposed coronal heating mechanisms (see §1.3.2). The basic idea behind reconnection is illustrated in Fig. 1.5.

Fortunately, we can still learn something about the corona without completely solving the problem of the origin of the driving magnetic field. The corona constitutes what is commonly referred to as a “low-beta plasma” such that $\beta = p_{\text{thermal}}/(B^2 8\pi)$, the ratio between the gas pressure and magnetic pressure, is $\beta < 1$ (see Fig. 1.4). This means that coronal magnetic field acts as a guide for the plasma, with the flow directed primarily in the field direction with negligible cross-field motion. A useful analogy is that of water flowing through a pipe: the rigid pipe directs the flow of the water, but has no affect on the underlying fluid dynamics. Provided the field is reasonably stable and the relevant fluid equations are parameterized in terms of the field-aligned coordinate, our equations governing the plasma dynamics need not include the field at all!

Talk about drawbacks, mention MHD and hydrodynamic and hydrostatic; lead into coronal heating conversation; not sure if this is actually needed here...

1.3 The Coronal Heating Problem

Thus, far we have not addressed the important question of why the solar corona is so much hotter than the surface. From an intuitive, thermodynamic perspective, we would expect the atmospheric temperature to decrease as we moved away from the surface. However, nearly 70 years of observations have shown this is not the case

and these anomalously high temperatures, dubbed the “coronal heating problem,” continue to baffle solar physicists today.

The discovery of the $> 1 \times 10^6$ K corona was made over the course of nearly fifty years through many laborious spectroscopic observations. Spectroscopic measurements during the late-nineteenth and early twentieth centuries of solar eclipses and images obtained from coronagraphs yielded a surprising result: an unknown line at 5303 Å , dubbed the “coronal green line” (Golub & Pasachoff, 2010). Because the line could not be associated with any known element, the line was identified as a new element, “coronium”. Later, more detailed examinations of the coronal spectrum revealed several more unidentifiable spectral lines. Grotrian (1939) showed that many of these lines were due to highly ionized states of heavy elements such as iron and calcium. Additionally, Edlén (1943) identified four additional coronal lines, Fe X, Fe XI, Ca XII, and Ca XIII, providing more evidence for the presence of highly-ionized atoms in the corona and implying temperatures in excess of 1×10^6 K. Because of their work in coronal spectroscopy, Grotrian (1939) and Edlén (1943) are generally credited with the discovery of the million-degree solar corona. However, some (see Peter & Dwivedi, 2014) have argued that early coronal spectroscopists did not imply a million-degree corona and that it was in fact Nobel laureate Hannes Alfvén, in Alfvén (1941), who first proposed a hot corona, even arguing that it was the interaction between the magnetic field and the charged particles in the solar atmosphere that thwarted our usual thermodynamic intuition.

While these early spectroscopic observations are now better understood and a multitude of satellite observations have allowed a much clearer picture of the solar atmosphere, the exact mechanism responsible for the million-degree corona remains unknown. This is certainly not for lack of effort; over the last several decades, many different heating mechanisms have been proposed. These are traditionally divided into two-separate categories: *AC*, mechanisms that rely on waves to transfer energy from the lower atmosphere into the corona and *DC*, mechanisms that involve dissipation of energy stored in the stressed magnetic field. In order to be successful, a given mechanism must be able to explain the energy source of the heating, how the energy is converted to heat, how the plasma responds and accurately predict any observables from the resulting plasma emission (see Fig. 1 in Klimchuk, 2006).

1.3.1 AC Heating

The same turbulent sub-photospheric motions that stress the magnetic field can also generate waves capable of propagating into the upper solar atmosphere. The AC- or DC-type heating classification depends on the timescale of the stressing motion: if it is longer than a characteristic crossing time of the coronal structure, it is classified as DC heating. If the timescale is shorter than a crossing time, it is classified as AC heating. A variety of wave modes have been observed in both the open and closed corona, including acoustic waves, Alfvén waves, and slow- and fast-mode MHD waves (Aschwanden, 2006). However, the simple existence of these waves is not enough to

make them a viable candidate for coronal heating; they must be able to propagate into the corona with an adequate amount of energy and then efficiently dissipate this energy in order to heat the coronal plasma. For example, acoustic waves are capable of carrying an adequate amount of energy to heat the corona, but are almost entirely reflected by the steep density gradients in the transition region. Alfvén waves may also be capable of carrying enough energy to heat the corona, but specific frequencies are required to avoid reflection at the transition region. These particular modes have also been found to be non-dissipative under coronal conditions, making it hard for these waves to actually heat the corona even if they make it to the upper atmosphere (Klimchuk, 2006). Wave modes generated in the corona would of course overcome the problem of crossing the transition region boundary. However, while oscillations in the corona have been observed (De Moortel et al., 2002b,a), the properties of these waves have not been measured precisely enough to say whether or not they are capable of heating the corona (Klimchuk, 2006).

