Solar Eruptive Events:

Coronal Dimming and a New CubeSat Mission

by

James Paul Mason

B.S., University of California at Santa Cruz, 2009

M.S., University of Colorado at Boulder, 2012

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

Department of Aerospace Engineering Sciences

2016

This thesis entitled:

Solar Eruptive Events:
Coronal Dimming and a New CubeSat Mission
written by James Paul Mason
has been approved for the Department of Aerospace Engineering Sciences

Dr. Thomas Woods

Prof. Xinlin Li

Prof. Scott Palo

Dr. Amir Caspi

Prof. Jeffrey Forbes

Date ________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Mason, James Paul (Ph.D., Aerospace Engineering Sciences)

Solar Eruptive Events:

Coronal Dimming and a New CubeSat Mission

Thesis directed by Dr. Thomas Woods

Often the abstract will be long enough to require more than one page, in which case the macro “\OnePageChapter” should *not* be used.

But this one isn’t, so it should.

Dedication

To my late father, who inspired me from an early age to come this far.

Acknowledgements

First and foremost, my deepest thanks to Tom Woods. Through the projects he's introduced me to – in solar physics, in sounding rockets, and in small satellites – I've discovered a career path that excites me and that provides continuous opportunities to learn and contribute. Moreover, he's an excellent role model: dedicated and passionate about his work, patient with everyone without seeming to have to try, and exceptionally reliable. All of the above combined has made my time in graduate school likely to be, upon reflection long from now, one of the highlights of my life. Thank you to my committee for guidance and support, most of whom I've been fortunate to work with closely: Xinlin Li, Scott Palo, Amir Caspi, and Jeff Forbes. Finally, I couldn't have struggled through without the support of my peers, especially Allison Youngblood, whose work ethic inspires me and whom I've been extremely lucky to find. Oh, and my dog, Nessie, who requires three walks a day, has turned out to provide the periods of relaxation away from a screen that have aided in my ability to actually comprehend the work I'm doing.

Contents

Chapter

Tables

Table

Figures

Figure

Chapter 1

Introduction

- Solar eruptive events are rapid releases of energy on the Sun that are sometimes directed Earth-ward, making it important to understand them and to forecast their arrival time and magnitude of their impact

- Three basic types of eruptive event: flare, coronal mass ejection, energetic particles this dissertation focuses on the first two

- Some background about solar flare prediction provided in Chapter 2, including my own massive statistical study, which went to print in ApJ my first year of graduate school

- The relationship between coronal mass ejections and the void they leave behind in the solar corona is the primary topic of the dissertation and its discussion spans several chapters.

    * Chapter 3 discusses the various physical processes that can lead to an observation that may be interpreted as a dimming, and the amalgamation of related observations that can theoretically be used to identify and isolate each mechanism

    * Chapter 4 puts theory to the test in a detailed case study of a single, relatively simple, event. The aforementioned conglomeration of observations were used to determine that this was indeed a simple case with one dimming mechanism dominating the observation; that which theory says should be most strongly related to the associated CME

  * Chapter 5 expands the study of the relationship between dimming and CMEs by performing an analysis similar to that of the case study but for approximately 30 events. Thus, a tentative statistical correlation between dimming and CME parameterizations could be derived.

- The topic of solar flares is picked up again briefly in the science motivation for the solar CubeSat MinXSS. An overview of the mission is the topic of Chapter 6, which includes science motivation, system overview, and lessons learned.

- Chapter 7 delves deeper into the CubeSat engineering with a detailed thermal balance test and model analysis, culminating in the (likely) first ever tuned CubeSat thermal model that has been validated by dedicated testing and on-orbit measurements.

- Chapter 8 provides a summary of deliverables and results, and lays out plans for future work. The latter will be the first steps in my post-doc that has already been secured through my first grant being funded as well as SDO/EVE and MinXSS extended mission funding.

Chapter 2

Relevant Background

2.1 Brief Tour of the Sun

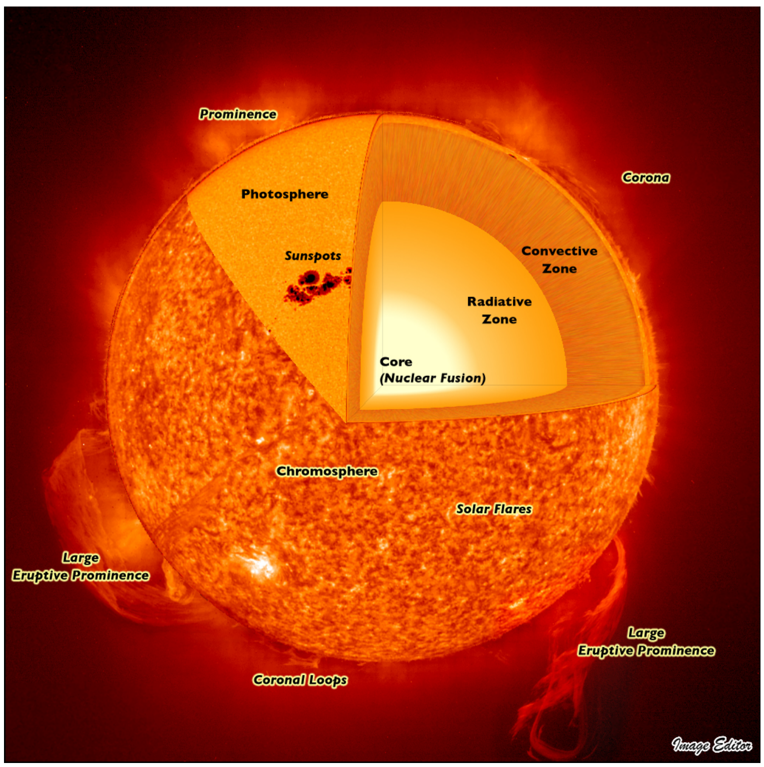


Figure 2.1: Sectional cutaway diagram of the sun to show basic structure. Figure courtesy of Image Editor on flickr

Figure 2.1 shows the basic structure of the sun. Nuclear fusion occurs in the core and produces high-energy photons that slowly travel outward through the radiative zone. In every imaginary spherical surface centered on the core, the net energy flux outward must be positive else the sun would explode. In the convection zone, the dominant form of heat transport becomes mass plasma motion that circulates hot matter upward where it cools and sinks back down. At the photosphere, the opacity drops rapidly and photons are free to fly. The undulating chromosphere lies just above the photosphere; it is vastly out-shined by the photosphere except in a few special wavelengths corresponding to dark absorption lines in the photosphere. The transition region is so named for the dramatic and unintuitive temperature increase from the chromosphere to the corona. Through the interior of the sun, the temperature and density steadily drop (see Figure 2.2) as one would expect from everyday experience, for example, temperature drops further from a campfire. Nevertheless, the transition region escalates the temperature, bringing the corona to 1 MK. Where the sun below and far above the corona are dominated by gas dynamics, the corona itself is dominated by magnetic fields. This trade-off is characterized by the β parameter:

$$\beta = \frac{p_{gas}}{p_{mag}} = \frac{n k_B T}{B^2/(2\mu_0)} \tag{2.1}$$

where p_{gas} is the pressure of a gas (or plasma in this case), p_{mag} is the magnetic pressure, n is the number density, k_B is Boltzmann's constant, T is temperature, B is the strength of the magnetic field, and μ_0 is the permeability of free space. When $\beta > 1$, normal gas pressure dominates and when $\beta < 1$, magnetic pressure dominates. The transition from $\beta > 1$ to $\beta < 1$ is an important one for understanding how vast amounts of energy can be stored in the solar atmosphere, providing the necessary power to drive solar eruptive events. β as a function of height above the photosphere is shown in Figure 2.3.

