Distinguishing Between Thermal and Non-Thermal Electrons in Solar Flares Using X-Ray Observations

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1. Science Summary

A large variety of astrophysical objects are sites of powerful particle acceleration and impulsive energy release. The Sun provides us with an excellent nearby opportunity to study the physical mechanisms that drive these processes. Rapid changes in the highly-stressed magnetic fields of solar flares lead to large-scale energy release of up to $\sim 10^{30}$ ergs per second. These explosions accelerate electrons up to hundreds of MeV and ions up to tens of GeV.

The accelerated electrons are non-thermal, possessing kinetic energies several times the thermal energy of the surrounding plasma. They travel along the field lines and interact with the ambient solar atmosphere, releasing part of their energy as bremsstrahlung X-ray photons. The remaining energy contributes to heating of the atmosphere, driving the plasma temperature to tens of millions of degrees – well above the pre-flare values. Thermal electrons interacting in the hot plasma also emit bremsstrahlung X-rays. We can directly observe the X-ray emission from both populations of electrons.

The non-thermal electron bremsstrahlung observed in solar flares has a characteristic power-law spectrum. From the shape, amplitude, and low-energy extent of the photon spectrum we may directly calculate the total energy contained in non-thermal electrons (Brown 1971; Lin 1974) and determine their kinetic energy spectrum (Johns and Lin 1992). The hard X-ray flux observed in many flares implies that the total energy deposited by non-thermal electrons is of the same order as the total energy output of the flare (Lin and Hudson 1971, 1976; Brown 1973). This suggests a direct connection between flare-energy release and particle acceleration.

Many flare models also predict that non-thermal X-ray emission should be linearly polarized due to beaming of the electrons. The degree of polarization depends on the directionality and amount of beaming (e.g. Brown 1972). By measuring polarization we can learn about the anisotropy of the electron acceleration and assess the validity of these models.

Thermal electron bremsstrahlung has a characteristic quasi-exponential spectrum, in contrast to the non-thermal spectrum. From the shape and amplitude of the thermal continuum, along with an estimate of the source volume, we can calculate the plasma temperature and density, and thereby obtain the total thermal energy of the plasma. This, in turn, allows us to learn how energy is deposited into the solar atmosphere by non-thermal electrons.

The high flare temperatures also ionize coronal atoms and excite atomic transitions that are characterized by spectral line emission. In particular, transitions of highly ionized iron (Fe) and nickel (Ni) generate numerous lines that comprise two "complexes" centered at ~6.7 keV and ~8 keV. Recent calculations by Phillips (2004) show that the equivalent widths and integrated fluxes of these complexes are strongly temperature-dependent. Observations of the Fe and Fe/Ni line complexes can thus provide confirmation of the continuum temperature measurement, and can also allow us to probe the Fe abundance in the solar corona.

2. Observations and Analysis

In order to unambiguously characterize the electron populations in flare plasmas, it is necessary to perform imaging, spectroscopy, and polarimetry at high spatial, spectral, and temporal resolutions. The *Reuven Ramaty High Energy Solar Spectroscopic Imager* (RHESSI) is a Sun-observing spinning spacecraft launched in February 2002, and fulfills that requirement. It is sensitive to hard X-rays and gamma rays from ~3 keV up to ~17 MeV, with an energy resolution of ~1 keV FWHM in the hard X-ray range and ~5 keV FWHM in the gamma-ray range. RHESSI utilizes nine identical coaxial germanium detectors (GeDs) segmented into front and rear portions. Photons incident on the GeDs are individually recorded and tagged with their energy and time of arrival, with an accuracy of a few microseconds.

Imaging is achieved through the use of rotating modulation collimators (RMCs). In front of each GeD, a pair of slit/slat grids separated by 1.55 m act as a collimator with a 1-degree field of view. As the spacecraft rotates, the grids modulate the solar flux incident on the GeDs. Each pair of grids has a different slit width, and thus samples a unique set of spatial frequencies. Through Fourier analysis of the modulated count spectrum, RHESSI is capable of imaging over its entire energy range with an angular resolution down to ~2 arcsec. This also enables imaging spectroscopy, by analyzing images made over discrete energy bands (Lin *et al*. 2002).

RHESSI can also perform limited polarimetry using a beryllium (Be) cylinder that is situated between four of the GeDs. Solar photons incident on the Be block can Compton scatter 90° into the unshielded rear segments of these four GeDs. Since solar photons below ~100 keV are absorbed entirely in the front segments, any photons at those energies measured in the rear segments may have been scattered by the Be block. Photons preferentially scatter perpendicularly to their direction of polarization, and thus any polarized flux that is scattered by the Be block and measured by the GeDs is modulated by the spacecraft's rotation. With proper background subtraction, this allows for polarimetry in the ~20-100 keV range with a polarization sensitivity of as low as a few percent for large, GOES X-class flares (McConnell *et al*. 2002).

