PhD Dissertation: Solar Eruptive Events Outline

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**CU & AES Dissertation Requirements**

* Dissertation title due by: 2016/03/07
* PhD defense deadline: 2016/04/08
* Dissertation due by: 2016/04/15
* Final grade card due by: 2016/04/20
* Double spaced + various requirements on title page, numbering, tables, etc
* External links not allowed
* Lauren Blum, Quintin Schiller, and David Gerhardt dissertations all have a short introduction that frames the dissertation
  + Particularly useful in cases like mine where there’s a bifurcation of topics – introduction provides a place to tie them together as best I can (same situation all 3 of them faced with science + CubeSat)

**Dissertation based on papers:**

1. Mason and Hoeksema 2010, ApJ, solar flare prediction (background)
2. Mason et al. 2014, ApJ, coronal dimming physics and case study
3. Mason et al. 2016a (*accepted*) Journal of Spacecraft and Rockets, MinXSS CubeSat overview
4. Mason et al. 2016b, (*submitted in early January)* ApJ, coronal dimming and CME relationship semi-statistical study
5. Mason, Lamprecht, & Woods 2016c, *(in prep at time of defense)* Journal of Small Satellites, thermal balance analysis

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# 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.

# Relevant Background

## Brief Tour of the Sun

* **Figure:** Typical cutaway image of sun
* Core, radiative zone, convection zone, photosphere, chromosphere, transition region, corona, heliosphere
* **Figure**: temperature, density from core to corona
* Everything below the photosphere is optically thick, defined by mean free path and is wavelength independent (Mihalas said this is a good assumption for the sun)
* Define beta
  + Everything below the photosphere is beta > 1, low corona is beta < 1, high corona and beyond is beta >1 again
* Core is where fusion occurs, takes about 100,000 years for photons to reach photosphere, high energy photons generated at core have a subtle bias that drives them outward but they also lower energy and become more numerous (conservation of energy) along the way (Zirker cells for this explanation)
  + **Figure**: elemental composition of the sun
* Radiative zone is where the dominant heat transport mechanism is radiation
* Convection zone is where dominant heat transport mechanism is convection, responsible for a lot of the dynamics observed at the photosphere and above: granules and supergranules in white light, generation of magnetic field
  + Base of convection zone is where most researchers agree the coronal magnetic field is spawned, the solar dynamo
  + **Figure** showing how the field gets wrapped up, kinks, and rises to the photosphere
* Photosphere is a thin (quantify) layer where photons can finally escape easily, i.e. transition from optically thick to thin in the visible spectrum (photospheric 3He absorbs most of the visible light from lower layers but it can then fly free)
  + Also can see granulation here, bubbles at the surface of the convection zone
  + Supergranules force the magnetic field to have a structure because beta > 1 up to the low corona so convective and photospheric plasma can push around the mag field
  + Sunspots, concentrated dark spots in white light, correspond to regions of concentrated magnetic field because the more intense magnetic pressure alleviates some of the gas pressure, which reduces the temperature, so black body peak gets longer in wavelength and intensity lowers according to Planck
    - Active regions defined by their observation in the photospheric magnetic field and are areas of extremely intense magnetic field (100x quiescent sun in terms of magnetic field strength), see earlier figure about how the field gets wrapped and kinked to rise to the photosphere
    - **Figure**: sunspot observations side by side magnetogram
* Chromosphere mostly consists of spicules so it’s not a smooth layer
  + **Figure:** solar limb showing spicules
  + Observed originally for seconds at the beginning and end of eclipses but now best seen in H-alpha (first line of the Hydrogen Balmer series)
    - **Figure:** Balmer and Lymann atomic transitions from encyclopedia – this is likely to be the only figure of atomic transitions in the dissertation but should be included to set up the analogy for Fe
  + Collisionally dominated
* Brief subsection on EM radiation
  + Bound-bound (electronic transition within an atom)
    - Get single wavelength photon but numerous processes result in slight variations in the wavelength – line splitting via Zeeman, collisional broadening, Doppler broadening
  + Free-bound (radiative recombination, atomic capture of a free electron)
    - Results in continuum emission because the free electron can have any kinetic energy prior to capture, though it will have a fixed energy after capture corresponding to its atomic orbital, which places a lower limit on the kinetic energy of the initially free electron
    - Reverse, bound-free (ionization), is where a photon is absorbed by an atom and an electron is liberated from the atom
  + Free-free
    - Bremsstrahlung “braking radiation”, electrons are charged particles so when they accelerate, the emit according to Maxwell’s equations
    - Continuum emission because there are no quantum constraints on the kinetic energy of the electron before or after and the photon energy is precisely the difference in the kinetic energy before and after the acceleration
