

The Probability for Two Distinct High-Temperature Components in the 23-July-2002 Solar Flare

J. McTiernan

A. Caspi

Space Sciences Lab, University of California

For RHESSI observations of large solar flares, the thermal component often is best fit by a two-temperature model. It is not clear, however, that there truly are two distinct components, since the typical spectral fitting process only allows two components. In this calculation we allow as many components as needed in the temperature-dependent emission measure distribution, $EM(T)$. We then ask the question: Does the best-fit $EM(T)$ function resolve into two easily-identifiable components?

We use RHESSI data from the X-class flare of 23-July-2002 and recently developed calibrations and pulse-pileup corrections for the data analysis. We also include a discussion of the fitting process and the expected temperature resolution for the RHESSI spectrometers, since this is crucial information for our calculation.

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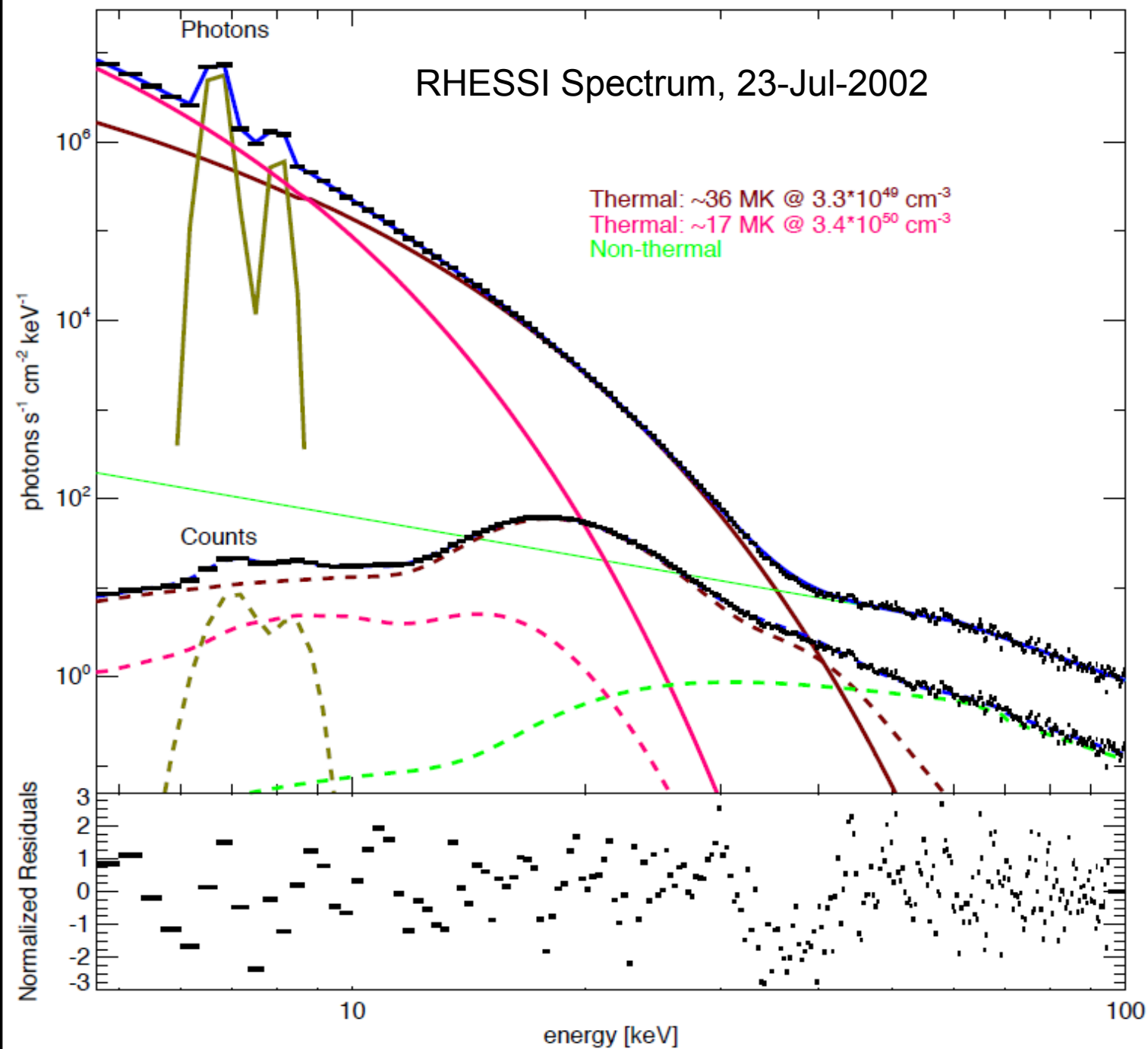


