Thermal X-ray spectroscopy with RHESSI

1. Objective of Proposed Work

Solar active regions and flares emit a wide range of radiation extending from radio waves through γ-rays. The focus of this proposal will be the X-ray emission from the high temperature plasma that is present in flares. In particular, we seek to use data from RHESSI data along with that of other instruments, (GOES, GOES-SXI, TRACE, EIT, CDS) when it is available to describe the thermal emission from solar flares. This is important for calculating the energy released in flares not only because this will provide good estimates for the energy in the thermal plasma itself, but it is also crucial for good estimates of the energy that is contained in the nonthermal electrons accelerated in flares.

The RHESSI spacecraft observes solar X-rays in the energy range from 3 keV to approximately 18 MeV. It has the ability to detect emission from plasma with temperature greater than 5 MK. From RHESSI data, we can obtain images with 2 arcsec spatial resolution, and spectra with energy resolution better than 1 keV (Lin et. al. 2002). Since February 12, 2002 RHESSI has observed thousands of flares, including tens of GOES X-class flares, the largest of these phenomena. While plasma temperature may reach $\sim 10 - 15$ MK in an average flare, the temperature in X-class flares can reach 30 MK or beyond (Holman et. al. 2003). At these temperatures, the thermal X-ray emission can be significant up to ~ 30 keV or above, and thus is clearly visible in RHESSI spectral data. These powerful flares tend to be large and morphologically complex, and include a wide distribution of temperatures. In fact, observations show that the solar flare plasma is not isothermal for even for small flares of GOES C and B class (McTiernan, et. al. 1999). The value of temperature measured using the isothermal assumption always depends on the wavelength band or energy range of the detector used.

This complicates the analysis of the thermal emission, but it is not the only complication. The highest temperatures generally occur during the impulsive phase and peak of the flare, when nonthermal emission is also significant down to 10 keV. Relatively low temperature emission dominates below 10 keV, and high temperature emission is most directly observable in the 10-30 keV range, where it is difficult to distinguish from (or may be entirely obscured by) nonthermal emission. As such, characterizing high temperature electron populations purely from thermal continuum emission in the isothermal approximation is problematic (Caspi et. al. 2003a).

A solution to this problem is to obtain the differential emission measure (DEM) for a range of temperatures. Recently there has been work with DEM calculations for active region loops using SOHO CDS data. From CDS data one can recover the DEM in the range from appoximately 10^4 K up to 3×10^6 K (Harrison et. al. 1995; Schmelz et. al. 2003). This covers a large part of the range of temperature present in solar flares, but not the whole range, also CDS data for flares is rare. There has been very little work done using the DEM for solar flares (e.g., McTiernan, et. al. 1999; Fludra & Schmelz 1999; Kepa & Sylwester 2002); this is a process that requires the use of multiple instruments. We have a well-defined and proven method for combining data from different instruments to obtain the DEM and will use that in the proposed study.

For the proposed work we will:

(1) We will use multi-temperature spectral fits to reconcile the differences between isothermal model predictions and observations of the ratios between the 6.7 keV Fe line complex and the 8 keV Fe-Ni line complex observed by RHESSI in solar flares.

(2) We will use RHESSI imaging spectroscopy, along with data from other X-ray and EUV instruments, to spatially separate thermal from nonthermal sources in solar flares, and obtain estimates of the energy in the thermal and nonthermal components.

(3) We will use multi-temperature multi-instrument spectra to characterize the thermal emission for a large sample of flares to estimate the energy in the thermal and nonthermal components, and perform a statistical study to obtain the energy distribution in thermal and nonthermal energy for flares.

2. Fe and Fe-Ni line ratios in flares

Atomic physics presents a useful method of determining the flare temperature distribution. In particular, iron (Fe) and nickel (Ni) generate numerous lines that comprise two line complexes centered at 6.7 keV and 8 keV. Recent theory shows that the integrated fluxes in each of these two line complexes are strongly temperature-dependent, suggesting that they may be useful as diagnostics of the dominant plasma temperature in flares (Phillips 2004).

