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 Wooods

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)

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Thesis directed by Dr. Thomas Wooods

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.

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Chapter 1

Introduction

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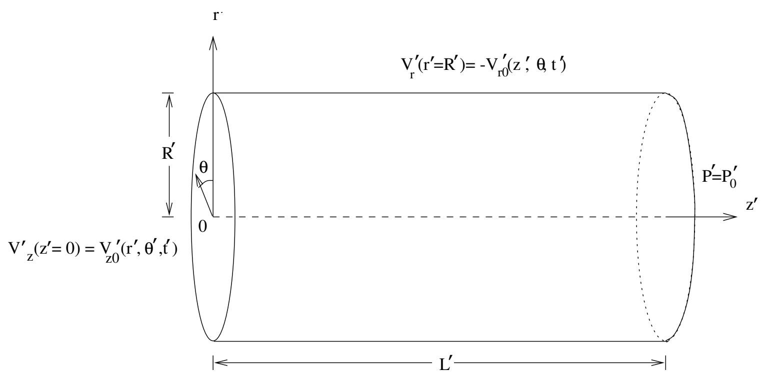

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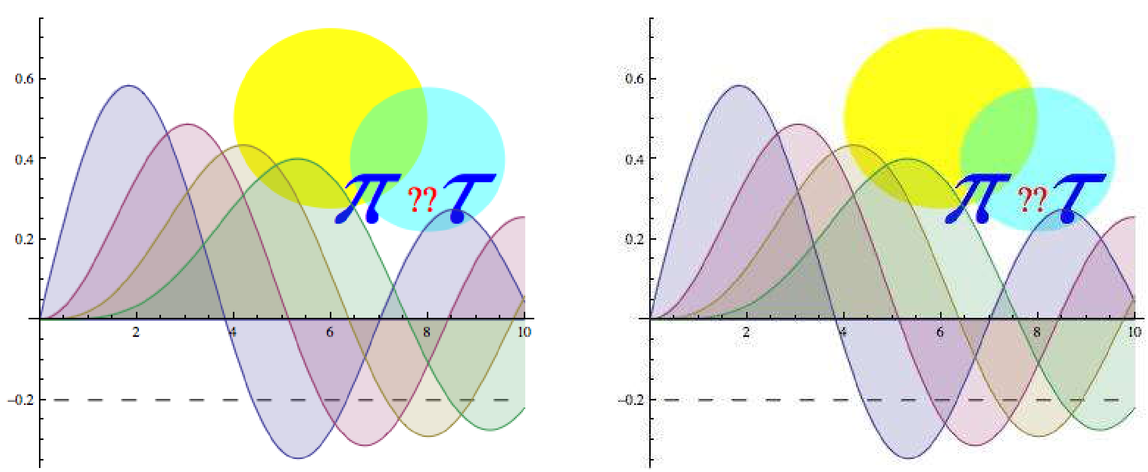

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*kVAr means reactive power.
†kVAd means distortion power.

Chapter 2

Relevant Background

The objective of this fake thesis document is to demonstrate a multitude of LaTeX features as well as features specific to the thesis class. We start by giving one short formula, and one big hairy multi-line formula (one of the non-dimensional Navier-Stokes equations):

$$A = \pi r^2 \tag{2.1}$$

$$\begin{aligned}
\rho\left[\frac{DV_r}{Dt} - M\epsilon^2\frac{V_\theta^2}{r}\right] \quad = \quad & -\frac{\delta^2}{\gamma\ M}\frac{\partial P}{\partial r} + \frac{M\ \delta^2}{Re}\left\{2\frac{\partial}{\partial r}\left[\mu\left(\frac{\partial V_r}{\partial r} - \frac{1}{3}\nabla\cdot\overline{\mathbf{V}}\right)\right]\right. \\
& +\frac{1}{r}\frac{\partial}{\partial\theta}\left[\mu\left(\frac{1}{r}\frac{\partial V_r}{\partial\theta} + \epsilon\frac{\partial V_\theta}{\partial r} - \epsilon\frac{V_\theta}{r}\right)\right] \\
& +\frac{\partial}{\partial z}\left[\mu\left(\frac{1}{\delta^2}\frac{\partial V_r}{\partial z} + \frac{\partial V_z}{\partial r}\right)\right] \\
& \left.+2\ \frac{\mu}{r}\left[\frac{\partial V_r}{\partial r} - \frac{\epsilon}{r}\frac{\partial V_\theta}{\partial\theta} - \frac{V_r}{r}\right]\right\},
\end{aligned} \tag{2.2}$$