1.3.2 DC Heating

As discussed in §1.2, the magnetic field that extends into the corona is rooted in the photosphere. Because of the underlying convection zone, the footpoints of these magnetic loops are subject to a turbulent velocity field and thus undergo a random walk across the surface. The turbulent motion of the footpoints causes the overlying loops to become twisted and braided around each other, leading to a highly stressed

magnetic field above the solar surface. Gold (1964) first proposed the idea of a twisted field created by photospheric footpoint motions, suggesting that it was the relaxation of the stressed field to its equilibrium (or force-free) state that provided the energy release mechanism needed to power flares. Parker (1983a,b) applied this same concept to the corona and showed analytically that closely-packed magnetic flux tubes are subject to “dynamical nonequilibrium and reconnection” and that such a configuration easily leads to braided and twisted field lines with enough free energy to power the corona. Fig. 1.6(a) shows a cartoon of Parker’s braided field lines.

While Gold (1964); Parker (1983a,b) included few comparisons to observations (mainly due to the lack of high-resolution instruments of the day), observations from the recently-launched High Resolution Coronal Imager (*Hi-C*) seem to support the idea of magnetic braiding. Cirtain et al. (2013) report two observations, in particular, from the *Hi-C* instrument that show braided magnetic fields, supporting the idea of a DC heating mechanism. Something here about Hi-C resolution maybe

This concept of braided and twisted fields illustrates the basic idea behind DC heating: energy is allowed to build up over time, most likely in the braided and twisted magnetic field as stressed by the turbulent footpoint motions, and then released, most likely through reconnection, as the field relaxes to a near-potential state. Parker expanded on his early coronal heating theory with the now-seminal (Parker, 1988) in which he proposed that the 2-3 MK temperatures and 10^7 ergs cm^{-2} s^{-1} observed coronal energy input (Withbroe & Noyes, 1977) could be explained by many small,