The following sections will step through each layer of the sun with descriptive detail proportional to their relevance to the work to be presented in later chapters.

2.1.1 Core

The gravitational pressure and density in the core of stars is sufficient to ignite nuclear fusion. In a main sequence star at the midpoint of its life, like the sun, the primary fusion reaction is the conversion of hydrogen to helium. The majority of the sun is made of hydrogen (see Figure 2.4) – a

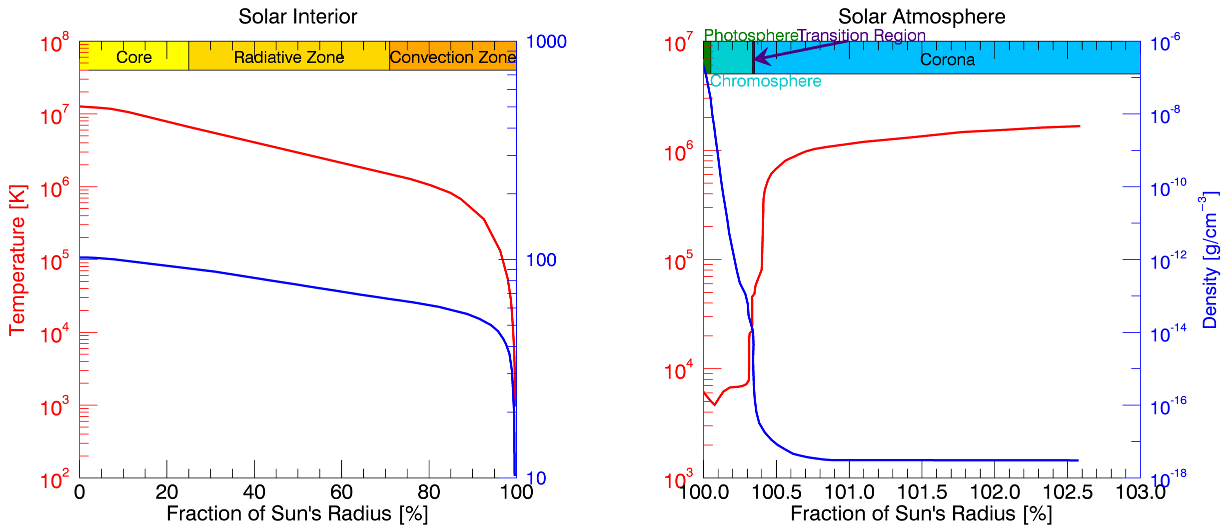


Figure 2.2: Solar temperature and density versus height from the core to the corona. Data adapted from various sources. Atmospheric temperature and density from Eddy (1979), interior temperature from Lang (2001), and interior density from Christensen-Dalsgaard et al. (1996).

reflection of its relative abundance in the universe at large. Fusion in the core of stars is responsible for producing elements up to iron; the fusion process for elements heavier than iron is endothermic and thus cannot be used by the star to support itself against gravity. Instead, heavier elements are produced during supernovae. Supernovae also spread the source star's fusion products far away where they are incorporated into newly forming stars. Thus, the sun has observable metals[1] such as Fe even though it has not reached the point in its life where it produces them itself. The metals in these second and third generation stars are not confined to the core; rather, they can be found even in the corona. In subsequent sections it will become clear that having various elemental species at different stages of ionization in the directly observable solar atmosphere provides a means of determining temperature and structure.

[1] "metals" here is in the astrophysical sense of any element that is not hydrogen or helium

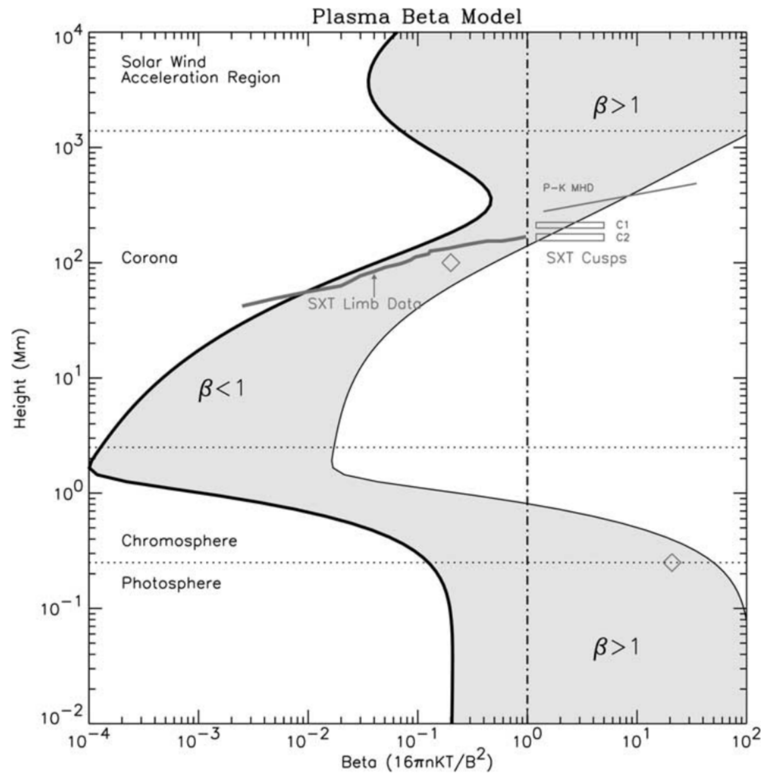
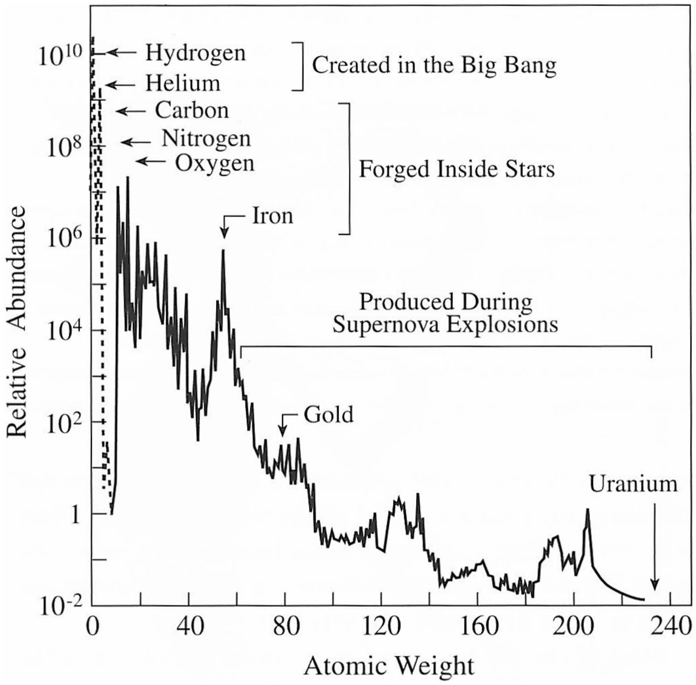


Figure 2.3: Solar plasma β versus height from the photosphere through the corona. Figure courtesy of Gary (2001).