2.1 Solar Corona

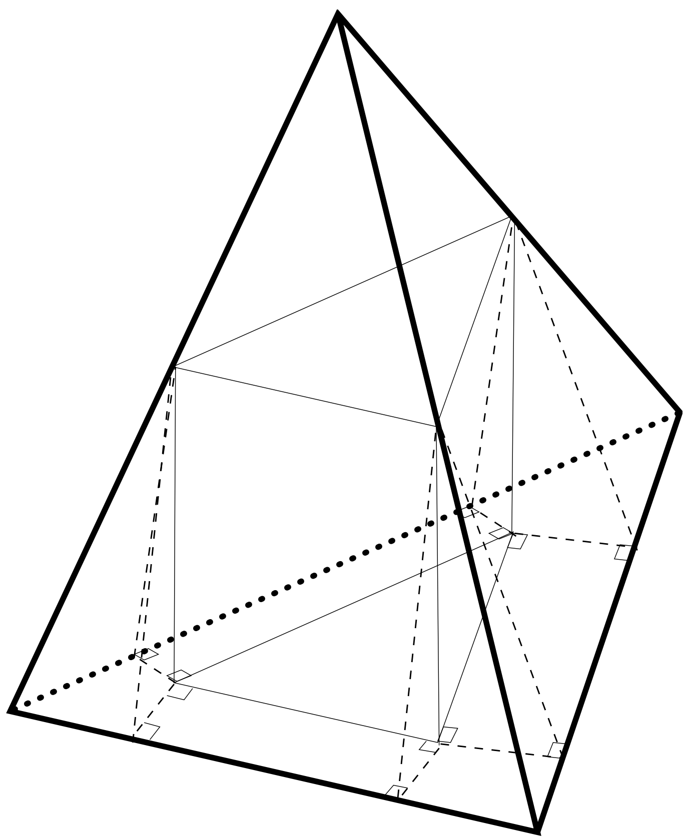
The latter equation is non-dimensionalized using the following definitions:

$$r = \frac{r'}{R'}, \quad z = \frac{z'}{L'}, \quad t = \frac{t'}{t'_a}, \quad \kappa = \frac{\kappa'}{\kappa'_0}, \quad \mu = \frac{\mu'}{\mu'_0}, \quad C_V = \frac{C'_V}{C'_{V0}},$$

where P'_0 is the initial static pressure in the cylinder, and ρ'_0 and T'_0 are the density and temperature of the fluid being injected from the sidewall.

Here is an example of using the macros `\singlespacing` and `\doublespacing`:

Figure 2.1: A triangular pyramid may be cut up as shown, to yield one top pyramid (with one-eighth the volume of the full pyramid), three bottom corner pyramids (which, when joined, are congruent to the top pyramid), three prisms along the bottom edges (the area of whose bottom faces total $B/2$) and the large central prism (volume $= (B/4)(h/2) = Bh/8$). The image, from PDF file "pyr.pdf", was read in using the `\includegraphics` command, from the `graphicx` package.



This paragraph was preceded by the command `\singlespacing`. See the Specifications of the Grad School for instructions about when single spacing is appropriate in a thesis.

And now, here is an example of using the macros `\begin{singlespace}` and `\end{singlespace}`; another way to get single-spacing.

Two cases are studied in the present work which differ only in the boundary conditions. Each different boundary condition model a different source of instability. The boundary of the first case consists of a steady, axisymmetric sidewall radial velocity boundary and a time-dependent, non-axisymmetric endwall axial velocity boundary. The second case is studied with a fixed impermeable axial velocity along the endwall and a combination axisymmetric steady and non-axisymmetric unsteady radial velocity along the sidewall.

Usually you want to use a table produced by some other software, such as Excel, rather than try to do it using LaTeXmacros. If the table is saved/printed to a PDF file, then it can be displayed using the \`includegraphics` macro inside a `table` environment:

Some of the boundary conditions are:

$$z = 0; \qquad V_z = \begin{cases} 0, & t \leq 0 \\ \widetilde{F}_{zw}(r, \theta, t), & t > 0 \end{cases} \tag{2.3}$$

$$z = 0; \qquad V_\theta = V_r = 0 \tag{2.4}$$

$$r = 0; \qquad P, \rho, T, V_r, V_\theta, V_z \text{ finite,} \tag{2.5}$$

$$r = 1; \qquad V_r = F_{rws}(z), \tag{2.6}$$

$$r = 1; \qquad V_z = V_\theta = 0, \tag{2.7}$$

and solutions must be periodic in θ.

If you don't believe this stuff, check out Mulick**?** and Baylor**?**.