    - Very likely to occur in a hot plasma where electrons are traveling fast and there’s an ample supply of ions (oppositely charged particles) that induce an acceleration on the electrons due to their mutual electromagnetic attraction
    - The ions don’t really move because they are many orders of magnitude heavier than the electrons (even the most abundant ion, H- i.e. a proton, is 1836 times heavier than an electron)
* Transition region is defined by the rapid transition in temperature between the chromosphere and the corona
  + It is ill defined spatially, somewhere in the spicules of the chromosphere? In the lower part of the large magnetic loops of active regions?
  + How do we know the temperature is changing through the transition region?
  + We can infer the temperature in the solar atmosphere via several means
    - The simplest is observation of an emission line that has been identified in the laboratory, thus we know the corresponding ion and bound-bound energy transition
      * Lab and theory also provide the ionization fraction of elements as a function of temperature
      * For elements that do not resemble H, He, or Li, the ionization fractions have well defined peaks
      * **Figure**: Ionization fractions versus temperature for Fe
      * **Table**: Select emission lines and their peak formation temperatures
      * Thus, strong observation of a particular emission line indicates that the corresponding ion is abundant and provides a good indicator of the plasma temperature
    - The next most common method for temperature determination is emission line ratios
      * Not used in this dissertation so won’t go too far into details
      * The flux in each line depends on the energy of the bound-bound transition and the collision rates for that transition
      * Show equations from Solar TR book
      * Ratio will be temperature sensitive if the difference in the deltaE’s is larger than kT
      * This method can handle non-isothermal plasmas by integrating the collision rates over volume
      * This method fails if the two lines used are coming from different spatial locations, so one must be careful when observing plasma with spatial variations in density and temperature, which is true of the Sun
      * The equations used in this method also depend on the relative ion abundances, so if the ionization balance is changing as a function of time, need to take into account
  + The mechanism responsible for the rapid temperature change through the transition region is poorly understood and one of the biggest problems in solar physics; theories abound but are beyond the scope of this dissertation. Here, we simply accept that the transition region *does* lead to a much hotter corona, which has long been established and accepted
* Thermodynamic Equilibrium
  + LTE requires
    - electron and ion velocity distribution is Maxwellian (valid assumption for processes involving only continuum [free-free and radiative recombination] and is also pretty valid for atoms/ions)
    - ionization equilibrium is given by Saha
      * radiative ionization dominates for low-lying levels
      * collisional ionization dominates for very high-lying levels and high temperature/density
      * if collisions dominate then you get LTE, otherwise you only get LTE if the radiation field is Planckian
    - excitation equilibrium is given by Boltzmann
      * radiative ionization dominates just as above so can’t use LTE in general
  + In LTE, distribution of thermally emitted photons from Planck
  + Non-LTE factors in the fact that the radiation field also impacts the populations of electrons in atomic energy states (rather than like in LTE which assumes those are only dependent on temperature and density)
* Corona is the highly dynamic, tenuous upper-atmosphere of the sun
  + Basic structure – spatial extent, temperature, density, magnetic field
  + Dynamics – what beta < 1 can do, timescales of magnetic evolution
  + Optically thin plasma, like the corona, is not collisionally dominated (it is radiatively dominated) so the plasma is not in LTE with the radiation
    - There should be a different temperature for photons, electrons, protons, and ions
    - But since most of the emission lines in the corona are emitted by collisionally excited, highly ionized atoms (e.g., Fe IX+), and these lines can only be formed at certain temperatures, the observation of that emission line is still a good indicator of the plasma temperature
    - Emission line flux is dependent on differential emission measure, which is strongly dependent on density
      * Equations 4.12 and 4.13 from Mariska’s transition region books
* Heliosphere encompasses the solar system – it is the region where solar influences dominate interstellar
  + Tenuous plasma from the sun constantly streams out, applying subtle pressure outward, which is at odds with similar outward streams for the stars
  + The heliopause is defined as that surface where solar and interstellar pressures are equal
  + This gentle solar wind is periodically disturbed by spasms in the sun, solar eruptive events
  + Those disturbances can impact the earth and cause various problems with human technology
  + The physics of these solar eruptive events will be covered in Section 2.2 and the impacts and forecasting of space weather will be the subject of Section 2.3