Since its launch, RHESSI has observed thousands of flares, including ~200 large flares of GOES class M or higher. Their spectra show what appears to be thermal continuum emission that dominates below ~10 keV, and non-thermal continuum emission that dominates above ~30 keV. The two line complexes of Fe and Fe/Ni are also seen with good statistics in such flares.

Observations of large flares thus provide the best opportunities to simultaneously probe the thermal and non-thermal electron populations. However, the interpretation of the ~10-30 keV emission is ambiguous. During the impulsive phase, non-thermal emission may be significant down to 10 keV or below. Concurrently, peak temperatures in high M and X-class flares can reach above 30MK (e.g. Holman *et al*. 2003), and the thermal X-ray emission of such hot plasmas can be significant up to 30 keV or above. This complicates the determination of the low-energy extent of the non-thermal emission and of any low-emission high-temperature thermal components, both of which are essential to calculate the flare energetics.

Furthermore, calculation of the thermal energy from the photon spectrum is straightforward only for isothermal sources. As large flares tend to be morphologically complex, there is little reason to believe that a single temperature dominates the plasma (e.g. Masuda *et al*. 1994; Tsuneta *et al*. 1997; Warren and Reeves 2001). As such, characterizing high-temperature electron populations purely from thermal continuum emission is difficult (Caspi *et al*. 2003a).

For these reasons, it is imperative to be able to reliably distinguish between thermal and non-thermal emission across all energies and to determine the temperature distribution of the thermal plasma. This determination is essential to understanding the physical mechanisms that drive impulsive energy release and particle acceleration. To that end, observations of the Fe and Fe/Ni line complexes can provide a constraint on the thermal emission, while sensitive polarization measurements can provide a constraint on non-thermal emission.

3. Ongoing Work with RHESSI

Much of my research with RHESSI has been to investigate the Fe and Fe/Ni line complex emission as an independent diagnostic of thermal emission in flares. Thermal plasma is most likely the sole source of line complex emission, as such emission has never been observed from a non-thermal flare source. Thus, observations of the complexes are useful probes of the thermal plasma characteristics, as well as of the Fe abundance at the source.

Although the integrated flux in each complex depends upon the elemental abundances within the source region, ~95% of the emission in the Fe/Ni complex is from Fe excitation. Thus, the *ratio* of the fluxes depends essentially only on the source temperature. Phillips (2004) used the CHIANTI atomic spectral database to predict a specific correlation curve between the flux ratio and the isothermal continuum temperature. Using RHESSI, we may empirically determine both values and use Phillips' predictions to constrain the thermal plasma temperature.

For most RHESSI spectra of large flares, an isothermal continuum fit over the ~5-30 keV range provides a reasonable first-order approximation of the dominant plasma temperature. Also, because RHESSI cannot resolve the individual lines that comprise the Fe and Fe/Ni complexes, each complex appears as a single pseudo-Gaussian "line" about 1 keV wide. For a given flare, we can build an empirical correlation curve between the continuum temperature and flux ratio by dividing the flare into multiple time intervals and then simultaneously fitting two Gaussians and an isothermal continuum to the spectrum at each interval. I have performed this analysis on a number of large flares, and have verified that a strong temperature correlation does indeed exist for each flare. My early results were crucial in identifying and correcting a significant error in the initial predictions due to incomplete modeling of the atomic excitations by the CHIANTI code (Caspi *et al.* 2003b). The code was subsequently revised, and the predictions now match some of the flare data very well.

However, the temperature/flux ratio correlation curves do not often agree from flare to flare. One possible explanation is the existence of multi-thermal temperature distributions. Each temperature component in a multi-thermal plasma would contribute to the fluxes in the complexes, and thus the flux ratio would depend upon the specific temperature distribution. The flare-to-flare differences between the correlation curves may imply a different distribution of plasma temperatures within each flare (Caspi *et al.* 2004a). Lately, I have been exploring the contributions of a multi-thermal temperature distribution to the Fe and Fe/Ni line complexes (Caspi *et al.* 2004b). Additionally, I am working on utilizing the line complexes to provide limits on the temperatures and emission measures present in such a distribution.

I intend to continue this line of research to develop the Fe and Fe/Ni line complexes as diagnostics and constraints of the thermal flare emission.

4. Position-sensitive Polarimeter Development

X-ray polarimetry may offer the desired constraints on the non-thermal flare emission, to aid in distinguishing it from thermal emission. Many flare models predict an X-ray source polarization of >10% due to beaming of the non-thermal electrons. In contrast, thermal electron populations are generally isotropic and thus thermal emission should exhibit no source polarization, although backscatter from the photosphere can contribute a polarization of ~4% (Bai and Ramaty 1978). Thus, the level of polarization is a good discriminator of non-thermal emission. Previous measurements have claimed to show polarization in flares (e.g. Tindo *et al.* 1970), but most of the results were questionable due to calibration and instrumental problems.