2.2 Physics of Solar Eruptive Event Initiation

2.2.1 Just meaningless text to test lines per page

According to the Grad School specs. there should be 24–27 lines of print per page of a thesis. This should be true whether the font size is 10, 11, or 12. Count them up; does this document

Table 2.1: This table wasn't constructed with LaTeX commands, but resides in PDF file (`tableD.pdf`) created by some other software.

n	**n^2**	**n^3**	**n^4**	**n^7**	**n^{13}**
2	4	8	16	128	8192
3	9	27	81	2187	1594323
4	16	64	256	16384	67108864
5	25	125	625	78125	1220703125
6	36	216	1296	279936	13060694016
7	49	343	2401	823543	96889010407

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What is it? This is a labelled paragraph. The heading of the paragraph is emphasized. This is a labelled paragraph. The heading of the paragraph is emphasized.

2.2.2 Space Weather

This is a subsection. Filler filler filler filler filler filler filler filler. Filler filler filler filler filler filler filler filler.

2.2.3 This is another subsection

This is another subsection. Filler filler filler filler filler filler filler filler. Filler filler filler filler filler filler filler filler.

This is paragraph number 2. It used a `\paragraph{}` header, which are always inlined (with extra space) and boldfaced.

This is the third paragraph of the subsection. Filler filler filler filler filler filler filler filler. Filler filler filler filler filler filler filler filler.

2.2.3.1 This is a subsubsection (1)

This is the first paragraph of the subsubsection. Whether it is numbered or inlined depends on the option selected at the beginning of the thesis.

By default, a `\subsubsection` heading is numbered and set off on a separate line, left-justified.

However. Using the `inlineh4` option, subsubsection headers are inlined. And using the `nonumh4` option suppresses numbering of the subsubsections. Together they make subsubsection headings just the same as paragraph headings.

2.2.3.2 This is another subsubsection (2)

Once again, whether its heading is numbered and/or inlined depends on the class options chosen at the start.

There is no "subsubsubsection" entity, and "subparagraph" gets no special treatment in **thesis** class.

2.3 EUV Emission

Finally, this is the end. The bibliography starts on the next page. Note how the `\hyperref` package (mentioned in chapter **??**) also makes hyperlinks from references (e.g., Mulick**?**) to entries in the bibliography.

Chapter 3

Mechanisms of Coronal Dimming

This chapter details the physics of coronal dimming. There are theoretically many physical processes that can lead to an uncareful observer identifying "dimming", which may have little to do with coronal mass ejection (CME). Traditionally, the term "coronal dimming" has been assumed to refer to the void left in the corona after a CME departs. This is one cause of a transient hole in the corona, and is of the greatest concern to space weather forecasters. Typically, a single dimming-sensitive wavelength or band will be observed and analyzed. However, changing temperatures, common during solar eruptive events, cause ionization fraction shifting, resulting in some emissions dimming while others brighten. Additionally, dark material (e.g., a filament) can pass between a bright region (e.g., flaring loops) and the observer, causing a transient dip in emission. Third, solar eruptive events sometimes have associated waves that propagate across the solar disk. These waves are observed as narrow bright fronts with a trailing dark region. The trailing dark region is another way to achieve a transient dimming of emission. Next, there are two ways that Doppler effects can cause transient dips in emission. The first is called Doppler dimming and results from fast moving plasma being sufficiently Doppler-shifted to reduce resonant fluorescence from the solar emission line sources; a phenomenon which is independent of the observation angle. The second occurs if eruptive plasma is moving fast enough in the line-of-sight to shift its emissions outside the bandpass of an observing instrument, which we have named "bandpass shift dimming". The physics, instrument effects, and mitigation strategies for each of these types of theoretically observable dimming are summarized in Table 3.1 and are discussed in detail in the sections that follow.

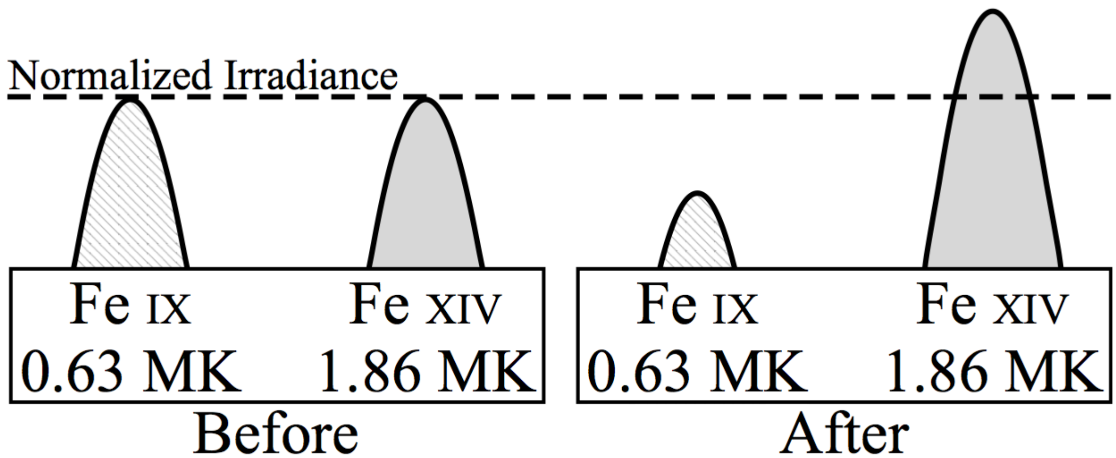
Table 3.1: Summary of physical processes that can manifest as observed dimming