2.1.2 Radiative Zone

Every nuclear reaction in the core generates high-energy photons. It takes thousands to hundreds of thousands of years for these photons to reach the surface because the incredible density of the solar interior results in a mean free path for photons on the order of centimeters. Because the density decreases with radial distance from the center (blue line in Figure 2.2), there is a subtle bias in the mean free path of the photons that causes the net direction to be outward. This is the physical process that characterizes the radiative zone. The net outward flux of energy (heat/photons) must be positive else the energy build up would result in an explosion. Additionally, temperature decreases with distance from the center (red line in Figure 2.2). When in thermodynamic equilibrium, as the solar interior is, atomic emission of photons obeys Planck's law, which describes



Element	Symbol	Atomic #	Abundance
Hydrogen	H	1	2.79×10^{10}
Helium	He	2	2.72×10^{9}
Carbon	C	6	1.01×10^{7}
Nitrogen	N	7	3.13×10^{6}
Oxygen	O	8	2.38×10^{7}
Neon	Ne	10	3.44×10^{6}
Sodium	Na	11	5.74×10^{4}
Magnesium	Mg	12	1.07×10^{6}
Aluminum	Al	13	8.49×10^{4}
Silicon	Si	14	1.00×10^{6}
Phosphorus	P	15	1.04×10^{4}
Sulfer	S	16	5.15×10^{5}
Chlorine	Cl	17	5.24×10^{3}
Argon	Ar	18	1.01×10^{5}
Potassium	K	19	3.77×10^{3}
Calcium	Ca	20	6.11×10^{4}
Chromium	Cr	24	1.35×10^{4}
Manganese	Mn	25	9.55×10^{3}
Iron	Fe	26	9.00×10^{5}
Nickel	Ni	28	4.93×10^{4}

Figure 2.4: (Left) A plot of the abundance of all elements in the sun. (Right) A corresponding table of the 20 most abundant elements. Values in the plot and table are normalized to the abundance of Si, 1.00×10^6. Figure and plot are adapted from Lang (2001).

blackbody emission:

$$S_\lambda = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda k_B T} - 1} \tag{2.2}$$

where S is the spectral radiance of a body at a particular temperature, λ is wavelength, h is Planck's constant, c is the speed of light, k_B is Boltzmann's constant, and T is temperature. This equation can be interpreted simply as a lower temperature resulting in lower energy emission (i.e., longer wavelength). Thus, as photons move outward from the core, they are absorbed by atoms at lower temperature and reemitted at longer wavelengths. In order to conserve energy, multiple photons of lower energy must be emitted. All sunlight is essentially an attenuation of the light generated in the fusing core.

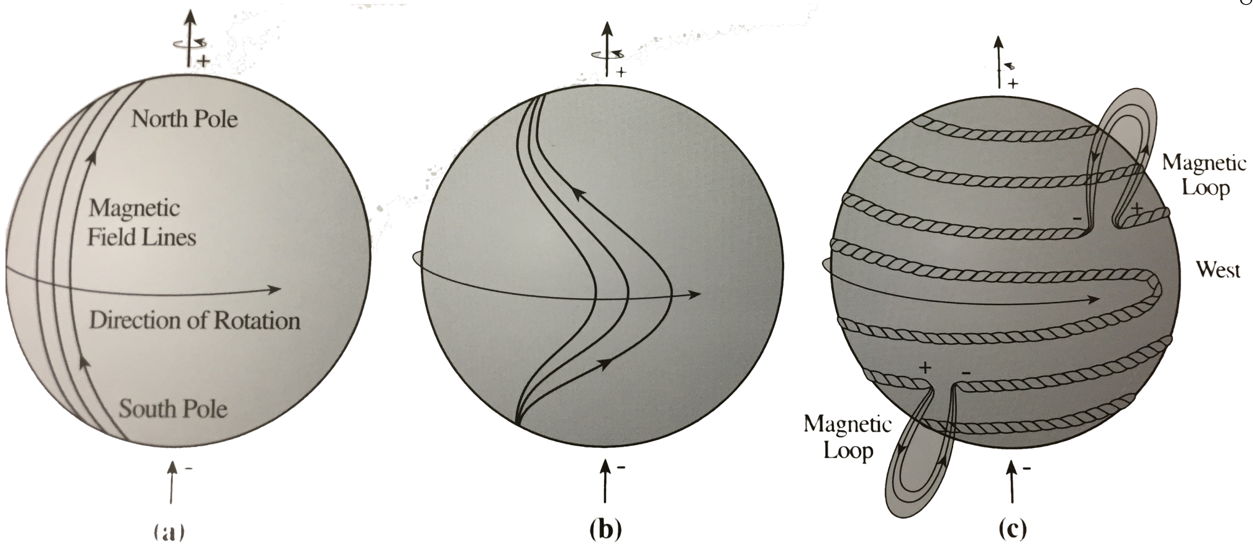


Figure 2.5: (Left) Once the solar dynamo generates a magnetic field vertically around the sun, (middle) differential rotation of the sun causes the field to wrap around the sun, (right) and any small kinks in the field are lifted by their buoyancy in an Ω loop. Figure courtesy of Lang (2001).

2.1.3 Convection Zone

At approximately 70% of the sun's radius, the dominant outward heat transport mechanism changes from radiation to convection. Plasma stores heat near the base of the zone and its buoyancy causes it to rise to a point where its heat can be rapidly dissipated (this point is the photosphere where radiative cooling becomes highly effective). The cooled plasma then sinks back down where it will again be heated at the base of the convection zone, establishing the cycle of heat transport. The observed convective cells at the photosphere are known as granules and supergranules. The difference between them is size and that supergranules have much slower horizontal plasma flow. Additionally, the convection zone is responsible for many of the dynamics observed in the corona (to be described in subsequent sections), which are due to the strong magnetic field and $\beta < 1$ in the corona. The magnetic field is thought to be generated at the base of the convection zone. The precise mechanism of the solar dynamo is not yet well understood, but the surfacing of the field is likely described by slight kinks in the field being lifted by plasma buoyancy (see Figure 2.5). $\beta > 1$ in the convection zone, so the magnetic field generated at the base is subject to the upward plasma motion as just described. Once it reaches the solar atmosphere, the magnetic field dominates and so is not pulled back down with the sinking plasma.