Fig.1: This shows the photon and count spectrum for an interval of the 23-Jul-2002 X flare for RHESSI detector #4. Energy channels are 1/3 keV in width, from 3 to 100 keV.

The spectrum is fit best by a two component thermal model with a nonthermal power law at high energy. The line complexes at 6 and 8 keV are fit separately. For the calculations in this study we consider only the thermal continuum.

See A. Caspi, 320.01D and ask about details regarding calibration and pulse-pileup calculations.

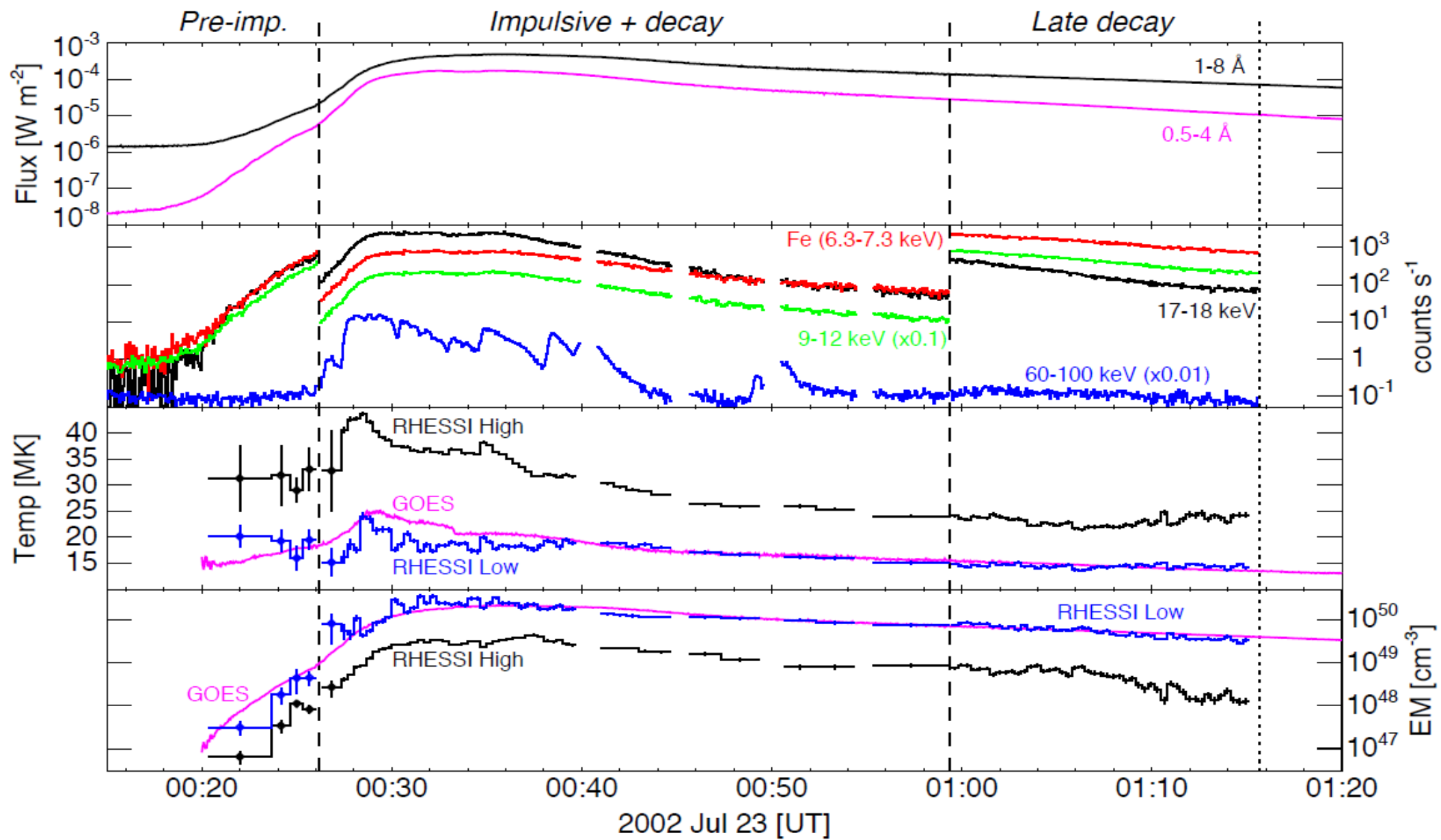
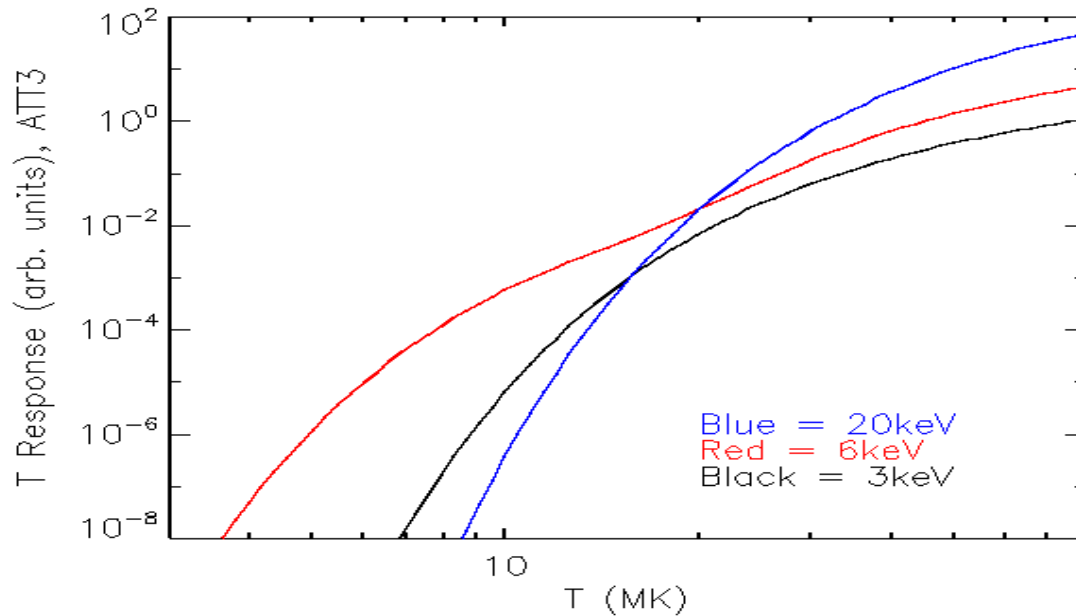