Short Name	Physical Process	EVE Observational Identifiers	AIA Observational Identifiers
Mass loss (Fig. ??)	Ejection of emitting plasma from corona	Simultaneous intensity decrease in multiple coronal emission lines, with percentage decrease indicative of percentage mass lost	Area over and near the erupting active region (AR) darkens
Thermal (Fig. ??)	Heating raises ionization states (e.g., a fraction of Fe IX becomes Fe X); cooling does the opposite	Heating: Emission loss in lines with lower peak formation temperatures and near simultaneous emission gain in lines with higher peak formation temperatures; vice versa for cooling	Heating: Area near AR darkens in channels with lower peak formation temperature and near simultaneous brightening in channels with higher peak formation temperatures; vice versa for cooling
Obscuration (Fig. ??)	Dim feature (e.g., filament material) moves into line-of-sight over a bright feature (e.g., flare arcade)	Drop of emission lines proportional to their absorption cross section in the obscuring material	Direct observation of this obscuration process
Wave (Fig. ??)	Wave disturbance propagates globally, causing compression/rarefaction of plasma as wave passes by	No effects have been identified	Direct observation of this wave process, especially apparent with difference movies
Doppler	Fast moving plasma Doppler shifts away from resonant fluorescence with solar emission lines	Doppler wavelength shift of emission lines and change in intensity, possibly also observed as line broadening	Change in intensity of moving plasma as its velocity changes
Bandpass	Emissions from fast moving plasma have Doppler wavelength shift	Emission line shifts in wavelength or has broadening	Doppler shift convolves with band-pass sensitivity to cause apparent reduction in emission

3.1 Thermal Dimming

Temperature evolution of emission lines is only interpreted as observed dimming if one is not careful to observe co-spatial emission lines at different peak formation temperatures. As plasma is heated or cooled, the ionization fraction changes, necessarily causing the emission intensity to change (Figure 3.1). For example, heating causes some Fe IX to become Fe X and thus, in the absence of competing physical processes, 171 Å emission drops while 177 Å rises. This pattern was identified observationally in Figure 6 of Woods et al. (2011) using SDO/EVE data, Robbrecht and Wang (2010) using STEREO/EUVI, Jin et al. (2009) and Imada et al. (2007) with Hinode/EIS. It can also be observed in the standard composite (multi-wavelength) movies produced by the AIA team; indeed, this is one of the prime purposes for the composites. The initiation time and duration of temperature evolution tends to be quite similar to mass-loss dimming, as they are typically both responses to the rapid release of magnetic field energy in active regions and require several hours of recovery time. Thus, thermal processes could be mistaken for mass loss if only a single spectral line was observed. Ideally, unblended emission lines from an entire coronal ionization sequence (e.g., Fe I to Fe XVIII) could be used to mitigate this convolution of dimming observations. However, as we will show in Section 4.3, it may be sufficient to have observations of two sufficiently separated ionizations states to differentiate between thermal evolution and mass-loss dimming. This is due, in part, to the fact that hotter lines (e.g., Fe XV and above) are primarily emitted from confined loops near the flare and are thus not strongly impacted by mass-loss dimming. Multi-wavelength Doppler studies have shown that while all (measured) emission lines become blue-shifted (indicating an outflow), the magnitude of the shift is strongly directly proportional to the lines peak formation temperature (Imada et al., 2007; Jin et al., 2009). In particular, Fe IX 171 Å emission can be depressed further after open magnetic field lines from the departing CME close down and cause another bout of heating; causing e.g., Fe IX to become Fe X and beyond, which propagates outward as a "heat wave dimming" (Robbrecht and Wang, 2010). It may even be that cool emissions like Fe IX 171 Å are simply moving too slow to account for mass depletion and that warmer lines, such as Fe XII 195 Å better represent the mass being ejected (Robbrecht and Wang, 2010). However, Mason et al. (2014) found that the onset time, slope, and duration of dimming are comparable in SDO/AIA 171 Å and 193 Å[1] and in SDO/EVE 171Å and 195 Å (described in Chapter 4).