Fig. 1.— RHESSI photon spectrum of the 23-July-2002 X-class flare.

These two line complexes are visible in most RHESSI flare spectra. Figure 1 shows an example of this for the X-class flare that occurred on 23-July-2002. The 6.7-keV Fe complex is more easily excited at lower temperatures, and thus is strongly seen in all but the smallest flares. The 8-keV Fe/Ni complex requires higher temperatures, and thus is seen with good statistics only in flares of GOES M-class flares or larger. Although the flux within each line complex is dependent upon the elemental abundances within the emission region, Fe and Ni abundances tend to be statistically equal; thus, the ratio of the fluxes should be dependent only on the temperature at the emission region. Phillips (2004) predicted a specific correlation curve between the flux ratio and the isothermal continuum temperature. Using RHESSI, we may obtain these values empirically and thus obtain an empirical correlation curve, which may be useful in flares where the line complexes are easily observed and the thermal emission is not well-fit by an isothermal continuum.

Using the RHESSI spectral data for various large flares, one can approximately fit the 5-30 keV range with an isothermal continuum. This is not often the best fit, but is a good first-order approximation of the dominant plasma temperature. RHESSI has better than 1-keV FWHM spectral resolution at these energies but cannot resolve individual lines within the complexes, thus the data shows each line complex as a single line about 1 keV wide that can be modeled as a Gaussian. By simultaneously fitting two Gaussians and an isothermal continuum to each spectrum, we obtain the best-fit continuum temperature and flux ratio, which we may then correlate for each flare. Preliminary results from six large flares verify that a strong temperature correlation does indeed exist. However, although the six correlation curves appear well-defined and have the same general shape and amplitude, they do not match each other. Further, none of the empirical curves even closely matches the theoretical curve (Caspi et. al. 2003b). One possible explanation points again to multitemperature temperature distributions. Since the flux in the line complexes comes not from an isothermal plasma but from a multitemperature distribution, the flux ratio is dependent upon the distribution parameters, and thus the difference in the correlation curves may imply a different distribution of plasma temperatures within each flare.

The first task of the proposed work will be to use multitemperature spectra to reconcile the observed flux ratio to the theoretical one for the sample of large flares. This is a preliminary step to our fitting DEM models to a large sample of flares.

McTiernan, et. al. (1999) used the following technique to obtain the DEM for solar flares using Yohkoh SXT and BCS data: The temperature range is divided into bins and an emission measure is assigned to each bin. The amount of emission measure in the bins is then varied to minimize χ^2. For the SXT-BCS work, four bins were used for the range between 3 and 30 MK, since there were only five data points available. This histogram-DEM typically fit the data well, but was improved by using the histogram-DEM as the starting point for a Maximum Entropy Method (MEM) calculation., with 1 MK bins.

For work with RHESSI, we have more data points; RHESSI spectra can be binned down to any energy channel size $\geq 1/3$ keV. This will allow us to use tempreature bins of width

1 MK in the initial calculation, which removes the the need for the MEM step. Nonthermal emission will be included in this fitting process in the form of a broken power law with a low energy cutoff. The parameters of the nonthermal spectrum will be fitted along with the DEM, for a self-consistent final result. Thus for each flare, we will:

- Fit the continuum emission to a DEM model with 1 MK resolution between 5 and 30 MK.
- Fit the continuum + line emission to a DEM model with 1 MK resolution between 5 and 30 MK. If the continuum DEM and the continuum + line DEM do not match, then we will vary abundances and ionization equilibria until we obtain consistent results.

3. Imaging Spectroscopy

Currently there exists no good method for separating the thermal emission from nonthermal emission in a solar flare. As previously mentioned, this is important when discussing the energy balance issues for flares. For large flares, the thermal emission can extend to energies exceeding 30 keV, well beyond the point at which flare emission is often assumed to be nonthermal. Work by Kane et. al. (1992) and more recently by Krucker et. al. (2002) has shown that in some cases (partially occulted flares and microflares, respectively) the nonthermal component dominates the emission down to below 10 keV.