2.1.4 Photosphere

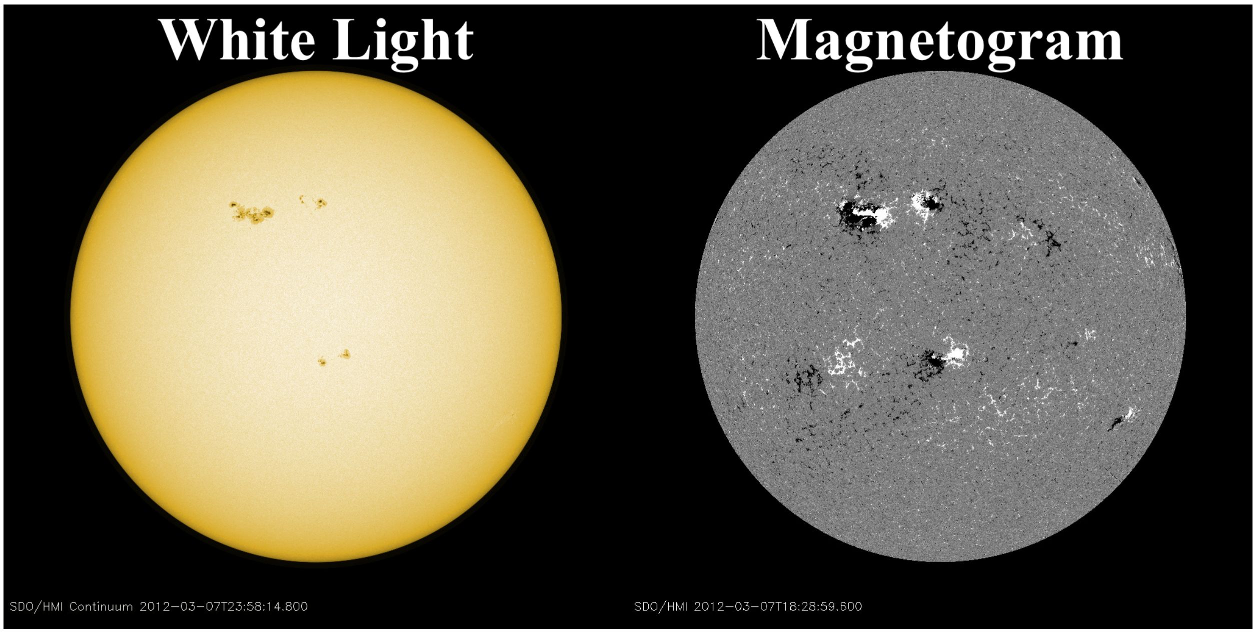


Figure 2.6: (Left) White light image of the solar photosphere on 2012 March 5. (Right) The corresponding photospheric line-of-sight magnetic field. Black indicates field into the page and white field out of the page. These data come from the Helioseismic Magnetic Imager onboard the Solar Dynamics Observatory spacecraft, to be described in Section 2.4.

The photosphere is a thin ($\tilde{3}00$ km or 0.05% of the solar radius) layer where the opacity suddenly drops and photons can escape to space more or less unscathed. It is often referred to as the "surface" of the sun but this label can be misleading since the density at the photosphere is 2500 more tenuous than the *air* on top Mount Everest. The photosphere is constantly roiling; the lifetime of a granule is only about 8 minutes and large-scale patterns of supergranules last about 24 hours. In each granule, hot plasma rises at the center and sinks at the edges. Magnetic field is collected at the edges of the supergranules as plasma motion can move magnetic field in the photosphere. Sunspots, concentrated dark regions in photospheric white light[2] (Figure **??**,

[2] "white light" refers to the integrated visible spectrum emission

left), correspond to regions of concentrated magnetic field. In these locations, magnetic pressure alleviates some of the gas pressure, which lowers the temperature (see numerator of Equation 2.1), and thus the emission peak wavelength and intensity decrease according to Planck's law (Equation 2.2). These areas are known as active regions when viewed in magnetogram data (Figure 2.6, right) and are the primary source for solar eruptive events (see Section 2.2).

2.1.5 Chromosphere

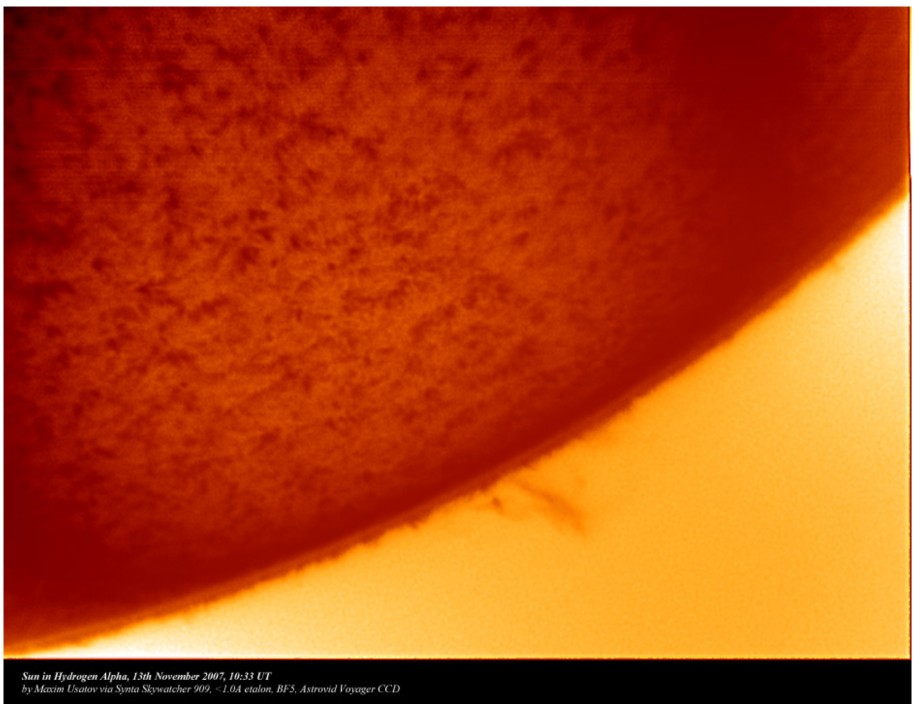


Figure 2.7: Chromospheric spicules visible on the limb[3] of the sun, imaged in Hα. This photo was taken by an amateur astronomer from the ground, Maxim Usatov.

The chromosphere is an irregular layer of the sun that mostly consists of small jets known as spicules (Figure 2.7). The chromosphere was initially discovered and only observable during natural solar eclipses for a few seconds around totality when the bright photosphere was blocked. The layer has a dominant red color, which guided the selection of its name ("chromo" comes from the Greek word for color). The red light comes primarily from Hα emission. Hα comes from the $n = 3 \rightarrow 2$ transition of hydrogen (Figure 2.8). The next section will go into the details of electromagnetic radiation, including this type of bound-bound emission. Instruments can use filters to select this particular wavelength, making observation of the chromosphere routine and independent of solar eclipses.