Figure 3.1: Schematic depicting the observational difference between dimming and non-dimming emission lines. Relative to a pre-eruption time (left), the Fe ix emission drops while the Fe xiv emission increases (right) due to heating of the plasma and redistribution of ionization states.



It is important to note that, in general, the magnitude of total observed dimming in a given line in EVE spectra is inversely proportional to its peak formation temperature, which can be inferred from Figure 3. This figure was generated using a simple algorithm that searched the EVE catalog for relative irradiance decreases greater than a specified threshold (1%, 2%, 3%) after flares exceeding GOES X-ray class of C1. The window of time searched was bounded by the GOES event start time and the sooner of either 4 hours after the start time or the next GOES event start time. This algorithm was applied to all EVE data from mission start to 23 September 2013. Figure 3 shows that the number of dimmings dramatically decreases as the magnitude threshold is increased, and decreases slightly with higher peak formation temperature. This latter effect is due to flare heating adding emission in the higher temperature, higher ionization state, lines that partially offsets the mass-loss dimming. These trends indicate that at sufficiently high peak formation temperature, no dimming may be observed at all, even at the lowest detection threshold,

[1] Note that the SDO/AIA 193 Å band encompasses 195 Å

which is consistent with the hotter lines being restricted to the confined flare loops and hence experiencing no mass loss. An instrument with spatial resolution like AIA can be used to isolate the confined flaring loops and create a time series of just the dimming region, and this is a procedure carried out in Chapter 4. AIA too has its own limitations: relevant in this case is the relatively lower spectral resolution that blends together emission from several ionization states of Fe. With EVE and AIA combined, it is possible to analyze thermal dimming but the idea instrument for fully characterizing this phenomenon would be a high-resolution hyperspectral imager in the EUV.

3.2 Obscuration Dimming

3.3 Wave Dimming

3.4 Two Possible but Unobserved Dimming Mechanisms

3.5 Mass-loss Dimming

Chapter 4

Coronal Dimming Case Study

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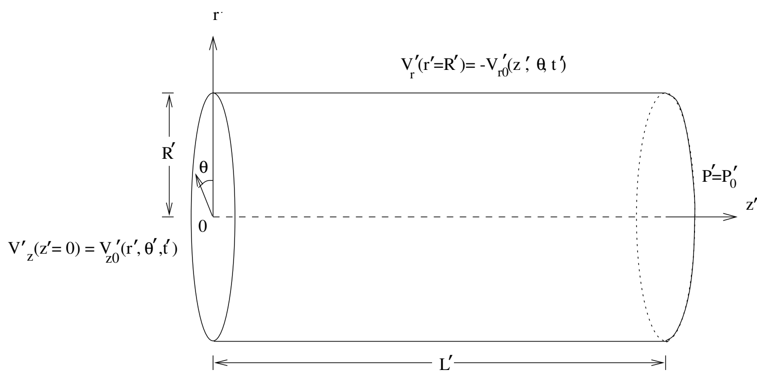

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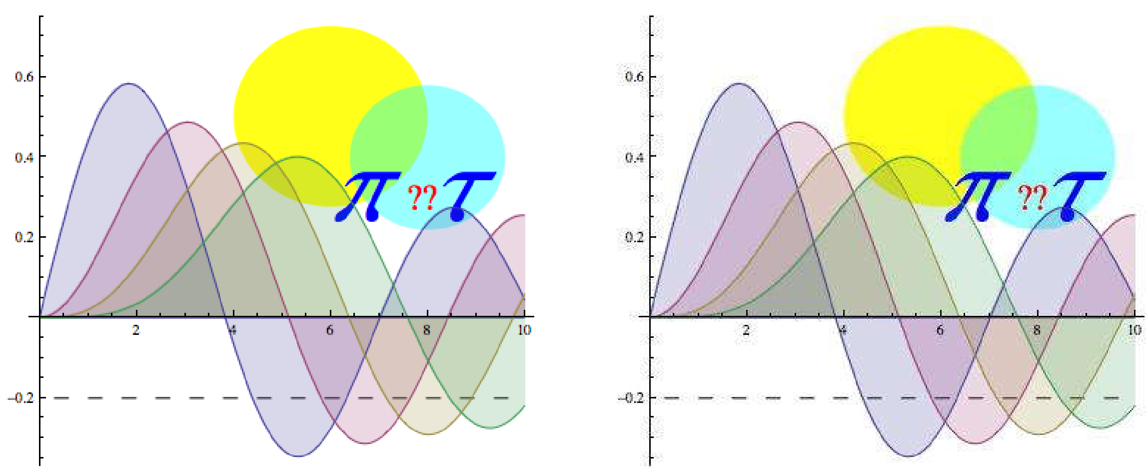