Fig. 2.— Image of the 23-july-2002 solar flare in the 6.3 to 7.3 energy band; the contours show the emission in the 25 to 50 keV energy band.

RHESSI Imaging Spectroscopy offers the opportunity to distinguish spatially between thermal and nonthermal sources. An example is shown in Figure 2, which shows images of the X-flare on 23-oct-2002. The image shows the emission in the 6.3 to 7.3 keV band that contains the Fe line complex discussed in the previous section. Note that this image includes the continuum emission but has been corrected for the effects of 16-17 keV photons which are seen in this energy band due to K-shell escape (Smith 2002). The contours show the nonthermal emission from loop footpoints, with the low energy thermal source between the footpoints, high in the corona (Emslie et. al. 2003).

RHESSI data can be used for source-based imaging spectroscopy. This is not comparing pixel to pixel as is often done for TRACE, EIT or CDS data, but obtaining spectra for different source regions such as those shown in the figure (see e.g., Emslie et. al. 2003). Ideally, we would like to get the DEM that includes low (> 5 MK) temperatrue plasma, since this will give a better estimate of total plasma energy. In this case the TRACE data can be combined with the RHESSI data for the thermal source. As described in the previous section, we have a well-defined, proven method of recovering the differential emission measure using data from multiple instruments. This was used by McTiernan, et. al. (1999) for solar flares using Yohkoh SXT and BCS data, and has been more recently been used by McTiernan & Klimchuk (2003) to recover the quiet-sun DEM using RHESSI and GOES12-SXI data. (A sample of the RHESSI-SXI DEM is shown in Figure 3). We will apply this method to the spatially distinct thermal sources that can be found in well-observed flares. The ideal combination of instruments for this study will be RHESSI, TRACE (or EIT) and SXI. In Figure 4, we show selected temperature response curves. Using the combination of wavelength bands/energy channels shown, we can get estimates of the DEM for temperatures from 0.2 MK up to 30 MK. The nonthermal component will be obtained separately from the thermal component by fitting traditional broken power law spectra.

Fig. 3.— The differential emission measure as measured by RHESSI and SXI

Fig. 4.— Temperature responses for different instruments, curve A is the TRACE 195 A filter, curve B is the SXI P_MED filter, curve C is the SXI B_THN filter, curve D is the RHESSI response in the 5.3 to 6.3 keV range, curve E is the RHESSI response including only the Fe line complex.

The first task for this work will be to obtain a good sample of solar flares. the requirements will be as follows: (1) The flares need to be relatively large, probably GOES M class or higher, to insure that there are enough photons available for imaging spectroscopy. (2) The morphology of the flare must be such that it is easy to see the difference between the thermal and nonthermal sources, and do separate spectral calculations. For this purpose, we also will use context data from other instruments, such as TRACE, EIT and MDI, which will allow us to locate the different sources with respect to the magnetic configuration in the active region in which the flare is located.

Once a representative sample of flares has been found, we will:

- Create RHESSI images in 1keV energy bands for the energy range from 3 to 20 keV.
- Establish that the source is dominated by thermal emission by checking for the presence of the Fe ine in spectra created from what we expect to be the thermal source. From the work described in the previous section, we will have a good idea of how much line emission we expect form a thermal source.

- Next, use these images to obtain the DEM. There is a trade-off involved, the temperature resolution of the DEM will not be nearly as good as for the non-imaged case. If there is good data available from lower T instruments, such as TRACE, EIT SXI, or CDS, we will include this data. This will give us a good estimate of the energy in the thermal plasma. We will also be able to get a good estimate for the energy "missed" by RHESSI by comparing the DEM for multi-instrument fits with the DEM obtained using only RHESSI data.
- Fit spectra to the nonthermal sources. From this we get a good estimate of the balance of energy between the thermal and nonthermal components.
- These results will be compared to the results obtained using non-imaging spectroscopy techniques.