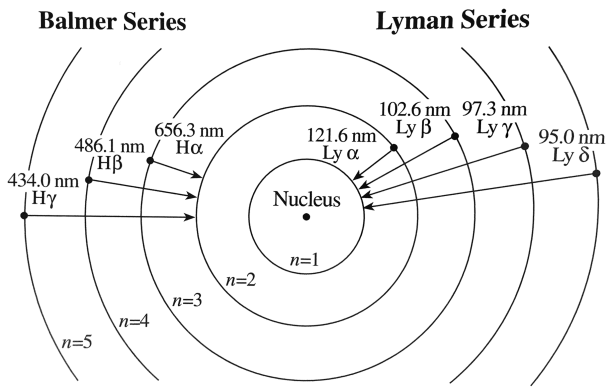


Figure 2.8: Diagram of the hydrogen atom, with electronic orbitals labeled (n). Two important transition series are identified: the Balmer series which includes transitions ending at n = 2 and the Lyman series with transitions ending at n = 1. The wavelength and common name for the resultant photon emission are also labeled.

2.1.6 Electromagnetic Radiation From Atoms and Charged Particles

There are three basic types of electromagnetic radiation that are emitted by electrons: bound-bound, free-bound, and free-free. Additionally, nuclei can emit photons.

Bound-bound When an electron transitions from one orbital energy of an atom to a lower one, a photon is emitted with the corresponding energy of the transition. Downward energy transitions can occur spontaneously or through a collisional de-excitation, where the atom impacts another particle and transfers some of its energy to the other particle. Upward energy transitions can also occur through collision or by absorption of a photon. The wavelength of the emitted photon is primarily determined by the electronic energy transition but can also be influenced by numerous other processes, for example, the strength of the surrounding magnetic field (Zeeman splitting), collisions during the energy transition, and the relative line-of-sight velocity of the atom with respect to the observer (Doppler). These and other effects result in line broadening, sometimes to the point of splitting the lines.

Free-bound Also known as radiative recombination, free-bound transitions are those where an atom captures a free electron. When a free electron is captured, a photon is emitted with energy equal to the difference between the kinetic energy of the free electron and the energy of the bound atomic state. The orbitals of the atom have discrete (quantized) energy values but the kinetic energy of free electrons exists on a continuum. Thus light from free-bound transitions is also a continuum in wavelength though it has a lower limit defined by the energy of the bound state it is captured into. The reverse process (bound-free) is ionization and occurs when a photon is absorbed by an atom and an electron is liberated.

Free-free Also known as Bremsstrahlung ("braking radiation"), any accelerating charged particle emits photons according to Maxwell's equations. The resultant emission is continuum because there are no quantum constraints on the kinetic energy of free particles before or after an acceleration event. Because electrons are much less massive than nuclei, they tend to experience many changes in direction and speed in a dynamic plasma. Even the lightest nucleus – hydrogen, which is just a proton – is 1836 times heavier than an electron. So, while the nucleus will also experience a change in kinetic energy, it is negligible compared to the electron's. The acceleration in this case is mediated through the powerful electromagnetic force between these oppositely charged particles. It is also possible for the similarly charged ions to accelerate each other, or electrons to accelerate other electrons, but these events are not responsible for the dominant observed emission.

Nuclear decay Nuclei can also be excited into a higher energy state through powerful collisions. When they return to a lower energy state, a photon is emitted and is typically in the gamma range of the spectrum.

2.1.7 Transition Region

The transition region is defined by the rapid increase in temperature between the chromosphere and corona (see Figure 2.2). It is only 100 km thick but is ill defined spatially. Is it in the spicules of the chromosphere? In the loops of active regions? Its location is not obvious and its existence seems to defy the laws of thermodynamics. The early discovery of how hot the corona was and that the transition region existed was controversial. It depended on temperature-sensitive observations, which have now become routine and widely accepted.

There are several means by which temperature of the solar atmosphere can be inferred. The simplest is the observation of an emission line that has been identified in the laboratory, which specifies the corresponding ion and bound-bound transition. Additional laboratory measurements and theory provide the ionization fraction of each element as a function of temperature (Figure 2.9). A higher temperature results in greater ionization. Thus, observation of an emission line known to correspond to a particular ion is an indicator of that ion's existence in the remote plasma and an approximate temperature can be inferred. Table 2.1 provides some examples for ionization state, corresponding temperature, and a known emission line, which will be used extensively in later chapters.

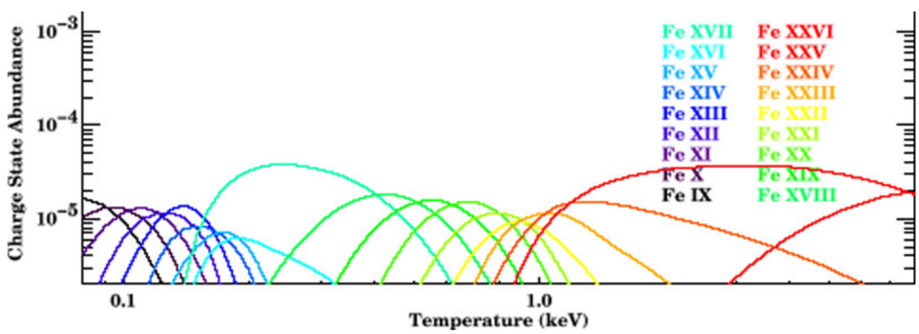


Figure 2.9: Ionization fraction for Fe as a function of energy. Here, energy and temperature are related by a constant value (Boltzmann's constant) and are thus equivalent. Charge state abundance is the product of elemental abundance and ionic fraction. Figure courtesy of Peterson and Fabian (2006).

The next most common method for temperature determination uses the ratio of two emission lines. The flux in each line is dependent on the energy of the bound-bound transition, ΔE, and the collision rates for that transition. The ratio of the line fluxes is temperature sensitive if $\Delta E > kT$. This method can handle non-isothermal plasmas by integrating the collision rates over volume. This method fails if there is two lines used have source regions that are distant from each other so

Table 2.1: Selected emission lines

Ion	Wavelength (Å)	Peak formation temperature (MK)
Fe IX	171	0.63
Fe X	177	0.93
Fe XI	180	1.15
Fe XII	195	1.26
Fe XIII	202	1.58
Fe XIV	211	1.86
Fe XV	284	2.19
Fe XVI	335	2.69
Fe XVIII	94	6.46
Fe XX	132	9.33

care must be taken when the source plasma contains spatial variations in density and temperature, as is the case with the sun. Additionally, this method depends on the relative ion abundances, so if ionization balance varies with time, that time variation must be taken into account. Line ratios are not used for temperature determination in this dissertation.