Fig 2: This plot shows GOES and RHESSI time histories for the flare. The Low T RHESSI component is similar to the GOES temperature.

Fig 3. Re: response matrices: We use a temperature response matrix obtained by integrating photon flux over the detector response matrix. The T response for RHESSI was calculated using the SSW program CHIANTI_KEV, (based on CHIANTI 5.2 (Young, et al. 2003, Ap.J Supp. 144, 135)). Coronal abundances were used. Note that responses increase monotonically.



Given $EM(T)$, model counts in channel i :

$$m_i = R_i(T) \int [EM(T) * dT]$$

- Gain offset and pulse-pileup are accounted for by adjusting the model count rate before comparison with observed data.
- The fit procedures use an Amoeba function for minimization of χ^2 and a Monte Carlo procedure to calculate uncertainties.
- Fits are to continuum thermal component – Observed counts spectrum minus the expected counts spectra for nonthermal and lines.

Methods for EM(T) calculation: NTEEMFIT

- NTEEMFIT: The EM(T) is a series of delta-functions. This is similar to the typical single or two-temperature fit, but calculated differently, and has the option of more than two components.
- For $i = 1$ to n data points, for nt temperature components, obtain reduced χ^2 , defined as:

$$\chi^2 = (n - 2nt)^{-1} \sum_{i=1}^n (m_i - o_i)^2 / \sigma_i^2$$

- o_i is the observed count rate in each RHESSI channel, m_i is the model count rate, and σ_i is the uncertainty in the observed count rate.
- This will eventually find a minimum value as nt increases. This tells us the fewest degrees of freedom needed to fit the data.
- For this case we hope that we get two components with T and EM close to the values given by the traditional fit process. This turns out to be true for most of the flare time intervals studied.
- This also provides a sanity check for the T response curves. If the T and EM values found here are much different from the traditional two-temperature fit, then there may be a problem.