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Chapter 5

Semi-Statistical Study of Coronal Dimming

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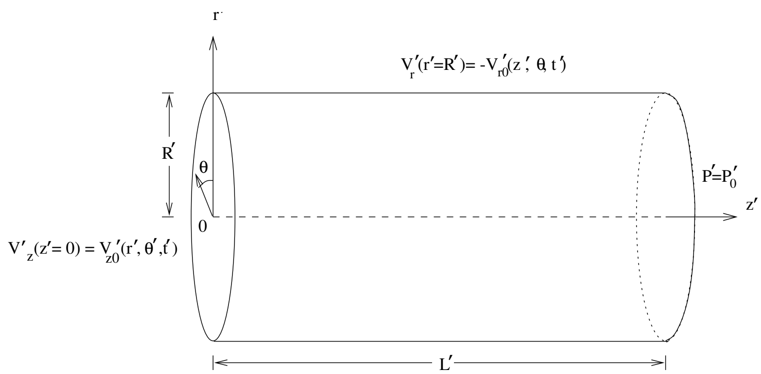

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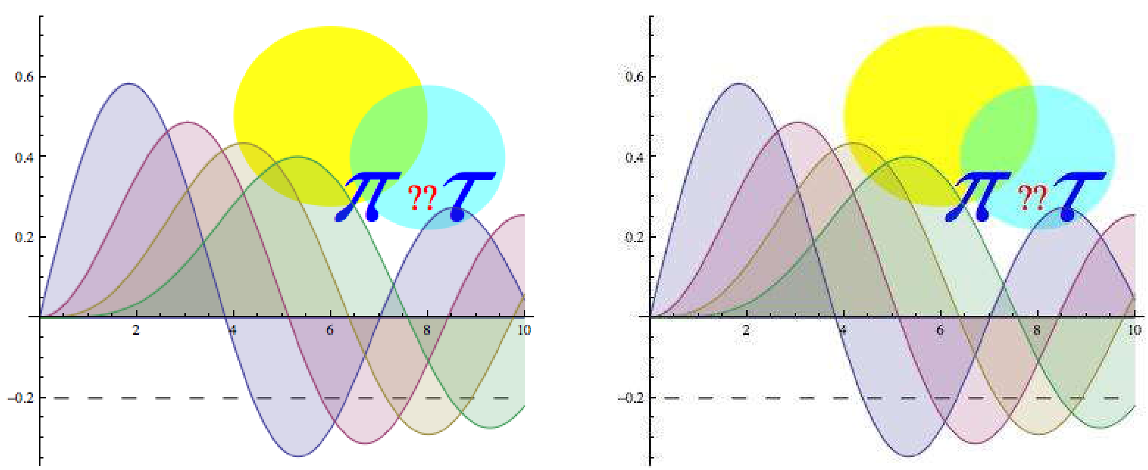

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Chapter 6

Overview of MinXSS Solar CubeSat

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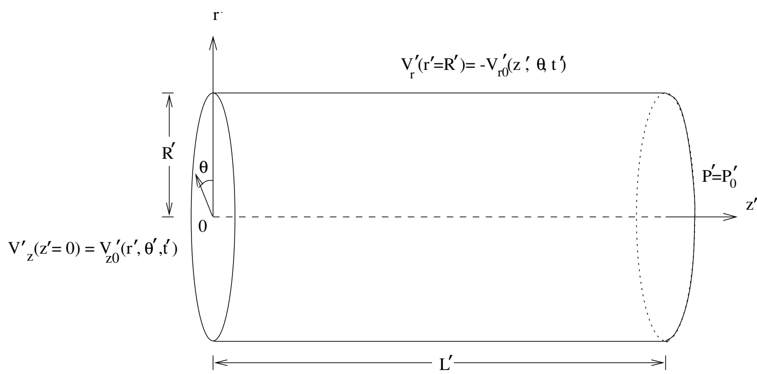