The mechanism responsible for the rapid temperature change through the transition region remains poorly understood and is one of the biggest problems in solar physics. Theories abound to explain it but are beyond the scope of this dissertation. Here, we simply accept that the transition region *does* lead to a much hotter corona, an observational fact that has long been established.

2.1.8 Thermodynamic Equilibrium

A large, dynamic body such as the sun shouldn't be expected to be in thermodynamic equilibrium everywhere. The term "local thermodynamic equilibrium (LTE)" appreciates this. There are many volumes of the sun where the laws and conveniences of thermodynamic equilibrium can be applied. LTE is a good assumption when three basic criteria are met: the electron and ion velocity distribution is Maxwellian, the plasma is only weakly ionized such that the Saha equation holds, and collisional excitation dominates radiative such that the Boltzmann equation can be applied.

The Maxwell-Boltzmann equation describes the velocity distribution of a population of particles:

$$f(v) = \sqrt{\left(\frac{m}{2\pi k_B T}\right)^3} 4\pi v^2 e^{-\frac{mv^2}{2k_B T}} \tag{2.3}$$

where f is the probability density function, v is velocity, m is particle mass, k_B is Boltzmann's constant, and T is temperature. This is a valid description for processes involving only continuum emission (free-free and free-bound) and is usually valid for atoms and ions in the sun. Particle acceleration during solar flares can push a population of electrons and ions outside of the Maxwellian distribution. The Saha equation describes the ionization state of a plasma as a function of temperature and pressure:

$$\frac{n_{i+1} n_e}{n_i} = \frac{2 g_{i+1}}{\Lambda^3 g_i} e^{-\frac{\epsilon_{i+1} - \epsilon_i}{k_B T}} \tag{2.4}$$

where n_i is the number density of ions in the $i-th$ ionization state, n_e is the number density of electrons, Λ is the deBroglie wavelength, g_i is the degeneracy of states for the i-ions, and ϵ_i is the energy to remove i ions from the neutral atom. In the solar atmosphere, the low-lying atomic levels are dominated by radiative ionization while the high levels are dominated by collisional ionization when the temperature and density are high. The Saha equation is valid when collisions dominate the overall plasma or when the radiation field is Planckian (Equation 2.2). The Boltzmann equation (not to be confused with the Maxwell-Boltzmann equation) describes the excitation distribution of electrons in an atom:

$$f(i) = \frac{e^{-\epsilon_i / k_B T}}{\sum_{i=1}^{M} e^{-\epsilon_i / k_B T}} \tag{2.5}$$

where M is the number of all states accessible to the system and all other terms are as defined previously. The Boltzmann equation is valid when collisions dominate excitation as compared to radiative excitation. The inherent simplifying assumption is that the excitation state depends only on the temperature and density of the plasma. This is not true in general so the assumption of LTE must be applied carefully. When LTE does hold, the distribution of thermally emitted photons is described by the Planck equation (Equation 2.2) . Non-LTE analyses must account for the fact that the radiation field also impacts the population of electrons in atomic energy states.

2.1.9 Corona

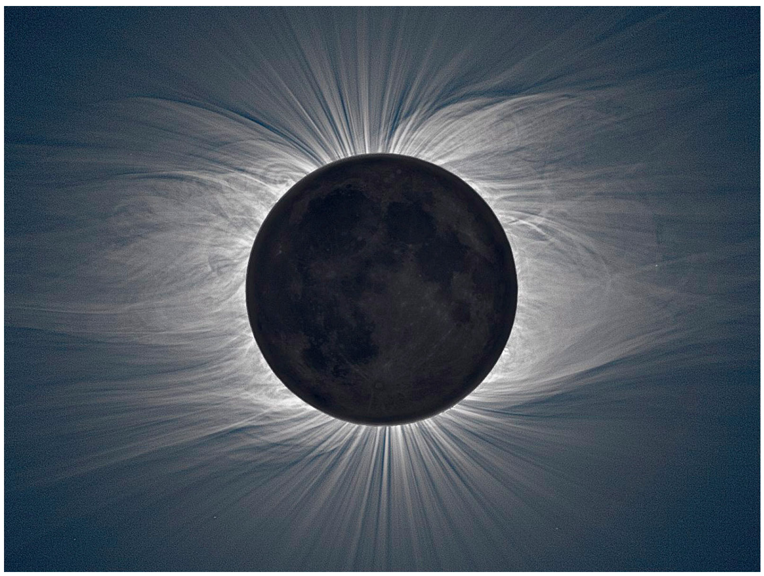


Figure 2.10: Composite white-light image of the corona from a total solar eclipse in the Marshall Islands in 2009 July. Feature on the moon can be seen in the foreground and a great deal of structure appears in the corona. Image courtesy of Miloslav Druckmuller.

The corona is the highly dynamic, tenuous upper atmosphere of the sun. Its lower boundary is defined by the transition region at approximately 2.45×10^5 km ($1.35 R_\odot$). Its outer boundary is determined by the Alfvn surface where information can no longer be propagated inward and has recently been discovered to be at a much higher altitude than previously thought: 8.35×10^6 km ($12 R_\odot$) above polar coronal holes and 1.04×10^7 km ($15 R_\odot$) at lower latitudes (DeForest et al., 2014). The average temperature of the corona is about 1.5 MK (Figure 2.2) but it ranges from roughly 6.00×10^5 K to 5.00×10^7 K. As mentioned in earlier sections, the ratio of gas to magnetic pressure, β, is less than 1 in the corona. This is why the we see structure in the corona. The magnetic field contorts, compresses, and opens dynamically to produce regions of varying plasma density and temperature (Figure 2.10). Those changes in the plasma impact the electromagnetic emission in terms of the emission line flux and differential emission measure (DEM):

$$F = \frac{2.2 \times 10^{-15}}{4\pi R^2} f A_{el} \int g G(T) Q(T) dT \tag{2.6}$$

$$G(T) = \frac{n_{ion}}{n_{el}} \frac{e^{\frac{-h\nu}{k_B T}}}{\sqrt{T}} \tag{2.7}$$

$$Q(T) = \sum_{i=1}^{N} \left(\iint\limits_{S_T} \frac{n_e n_i}{|\nabla T|} dS_T \right)_i \tag{2.8}$$

where F is the emission line flux, $G(T)$ is the contribution function, $Q(T)$ is the DEM; R is the distance between the emission and the observer, f is the oscillator strength (probability of absorption/emission between two atomic energy levels), A_{el} is the elemental abundance, g is the Gaunt factor (a correction for absorption/emission to account for quantum effects), ν is photon frequency, S_T is a constant temperature surface, the summation in $Q(T)$ runs across all regions along the line of sight in the temperature range T to $T + \Delta T$, and all other variables are as defined previously. The DEM, and hence the line flux, is strongly dependent on density and moderately dependent on temperature. All of this is to say that where the coronal magnetic field increases the density or temperature of the plasma, the intensity of the emission goes up; thus, images of the corona tend to show bright structures that provide an indicator of magnetic topology and intensity.