## Physics of Solar Eruptive Event

* Energetics – how much energy can be released in how short a time
* Energy storage via twisting etc. of magnetic field
  + Potential field is smooth — lines don’t wind around each other but nest beneath each other nicely
    - the energy stored here is just convection in the sun creating the field with some strength
    - lowest possible energy, none available to power a flare
  + loops pack together and push against each other
  + loops can become braided, single loop can be twisted, row of loops could be sheared
    - any such distortion = stored magnetic energy
    - **Figure**: classic energy storage figure
* Energy release via magnetic reconnection (details poorly understood) but provide the cartoon models of separatrix
  + Likened to sudden tectonic plates shifting (earthquakes), avalanches in sand pile or ski slope, quick snap of rubber band that has been twisted too tightly, or sudden flash and crack of a lightning bolt
  + somewhere in the loop system, a particular loop is stressed beyond a critical limit
  + it cannot adjust to additional stress so snaps suddenly into a new configuration to relieve its strain (my note: it probably suddenly finds a path of less resistance by breaking somewhere along its line and connecting to a different field line)
  + now neighboring loops have to adjust rapidly to that change
  + disturbance propagates rapidly
  + within seconds, all loops in the region are relieving their strain by reducing twists (or consuming their internal currents)
  + flare fathers energy as more sites dump their excess until rolling disturbance reaches a group of loops that aren’t near their critical limit
  + before reconnection you have fields close together with opposite direction (that means there’s a current in the space between them flowing perpendicular)
  + after reconnection you have two separate loops so that the nearby components are both going the same way (no current anymore)
* that excess energy had to go somewhere: direct particle acceleration (relatively few particles to relativistic speeds), massive kinetics with CMEs (vast quantities of mass to a few hundred km/s)
* N% of CMEs occur with a flare and M% of flares occur with a CME – they are both manifestations of magnetic energy release and they both represent approximately the same amount of energy (X Joules)
* Subsection: flare physics
  + **Figure**: solar flare cartoon
  + one natural place for it to go is for electrical resistance of the plasma to convert the current to heat, like the coil in a toaster converting electric current into heat (Joule heating)
    - Joule heating = electrons are accelerated by an electric field and have electrostatic potential energy, which sometimes collide with ions in the conductive medium causing them to scatter randomly (but according to a Maxwellian distribution), which increases the temperature of the system as they continue to move along
  + Particle acceleration is poorly understood but there are numerous proposed mechanisms that could produce electron and ion beams, though each has issues and existing observations have not placed sufficient constraints to figure out which mechanism is right for what scenario
    - Cite papers Amir pointed me to
    - Acceleration occurs near or above the top of the coronal loops
    - Some particles accelerated outward (SEPs), some downward
  + Electron and ion beams going downward are trapped by the mag field since beta < 1, so they run down the legs of the loop until they reach the dense chromosphere, which reacts in a process known as chromospheric evaporation, something of a misnomer since the event is not as gentle as the name implies
    - As the charged particles in the beam approach the plasma in the chromosphere, their electromagnetic attraction/repulsion causes them to accelerate (resulting in bremsstrahlung continuum radiation), and sometimes they collide with particles there causing direct heating, ionization, atomic excitation of electrons (which may then spontaneously decay in a bound-bound transition for an emission line or collisionally de-excite which is another heating mechanism), and atomic excitation of the nucleus
    - The heating causes the plasma to rapidly expand, causing it to fill up the active region loops which then appear bright in images
      * **Figure**: flare loops in AIA or Yohkoh
    - These processes result in a multitude of high energy emission, from UV to gamma, and also microwave emission at the characteristic plasma frequency as the electron beam causes a small oscillation in the elements of the target plasma
  + The HXRs and microwave emission tend to cut out within minutes as the electron beam stops, and this period of the flare is known as the impulsive phase
  + The gradual phase is basically the atmospheric response to the disturbance of the impulsive phase; the hot plasma (upwards of 50 MK) cools and lower ionization states see an enhancement, which can be observed from their characteristic emission lines many of which are in the EUV
* Subsection: CME physics
  + **Figure**: CME cartoon
  + Magnetic stored energy can also go into accelerating a great mass to escape velocity and beyond
  + Prior to flare, the strong magnetic fields of the active region in a low beta environment can prevent a great mass of plasma from escaping due to plasma pressure as solar wind
  + The sudden reconfiguration of the magnetic field changes that situation, the restraining magnetic field can be disconnected from lower down, effectively pinching off a magnetic bubble
  + Often times highly-stable filaments/prominences can be found resting in regions of strong magnetic field, which tend to be in and near active regions
    - These features have orders of magnitude higher density than their surroundings and orders of magnitude lower temperatures which is possible due to the strength of the magnetic field encapsulating them
    - When a CME departs, often times a filament/prominence that was a part of the local magnetic structure will be torn away with it, greatly adding to the mass of the CME and making for beautiful images
      * **Figure**: Prominence eruption seen in AIA
  + Here too, the precise mechanism responsible for accelerating the CME is poorly understood
  + As the CME leaves, it brings its emission with it and leaves a temporary void in the corona in a phenomenon initially described as “transient coronal holes” but has since been relabeled “coronal dimming”. This phenomenon will be the focus of Chapters 3-5