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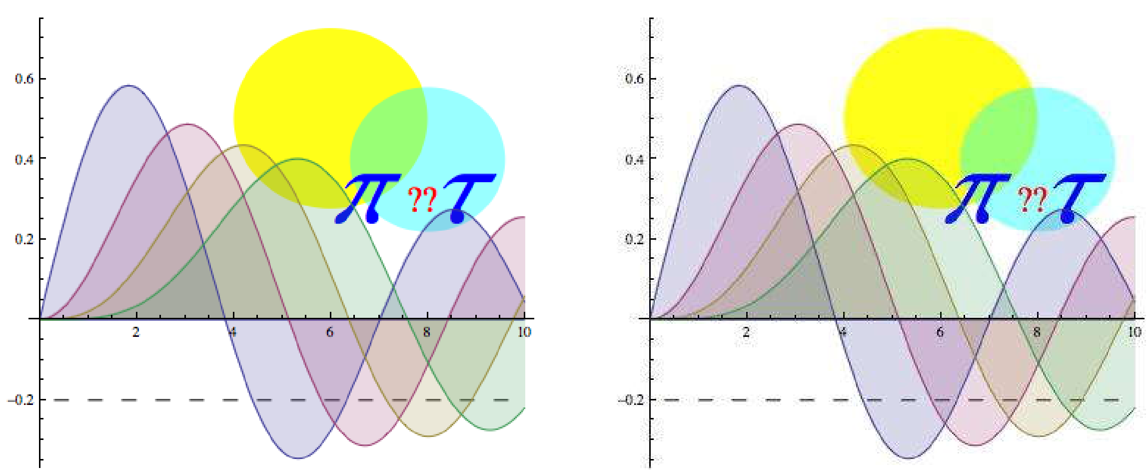

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Chapter 7

Thermal Balance Analysis for a CubeSat

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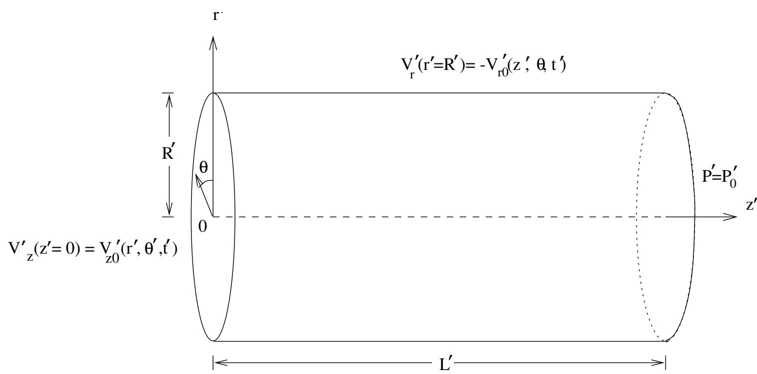

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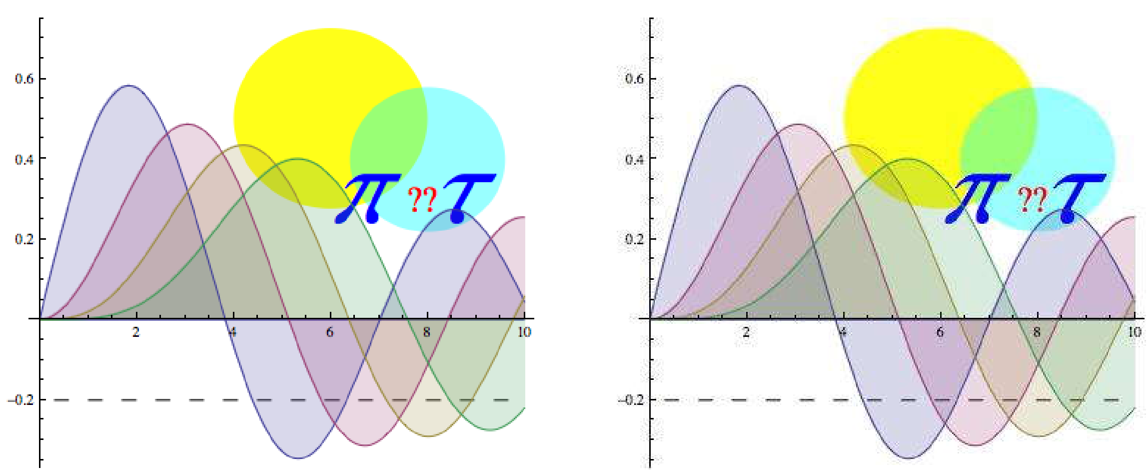