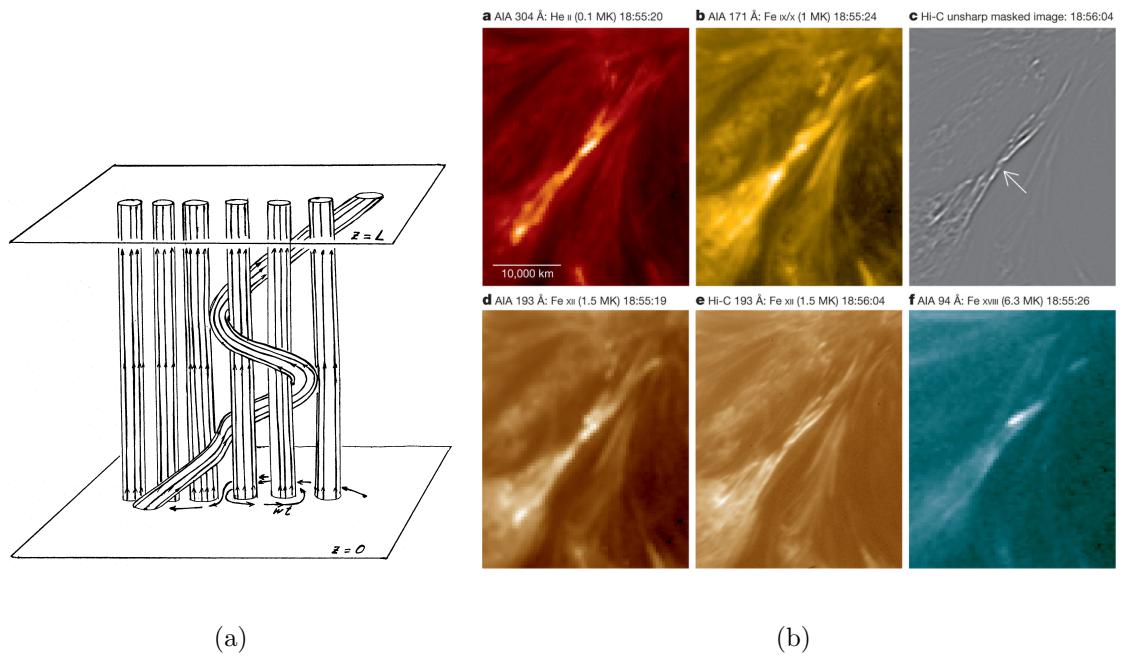


Figure 1.6 : **(a)** Cartoon showing braided flux tubes rooted, or line-tied, to the solar surface. Braiding allows for the build-up and relaxation of the field, providing an energy release mechanism capable of heating the solar corona. Taken from Parker (1983b). **(b)** Image from the *Hi-C* sounding rocket mission showing spatially-resolved braided flux tubes in the solar corona. Image taken from Cirtain et al. (2013).

impulsive bursts of energy that he called *nanoflares*. These nanoflares are caused by the many tangential discontinuities that arise in the complex coronal magnetic field, leading to magnetic reconnection and the subsequent dissipation of the mechanical energy stored in the field by the random footpoint motions.

For the field, B , to become twisted and braided, the footpoints of the loop must have some transverse (with respect to the opposite footpoint, see Fig. 1.6(a)) velocity, v and thus a transverse field component, B_{\perp} . It can be shown that the work done on the field, W , by the footpoint motion is $W \propto vB_{\perp}B$, such that for $v = 0.5 \text{ km S}^{-1}$ and $B = 10^2 \text{ G}$, $W \approx 10^7 \text{ ergs cm}^{-2} \text{ s}^{-1}$, the observed value, when $\theta = \arctan B_{\perp}/B \approx 14^\circ$ (Parker, 1988). Using appropriate length scales, the energy per nanoflare event can be estimated as 10^{24} ergs , or about one-billionth of the energy of a typical flare. Thus, once $\theta = 14^\circ$, reconnection dissipates the stored energy and the field relaxes to equilibrium until it is wound up again by the footpoint motions, resulting in “bursty” energy release with the timescale and energy ultimately determined by the underlying velocity field and dissipation mechanism.

The Parker nanoflare concept has become one of the most favored and contentious coronal heating models (Cargill, 1994; Cargill & Klimchuk, 2004; Klimchuk, 2006). While many theoretical (e.g. Bradshaw et al., 2012; Reep et al., 2013) efforts have shown the feasibility of nanoflares, the idea has long suffered from a lack observational evidence, though recent high-resolution and high-cadence observations (Testa et al., 2013; Brosius et al., 2014; Testa et al., 2014) have provided encouraging results. The

term *nanoflare* has now become synonymous with impulsive heating in the energy range $10^{24} - 10^{27}$ ergs, with no specific assumption as to what underlying physical mechanism is responsible for this heating. Thus, in this work, the term nanoflare will refer to bursty energy release on a timescale of approximately 100 s or less.

1.4 Summary

End with outline of the rest of the thesis: in ch. such and such we will discuss such and such

Chapter 2

Coronal Loops

This chapter will discuss the discrete nature of corona in terms of coronal loop structures Need a section on general plasma dynamics of loops to discuss energy transfer/loss/gain through heating/enthalpy/radiation/draining/filling Also discuss general structure and how they are formed Give some general characteristics about them like length, temperature, density, through what layers they extend etc. Show nice schematic The solar corona is typically described in terms of discrete structures known as coronal loops. Heated

2.1 Observations

Discuss some observations of loops and what has been learned about them, what constraints, multi-stranded versus single stranded Show some pretty pictures

2.2 Modeling

Discuss modeling approaches, hydrodynamics versus magnetohydrodynamics, etc.