The corona is optically thin and as such is not in LTE, i.e., the plasma is not strongly locally coupled to the radiation field. In yet simpler terms, this means that photons generated from a very distant region can stream directly to a plasma parcel of interest and interact there. This makes modeling of the solar atmosphere a nontrivial task. There should be different temperatures defined for photons, electrons, protons, and ions. Their velocities need not be Maxwellian, making the definition of temperature at all somewhat murky. However, many of the emission lines in the corona are emitted by collisionally excited, highly ionized atoms (e.g., Fe IX 171 Å) and these lines can only be formed above certain temperatures. In regions of the corona that are relatively quiescent, the assumption of a Maxwellian distribution remains a good one, so temperature carries some meaning. Thus, observations of particular emission lines still provide a decent indicator of approximate plasma temperature. Herein, "peak formation temperature" or simply "temperature" will be used as a convenient shorthand that implies the caveats provided above.

2.1.10 Heliosphere

The heliosphere stretches from the end of the corona and encompasses the solar system. It is the region where solar influences dominate the interstellar. Solar wind, a tenuous plasma constantly streaming out from the sun, applying a subtle outward pressure. There are similar breezes coming from the stars. The heliopause is defined as the point of equilibrium between these pressures. The solar wind flows outward at about 400 km/s with a pressure at 1 astronomical unit (AU[4]) in the range of 1×10^{-9} N/m^2 to 6×10^{-9} N/m^2. However, this gentle wind is periodically disturbed by spasms in the sun known as solar eruptive events. These events can impact the earth and cause various problems with technology, health, and safety. The physics of solar eruptive events is the subject of Section 2.2 and the impacts and forecasting of space weather is the subject of Section 2.3.

2.2 Physics of Solar Eruptive Events

Solar eruptive events are some of the most energetic phenomena in the solar system. Solar flares can release 6×10^{25} J in minutes to hours – an energy that is hard to fathom. The total world energy consumption over the last 42 years was 1.17×10^{22} J[5] . A powerful flare has more than 5000 times that energy. Coronal mass ejections (CMEs) have a similar amount of energy. The general process for eruptive events is a long period (days or more) of energy storage and then a rapid release of that energy through numerous physical processes. The following subsections

[4] 1 AU is the average distance between the sun and earth, 1.50×10^8 km

[5] Analysis based on data from 1971-2013 in International Energy Agency (2015)

provide further detail into energy storage and release.

2.2.1 Magnetic Energy Storage

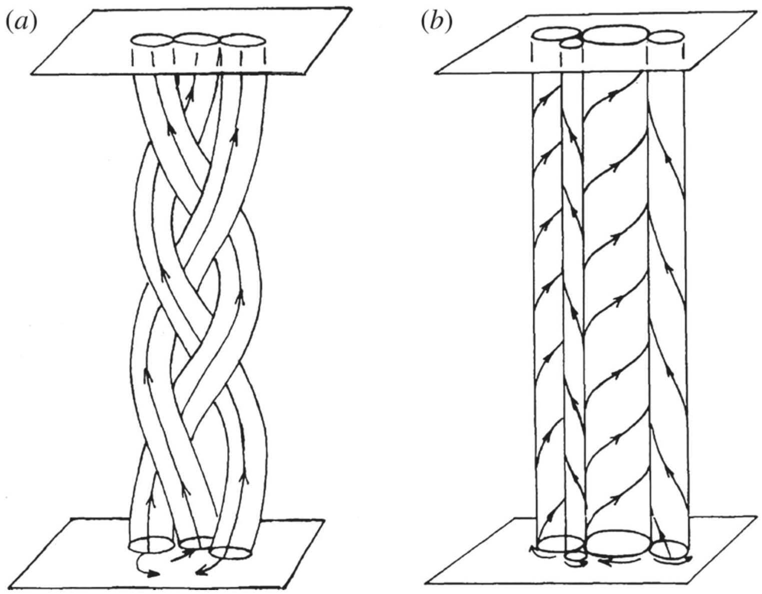


Figure 2.11: Schematic depiction of magnetic energy storage. (Left) Translation of magnetic fields/ropes/strands leads to braiding and tangling and (right) the field lines/ropes/strands can themselves be twisted. Figure courtesy of Klimchuk (2015).

The energy to power a solar eruptive event comes from stored energy in the coronal magnetic field. A "potential" field is defined such that the field is smooth e.g., it has no field lines twisting around each other and instead they nest alongside each other in an orderly way. This is the lowest possible energy configuration of the field, meaning there is no energy to power an eruptive event. When field lines are packed closely together, become braided, shear, or single ropes twist, energy is stored into the field (Figure 2.11). As described earlier, the convective motions at and below the photosphere are one important source of these motions. Additionally, a complex of magnetic fields such as an active region can be influenced by distant eruptive events through energy propagation through the coronal magnetic field, such as Alfvn waves (Schrijver and Title, 2011). Gentler disturbances in the large-scale coronal magnetic field likely occur frequently and could contribute to localized energy concentration.

2.2.2 Energy Release Overview

The rapid energy release of a solar eruptive event is no small topic. As mentioned earlier, worldwide energy consumption pales in comparison to the energy release of a single solar eruptive event and as such, a large number of physical processes are powered. Magnetic reconnection is the widely accepted mechanism that triggers the sudden energy release, though the microphysics remain poorly understood. Magnetic reconnection also occurs in planetary magnetospheres and laboratory experiments have sought to cause it, but the details of this active area of research are beyond the scope of the relevant background to this dissertation. Magnetic energy storage and reconnection is somewhat analogous to the sudden shifting of tectonic plates (earthquakes), avalanches on a ski slope, the snapping of a rubber band that has been twisted too tightly, and the sudden flash and crack of a lightning bolt (Lang, 2001).

As energy continues to build in the coronal magnetic field, eventually somewhere in the complex of loops, a particular strand is stressed beyond a critical limit. Because it can no longer adjust to the additional stress, it suddenly snaps into a new lower-energy configuration as it finds the path of least resistance like a stream of water working its way through rough downhill terrain. This sudden change to the local field configuration causes the neighboring loops to adjust rapidly as well and in this way the disturbance propagates. WIthin seconds, all loops in the region are relieving their strain by reducing their twists, shear, and other complexity as they strive toward the nonpotential field configuration. Eventually, a region of loops is reached that are not near their critical stress limit and the propagation ceases. The field configuration after the disturbance contains less energy than before. All of that energy has to go somewhere! It turns out that particle acceleration is one of the key processes powered by this energy release. A comparative few particles can be accelerated to relativistic velocities and/or a huge mass of particles can be accelerated to a few hundred km/s. The former is strongly associated with solar flares (Section 2.2.3) and SEPs (not discussed in detail here) while the latter is a simple description of coronal mass ejections (Section 2.2.4). Both are manifestations of magnetic energy release and they can occur together.