## Space Weather

* If these eruptive events are directed toward Earth there can be myriad negative consequences (cite NRC report and can go into some detail about the consequences), which provides a practical motivation to study the responsible events in addition to the scientific motivation
* Hard to predict when solar eruptive events will occur
* One popular method relies on using photospheric magnetic field measurements to forecast solar flares, but while a signal exists it not particularly effective for real time prediction (**Mason and Hoeksema, 2010**)
* New routine observations of photospheric vector magnetic field from SDO/HMI are now being used but hasn’t resulted in a windfall of prediction capability – next best observational promise is coronal magnetic field measurements
* Fortunately, CMEs are the most geoeffective type of solar eruptive event but take hours to days to reach the Earth, which makes nowcasting possible using observations of light emitted during the eruptive event; that light only takes 8 minutes to get to Earth and processing of it can take as little as a few seconds.

## Instrument Descriptions

* Describe the instruments to be used in this study and in cited articles
  + SDO/EVE
  + SDO/AIA
  + STEREO/COR
  + SOHO/LASCO

# Mechanisms of Coronal Dimming

(**Mason et al. 2014)**

## Thermal Dimming

## Obscuration Dimming

## Wave Dimming

## Two Possible but Unobserved Dimming Mechanisms

* Doppler
* Bandpass

## Mass-loss Dimming

# Coronal Dimming Case Study

(**Mason et al. 2014)**

## Observations

## Flare-dimming Deconvolution Method

## Error Propagation

## Dimming and CME Parameterization Results

# Semi-Statistical Study of Coronal Dimming

(**Mason et al. 2016b)**

## Observations and Selection Method

## Dimming Fitting Method

## Dimming and CME Parameterization

## Parameterization Error Analysis

## Comparison of Dimming and CME Parameters

# Overview of MinXSS Solar CubeSat

* This chapter can be nearly a copy-paste of the **Mason et al. (2016a)** JSR paper

## Science Objectives

### Solar Flare Studies

### Topics Beyond Solar Eruptive Events

* Since my dissertation is focused on eruptive events, I’ll collapse the quiescent Sun and Earth atmospheric science to a single section with only a few paragraphs

## Mission Architecture

* Consisting primarily of a subsystem breakdown

## Lessons Learned

# Thermal Balance Analysis for a CubeSat

(**Mason, Lamprecht, & Woods 2016c)**

## Thermal Vacuum and Balance Test Procedure

## Thermal Desktop Model

## Model Tuning and Comparison to Test Results

## Predicted Orbital Temperature Performance

## Actual Orbital Performance and Comparison to Prediction

# Summary and Future Work

## MinXSS Summary and Future Work

## Coronal Dimming Summary and Future Work

# Appendix A: Coronal Dimming Event List and Ancillary Data

# Appendix B: MinXSS CubeSat Mass/Power Tables

# Appendix C: MinXSS Thermal Model Parameter Tables