Chapter 3

Emission Diagnostics

This chapter will discuss emission measure (EM), differential EM (DEM), line intensities etc. and how they are interpreted in observational and modeling contexts

Discuss how this is how we know anything about plasma in the solar atmosphere Can discuss forward modeling as well; this sets us up for the rest of the thesis

Chapter 4

Numerical Modeling

This chapter will outline our numerical approach to studying the solar corona

Often, the full 3D magnetohydrodynamic (MHD) equations are used when modeling loops in the solar corona. However, such treatments are computationally expensive and are prohibitive when studies of large parameter spaces are needed. Instead, the one-dimensional (1D) hydrodynamic equations are used to model plasma dynamics in coronal loops. These hydrodynamic equations do not include the magnetic field B . This is because the corona These equations are parameterized in terms of time, t , and the field-aligned coordinate, s .

4.1 One-dimensional Hydrodynamics

List the 1D hydrodynamic equations and briefly discuss their origin (i.e. how they were derived) and how they differ from MHD approach Include plasma β justification of why we don't include the magnetic field

The single-fluid 1D hydrodynamic equations are given by,

$$\frac{\partial \rho}{\partial t} = -\frac{\partial(\rho v)}{\partial s} \quad (4.1)$$

$$\frac{\partial(\rho v)}{\partial t} = -\frac{\partial(\rho v^2)}{\partial s} - \frac{\partial(p)}{\partial s} + \frac{\partial}{\partial s} \left(\frac{4}{3} \mu \frac{\partial v}{\partial s} \right) + \rho g_{\parallel} \quad (4.2)$$

$$\frac{\partial E}{\partial t} = -\frac{\partial}{\partial s} ((E + p)v) - \frac{\partial F}{\partial s} + E_H - E_R + \rho g_{\parallel} v, \quad (4.3)$$

where

$$E = \frac{1}{\gamma - 1} p + \frac{1}{2} \rho v^2. \quad (4.4)$$

s and t are the field-aligned spatial coordinate and time, respectively, $\rho = mn$ is the mass density, v is the bulk velocity, μ is the viscosity coefficient and g_{\parallel} is the component of gravitational acceleration parallel to s , E is the energy density and $p = 2nk_B T$ is the pressure subject to closure by the ideal gas law.

Additionally, we also have three terms that are specific to energy balance in a coronal loop: the heat flux $F = \kappa_0 T^{5/2} \partial T / \partial s$, typically given by the classical Spitzer-Harm expression, the ad-hoc heating term E_H , and the volumetric radiative loss term $E_R = n^2 \Lambda(T)$, where $\Lambda(T)$ is the radiative loss function. Emphasize terms that are “non-standard” hydrodynamic terms (e.g. radiation, heat flux, ad-hoc heating, enthalpy transfer) Bring up HYDRAD model and discuss speed limitations

4.2 The EBTEL Model

When using hydrodynamic simulations to study coronal loops, it is often best to compare computed observables with observations in order to make constraints on

loop properties. To do this, one must explore a very large parameter space of initial conditions (e.g. loop length, heating frequency, power-law index, etc.). Though the 1D hydrodynamic equations have been shown to accurately model coronal loops,

Derive the EBTEL equations from the 1D hydrodynamic equations and discuss the physics behind the EBTEL model; what physics is left out? what physical insight can we still gain from this model? Say why EBTEL is important (i.e. large parameter sweeps that can't be done with HYDRAD) Discuss 0D nature, maybe include discussion of previous 0D models and why EBTEL is better Show comparisons between EBTEL and HYDRAD

4.3 The Two-fluid EBTEL Model

Discuss importance of two-fluid effects in hydrodynamic models of the solar corona; include some quick calculations to show how electron and ion fluids can become de-coupled Derive two-fluid EBTEL equations from 1D hydrodynamic equations Show several comparisons between HYDRAD and two-fluid EBTEL to justify its use in this study remember to show EM calculation, justification, how EBTEL treats DEM as opposed to HYDRAD Briefly detail solver(s) used, adaptive timestep, why this is necessary, etc. If there is time, discuss speed comparison between EBTEL and HYDRAD

Chapter 5

Results

This chapter will include the results of our numerical study. Here we will also describe how the study was performed and what tools were used to perform the study. It is best not to introduce any new tools here; just pool from those that have already been discussed and show how they were applied. Show lots of plots and tables.

Chapter 6

Conclusions

This chapter will discuss the conclusions that we can draw based on the results in the results section. What do these results mean? What are the implications in the context of loops in active region cores? May include some topics for future work in this section as well or just wait and put it in a different chapter

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