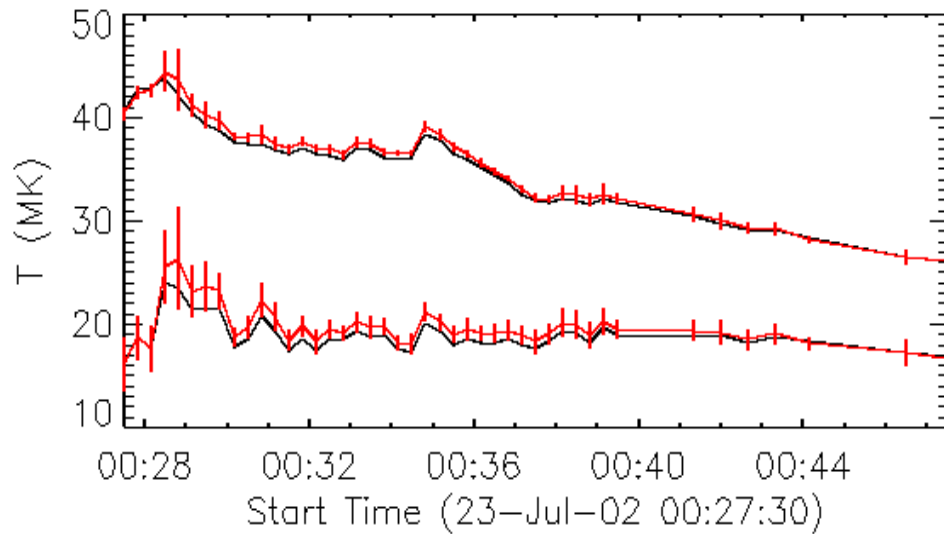
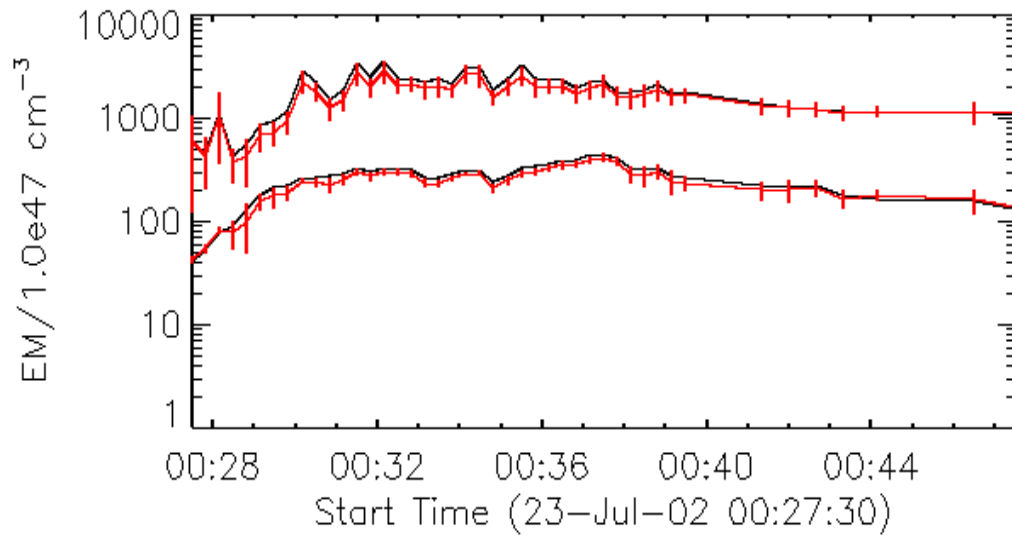


Fig 4. Sanity check. The top plot is the EM and the bottom plot is T. The red lines with error bars are for the two component NTEEM delta-function fit and the black lines are the original fit parameters from spectra using the SSW OSPEX package. **The good agreement between the two sets of curves indicates that the calculation of the T response curves was not screwed up.**

For most of the flare, the best fit is obtained using two T components, with the exception of the point near 00:29 UT (the one with the big error bar). For this interval, three T components fit best, with the extra component at a temperature of approximately 60 MK.