Recently, McConnell *et al*. (2004) analyzed RHESSI data to search for evidence of polarization in flares. They took the primary measurements from two GeDs directly adjacent to the Be block. As background, they took the signal from a similarly-oriented pair of GeDs far from the Be block, which would therefore not see any flux scattered by it. Their analysis revealed a polarization of ~20% in the 20-40 keV band for the 23 July 2002 flare. The measured angle of polarization is inconsistent with polarized emission from the flare footpoints. Determining the true source of polarization would help determine the location and mechanism of electron acceleration in flare loops.

Unfortunately, polarimetry with RHESSI is complicated by high background. A large fraction of the total signal is from backscatter of solar photons from Earth's atmosphere or from other parts of the spacecraft. Proper subtraction of this background requires complicated modeling that may itself be prone to error. The passive nature of the Be scattering block does not allow us to selectively analyze only scattered photons. Other polarimeter designs, such as the SOLPOL detector, work around this problem by using an active scattering core to simultaneously scatter and detect photons (McConnell *et al*. 2000). However, these detectors are not sensitive below ~40 keV, as the Compton scattering cross-section becomes negligible compared to the cross-section for photoelectric absorption. As such, Compton-based polarimeters are inherently limited to observing only the non-thermal parts of flare spectra, and are thus of limited use in distinguishing between thermal and non-thermal emission.

To overcome this limitation, I propose to develop a new position-sensitive polarimeter based on photoelectric absorption, which would take advantage of the dominant photoelectric cross-section in the ~5-50 keV range. Upon absorption of an X-ray photon, a photoelectron is emitted in a direction strongly correlated with the original photon's electric field. By imaging the track of the photoelectron, it is possible to measure the emission angle and thereby obtain the polarization of the parent photon. By measuring the photoelectron's energy, we can directly obtain the energy of the parent photon as well.

The recent demonstration of photoelectric polarimeters based on micro-pattern gas detector (MPGD) makes astronomical X-ray polarimetry a viable pursuit (Costa *et al*. 2001). Currently these detectors are optimized for soft X-rays below 10 keV, and are intended for observing astrophysical sources. I propose to adapt these detectors for solar observations, specifically to measure polarization in solar flares in the ~5-50 keV range.

MPGDs are essentially gas proportional counters with a small drift gap for photoelectric interaction. Coupling the proportional counter to a pixelized readout anode with ~100 micron pitch provides high-resolution (sub-pixel) position sensitivity with good (~15% FWHM) spectral resolution. A typical photoelectron track spans tens of pixels, and thus its direction of emission – and hence the polarization of the incoming photon – can be measured with an accuracy of a few degrees (e.g. Black *et al*. 2003; Bellazzini *et al*. 2004).

For solar polarimetry, we require sensitivity over the ~5-50 keV range to observe both the thermal and non-thermal X-ray emission in flares. I will investigate different filling gas mixtures and pressures to achieve sensitivity over this range. I will also explore different detector configurations – including drift gap heights, pixel sizes, and possible filter schemes – to determine the optimal configuration that will meet the desired science goals using the technology available in mid-2007, which is when I currently plan to model, fabricate, and test a prototype.

The eventual goal would be to develop a position-sensitive spectro-polarimeter capable of measuring source polarization in solar flares. Such an instrument would likely employ multiple detectors with different filling gases to optimize sensitivity across the entire energy range of ~5-50 keV. With proper design, an instrument based on MPGDs will be capable of measuring a polarization of as low as 2-3% for M- and X-class flares in only ~1-10s of integrating time. This sensitivity would allow us to measure polarization in non-thermal emission if it is present, and would also allow us to detect the small polarization predicted for thermal sources. Also, the proposed detectors could, in principle, be coupled with suitable X-ray optics to allow imaging polarimetry, which may be developed at a later time.

I plan to collaborate extensively with Dr. Brian Dennis and Dr. Philip Deines-Jones, both at NASA Goddard Space Flight Center. Dr. Dennis is the RHESSI Mission Scientist and has extensive expertise in the scientific analysis of solar flare observations. Dr. Deines-Jones is a leader in the use and development of MPGDs for X-ray polarimetry. During the detector development, I plan to utilize existing GSFC resources, including detector prototypes, simulation code, and testing facilities. The proposed adaptations of MPGDs for solar polarimetry will benefit not only solar physics, but also X-ray polarimetry in general.

5. Proposed Schedule

I entered the Ph.D. program at UC Berkeley in August 2001, and began my research at the Space Sciences Lab in February 2002. I passed my preliminary exams in September 2002 and plan to take my Ph.D. qualifying exams in June 2005. I will earn my M.A. in May 2005 and my Ph.D. in May 2008, after completion of the proposed thesis work.

6. References

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