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Chapter 8

Summary and Future Work

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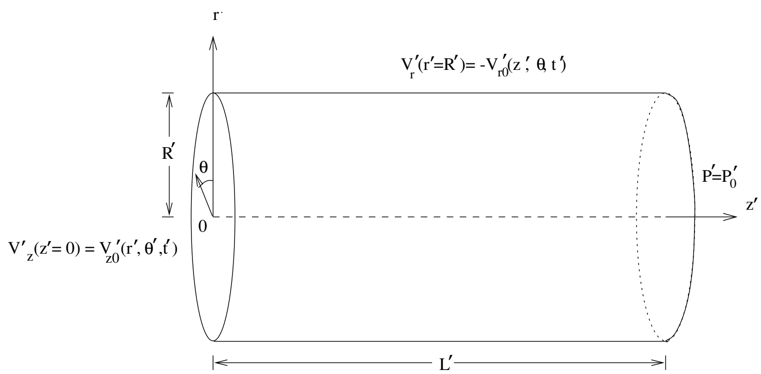

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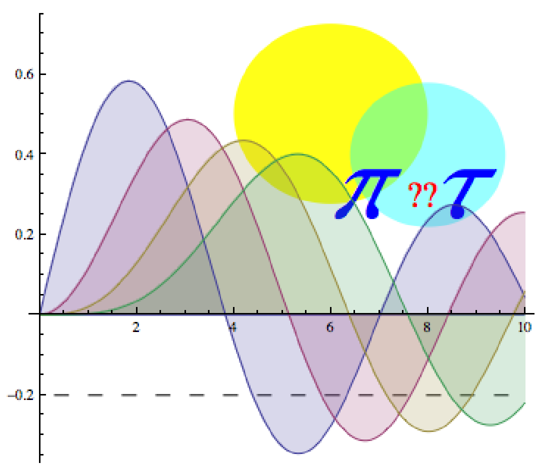

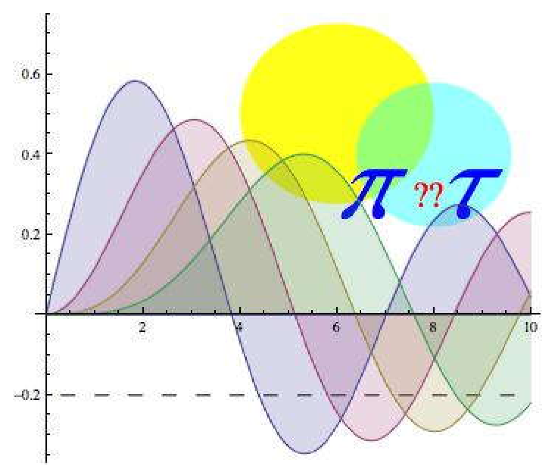

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Appendix A

Coronal Dimming Event List and Ancillary Data

About appendices: Each appendix follow the same page-numbering rules as a regular chapter; the first page of a (multi-page) appendix is not numbered. By the way, the following are supposedly authentic answers to English GCSE exams!

(1) The Greeks were a highly sculptured people, and without them we wouldnt have history. The Greeks also had myths. A myth is a female moth.

(2) Actually, Homer was not written by Homer but by another man of that name.

(3) Socrates was a famous Greek teacher who went around giving people advice. They killed him. Socrates died from an overdose of wedlock. After his death, his career suffered a dramatic decline.

(4) Julius Caesar extinguished himself on the battlefields of Gaul. The Ides of March murdered him because they thought he was going to be made king. Dying, he gasped out: Tee hee, Brutus.

(5) Nero was a cruel tyranny who would torture his subjects by playing the fiddle to them.

(6) In midevil times most people were alliterate. The greatest writer of the futile ages was Chaucer, who wrote many poems and verses and also wrote literature.

(7) Another story was William Tell, who shot an arrow through an apple while standing on his sons head.

(8) Writing at the same time as Shakespeare was Miguel Cervantes. He wrote Donkey Hote. The next great author was John Milton. Milton wrote Paradise Lost. Then his wife died and he wrote Paradise Regained.

(9) During the Renaissance America began. Christopher Columbus was a great navigator who discovered America while cursing about the Atlantic. His ships were called the Nina, the Pinta, and the Santa Fe.

(10) Gravity was invented by Issac Walton. It is chiefly noticeable in the autumn when the apples are falling off the trees.

(11) Johann Bach wrote a great many musical compositions and had a large number of children. In between he practiced on an old spinster which he kept up in his attic. Bach died from 1750 to the present. Bach was the most famous composer in the world and so was Handel. Handel was half German half Italian and half English. He was very large.

(12) Soon the Constitution of the United States was adopted to secure domestic hostility. Under the constitution the people enjoyed the right to keep bare arms.

(13) The sun never set on the British Empire because the British Empire is In the East and the sun sets in the West.

(14) Louis Pasteur discovered a cure for rabbis. Charles Darwin was a naturalist who wrote the Organ of the Species. Madman Curie discovered radio. And Karl Marx became one of the Marx brothers.

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.

Appendix C

MinXSS Thermal Model Parameter Tables

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