Methods for EM(T) calculation: NPLFIT

- NPLFIT: The EM(T) is now a continuous function, a power law with an arbitrary number of spectral indices and breaks. (Think of a connected set of straight lines on a log-log plot.)
- For $i = 1$ to n data points, for npl power law components, obtain reduced χ^2 , defined as:

$$\chi^2 = (n - 2npl)^{-1} \sum_{i=1}^n (m_i - o_i)^2 / \sigma_i^2$$

- This will eventually find a minimum value as npl increases. We used models with 3 to 8 power law components. Typically a 4 or 5 component model fits the data best early in the flare, with fewer components later in the flare.
- Due to the relatively steep slope of the T response, these calculations can be very sensitive to small variations in the count rate. To account for this, for each time interval, we run a number (30) of Monte Carlo trials, in which the detected count rate in each channel is varied by a small random amount consistent with the measured uncertainty.
- Here we are looking for a separate high T bump in the EM(T) distribution, hopefully with a peak near the value for the higher T value in the two-temperature fits.

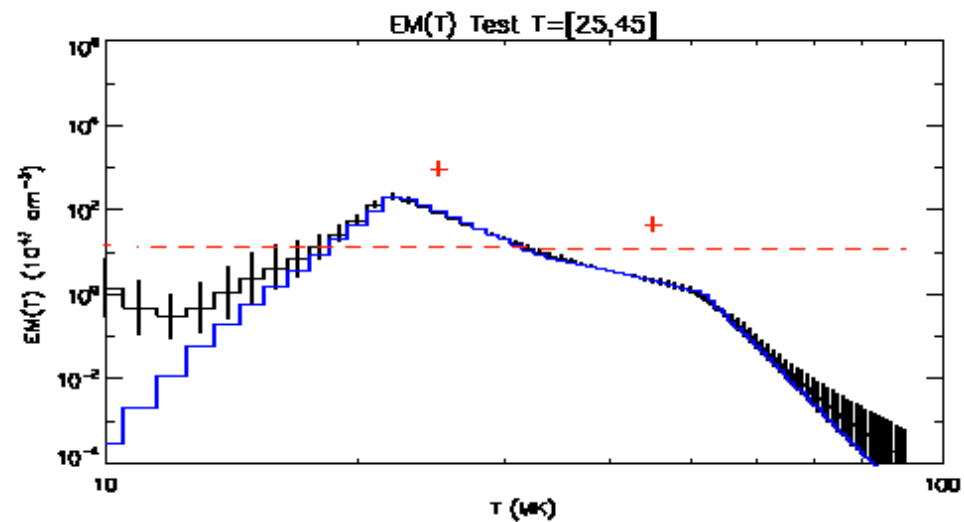
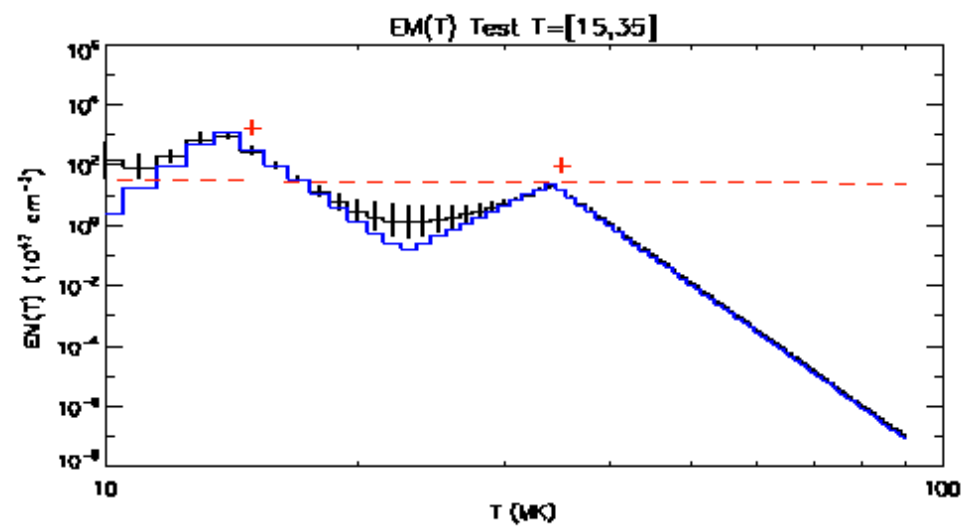
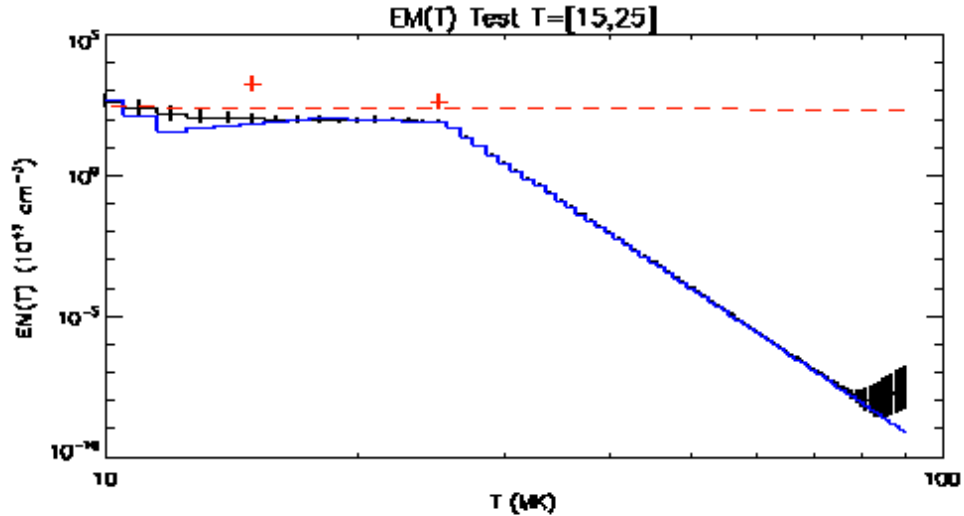