Flares are often categorized by the amount of soft x-ray emission they emit as measured by the Geostationary Operational Environmental Satellites (GOES) where each letter (A, B, C, M, X) indicates an increased order of magnitude. $\tilde{3}$0% of C-class, $\tilde{5}$6% of M-class, and $\tilde{9}$0% of X-class flares occur with CMEs (Yashiro et al., 2005; Wang and Zhang, 2007). Thus, larger magnitude flares tend to also have CMEs. The reverse is also true: 90% of the fastest CMEs (¿ 1500 km/s) are associated with flares while the association rate drops for slower CMEs (Wang and Zhang, 2008).

2.2.3 Solar Flares

2.2.4 Coronal Mass Ejections

2.3 Space Weather

2.4 Instrument Descriptions

2.4.1 Spectrographs

2.4.2 Spectral Imagers

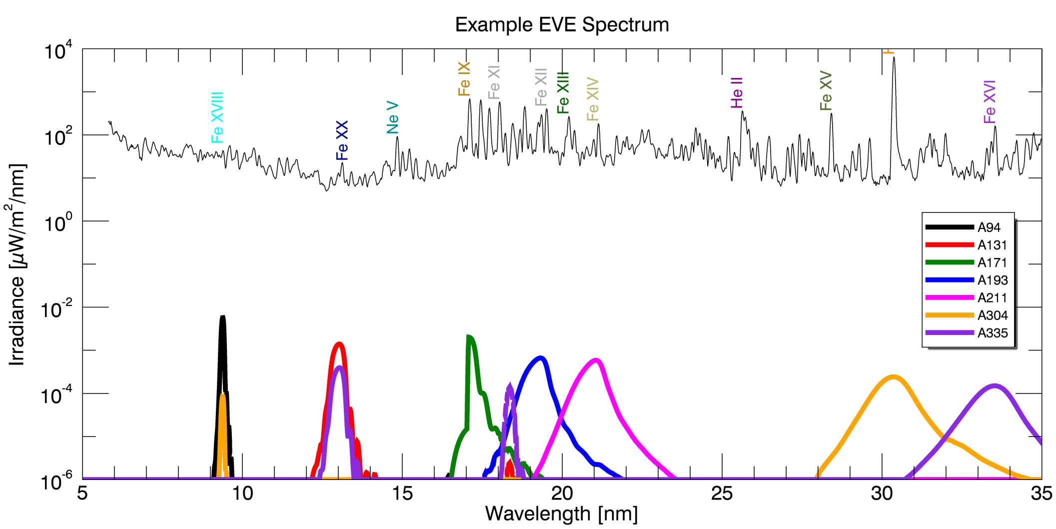


Figure 2.12: AIA bandpasses, model solar spectrum to provide an idea of the amount of blending.

2.4.3 Magnetic Imagers

2.4.4 Coronagraphs

2.4.5 In-situ Measurements

Bibliography

Christensen-Dalsgaard, J., Dappen, W., Ajukov, S. V., Anderson, E. R., Antia, H. M., Basu, S., Baturin, V. A., Berthomieu, G., Chaboyer, B., Chitre, S. M., Cox, A. N., Demarque, P., Donatowicz, J., Dziembowski, W. A., Gabriel, M., Gough, D. O., Guenther, D. B., Guzik, J. A., Harvey, J. W., Hill, F., Houdek, G., Iglesias, C. A., Kosovichev, A. G., Leibacher, J. W., Morel, P., Proffitt, C. R., Provost, J., Reiter, J., Rhodes, E. J., Rogers, F. J., Roxburgh, I. W., Thompson, M. J., and Ulrich, R. K. (1996). The Current State of Solar Modeling. Science, 272(5266):1286–1292.

DeForest, C. E., Howard, T. A., and McComas, D. J. (2014). Inbound Waves in the Solar Corona: A Direct Indicator of Alfvén Surface Location. The Astrophysical Journal, 787(2):124.

Eddy, J. A. (1979). A New Sun: The Solar Results from Skylab. National Aeronautics and Space Administration, Washington, D. C.

Gary, G. A. (2001). Plasma Beta above a Solar Active Region: Rethinking the Paradigm. Solar Physics, 203(1):71–86.

International Energy Agency (2015). 2015 Key World Energy Statistics. Technical report, International Energy Agency.

Klimchuk, J. A. (2015). Key aspects of coronal heating. Philosophical transactions. Series A, Mathematical, physical, and engineering sciences, 373(2042):20140256.

Lang, . (2001). The Cambridge Encyclopedia of the Sun. The Cambridge Encyclopedia of the Sun.

Peterson, J. and Fabian, A. (2006). X-ray spectroscopy of cooling clusters. Physics Reports, 427(1):1–39.

Schrijver, C. J. and Title, A. M. (2011). Long-range magnetic couplings between solar flares and coronal mass ejections observed by SDO and STEREO. Journal of Geophysical Research, 116(A4):69–80.

Wang, Y. and Zhang, J. (2007). A Comparative Study between Eruptive XClass Flares Associated with Coronal Mass Ejections and Confined XClass Flares. The Astrophysical Journal, 665(2):1428–1438.

Wang, Y. and Zhang, J. (2008). A Statistical Study of Solar Active Regions That Produce Extremely Fast Coronal Mass Ejections. The Astrophysical Journal, 680(2):1516–1522.

Yashiro, S., Gopalswamy, N., Akiyama, S., Michalek, G., and Howard, R. A. (2005). Visibility of coronal mass ejections as a function of flare location and intensity. Journal of Geophysical Research, 110(A12):A12S05.

Appendix A

Coronal Dimming Event List and Ancillary Data

Appendix B

MinXSS CubeSat Mass/Power Tables

(Data, Stardate 1403827) (A one-page chapter — page must be numbered!) Throughout the ages, from Keats to Giorchamo, poets have composed "odes" to individuals who have had a profound effect upon their lives. In keeping with that tradition I have written my next poem . . . in honor of my cat. I call it. . . Ode. . . to Spot. (Shot of Geordi and Worf in audience, looking mystified at each other.)

> Felus cattus, is your taxonomic nomenclature
> an endothermic quadruped, carnivorous by nature?
> Your visual, olfactory, and auditory senses
> contribute to your hunting skills, and natural defenses.
> I find myself intrigued by your sub-vocal oscillations,
> a singular development of cat communications
> that obviates your basic hedonistic predilection
> for a rhythmic stroking of your fur to demonstrate affection.
> A tail is quite essential for your acrobatic talents;
> you would not be so agile if you lacked its counterbalance.
> And when not being utilized to aid in locomotion,
> It often serves to illustrate the state of your emotion.

(Commander Riker begins to applaud, until a glance from Counselor Troi brings him to a halt.) Commander Riker, you have anticipated my denouement. However, the sentiment is appreciated. I will continue.

> O Spot, the complex levels of behavior you display
> connote a fairly well-developed cognitive array.
> And though you are not sentient, Spot, and do not comprehend
> I nonetheless consider you a true and valued friend.