4. Nonthermal and Thermal Emission, without Imaging Spectroscopy

We intend to use the imaging spectroscopy techniques on as many flares as can be analyzed. The use of imaging spectroscopy, however, requires "well-observed" flares; flares with imaging data from multiple instruments, and also a geometry for which we can clearly distinguish between the thermal and nonthermal sources. For most flares, imaging spectroscopy will not be an option. If we are to make a truly general conclusion, we need to analyze thousands of flares. The only data that is available for a majority of RHESSI flares is RHESSI and GOES data.

We propose to use this data to examine the relationship between thermal and nonthermal emission for a large sample of flares. As mentioned in section 1, we are extending the non-parametric method of obtaining the emission measure distribution to include the effects of nonthermal emission. To model the DEM, we divide the temperature range into bins and assign an emission measure to each bin. The amount of emission measure in the bins is then varied to minimize χ^2. The expansion to this method adds nonthermal emission in the form of a power law spectrum with a low energy cutoff. Using GOES and RHESSI data we can get good temperature coverage in the range from 2 to 30 MK.

We will do this for every flare that RHESSI has observed. The result of this work will be quantitative measures of the energy included in the high temperature thermal plasma and in nonthermal electrons for a large sample of flares, from the largest flares down to microflares. Using these results we will be able to to do statistical studies of flare size and energy (Crosby, et. al. 1993; Bromund et. al. 1995, but without the need for assuming that the nonthermal electron distribution has a constant low energy cutoff. In particular, we will be able to get an improved estimate of the frequency distribution of solar flares as a function of energy, and also of the correlation (if any) between flare size and the relative amount of energy in nonthermal electrons. This has important consequences for the nanoflare model of solar heating (Parker 1988; Cargill & Klimchuk 2004 The statistical studies of flares show that the size distribution is a power law with a slope of approximately $\delta = -1.8$, i.e., the number of flares with a given energy E in hard X-rays is given by $N(E) = CE^{-1.8}$. It was pointed out by Hudson (1991) that the energy distribution for small flares would need to have a slope of -2.0 in order for impulsive heating of the solar corona. If the nonthermal electron spectrum extends down to energies less than 10 keV for small flares, as implied by Kane et. al. (1992) and Krucker et. al. (2002) then the slope of the energy distribution may change, because the relation between flare size as measured by energy in photons and flare size as measured by energy in electrons may change as a function of flare energy. Or it may not change, in either case this will be an important result.

For the statistical studies we will use non-parametric methods, (Lee et. al. 1993) to account for selection effects. We will collaborate with Dr. James A. Klimchuk of NRL for the statistical study. The proposed work will proceed as follows:

- First choose the sample of flares. We will analyze every RHESSI flare for which there is GOES data, and which is not interrrupted by data gaps, particle precipitation events, or the South Atlantic Anomaly. Presently this includes approximately 10000 of 13901 total events in the RHESSI flare list. We will not restrict the study to flares which were observed without attenuators, unless we notice systematic differences in the results dependent on attenuator state. (RHESSI has attenuators that slide in front of the detectors at high count rates; these cut down the low energy count rates, to increase the dynamic range, seeLin et. al. (2002). Approximately 3000 flares have been observed with the attenuators in.) Since the RHESSI flare list is compiled for flares in the 12 to 25 keV channel, we are assured that there are enough photons in the lower energy range to allow good spectra for these flares.
- Next we will apply the spectral fit procedure for the flares. As stated, we will vary the emission measure in temperature bins, and also vary the temperature range (and thus the number of bins), along with the power law parameters. From the DEM and nonthermal power law, we will obtain estimates of the energy in the thermal plasma and nonthermal electrons. For the nonthermal electrons we will use numerical results based on the standard thick-target model (Leach & Petrosian 1983; McTiernan & Petrosian 1990) to obtain the energy estimate.
- The final step is to obtain the distribution of flare energy in thermal plasma and nonthermal electrons, applying non-parameteric methods to account for selection effects.

5. Impact of Proposed Work

6. Relevance of Proposed Work to the NASA Programs/Objectives

7. Work Plan and Personnel

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