Fig 5. For T resolution, take a model of 2 delta-function components and calculate the expected response. Use the power law EM(T) function to see if any hint of two components shows up. The top plot shows a test with temperatures of 15 and 25 MK, typical for the flare decay phase.

The average and standard deviation of Monte Carlo trials give the black line with error bars. The blue line is the result for the “true” data, i.e., the data for which the count rate has not been subject to small random variations. The dashed red line is the initial condition, a single power law with a slope of 0.1. Plus signs show T and EM for each delta-function.

The middle plot shows T of 15 and 35 MK, typical for the early impulsive phase. Here we see the separate peak!

The bottom plot shows the case for T of 25 and 45 MK, which are the highest seen in the flare. The separate peak is gone.

Tests show that the T resolution of RHESSI is about a factor of 2. If features in the EM(T) are closer, then they are not resolved.

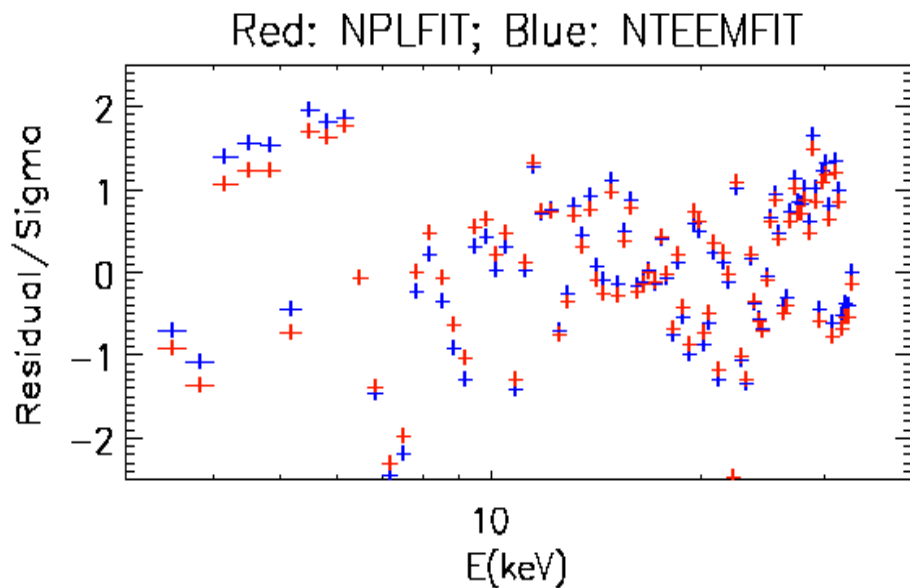
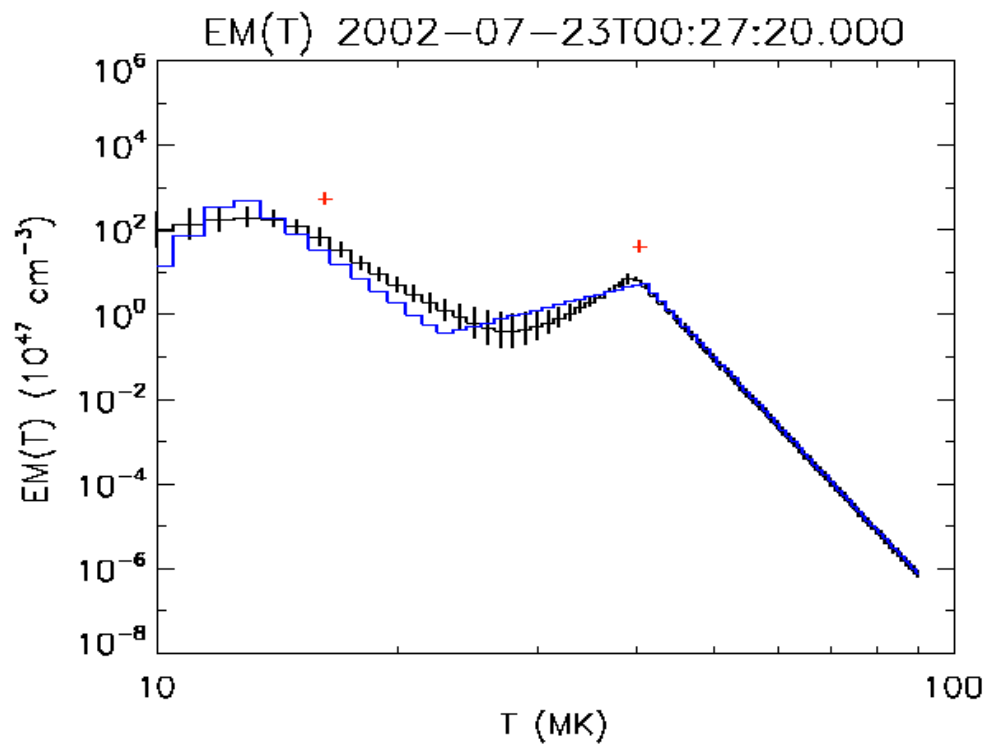


Fig 6. Here is real data, from a time early in the impulsive phase. The top panel shows the plot of the $EM(T)$. We get the separate peaks for all but one of the MC trials. This is generally true for the early part of the flare, where the two temperatures are well separated. Here the plus signs denote the results from the two-temperature delta-function fit at 16 and 40 MK.

(For quantitative purposes, we define a “separate peak” as a peak in the $EM(T)$, that is at least $e=2.718$ times as high as the minimum value between peaks.)

The bottom panel shows the values of the residuals for the two methods, as a function of energy. The residuals are generally low, and not systematically distributed, which is good.

This shows that for a time where we expect a separate high T peak, we definitely see it. So we can say that the assertion that there are “two thermal components” is consistent with the data in the early impulsive phase.

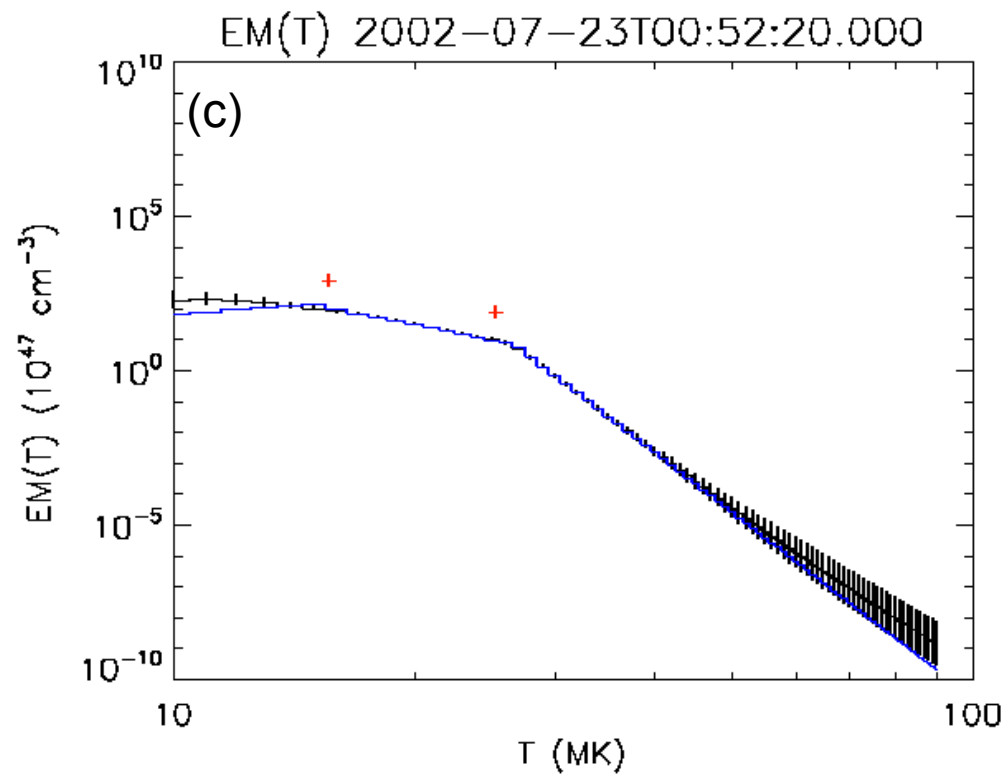
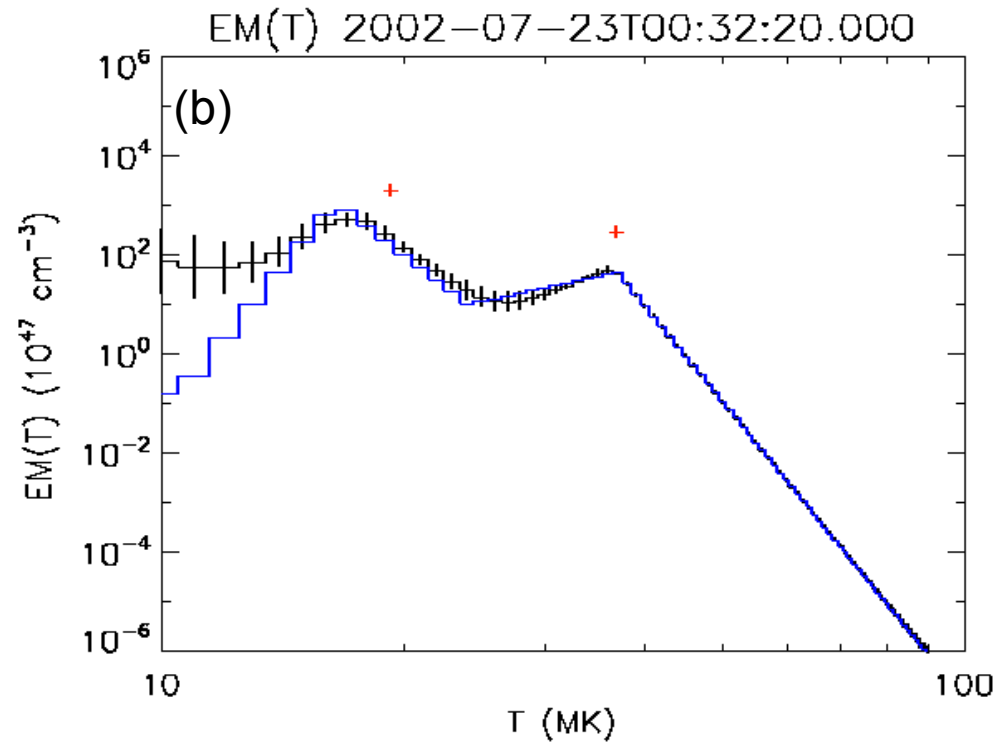
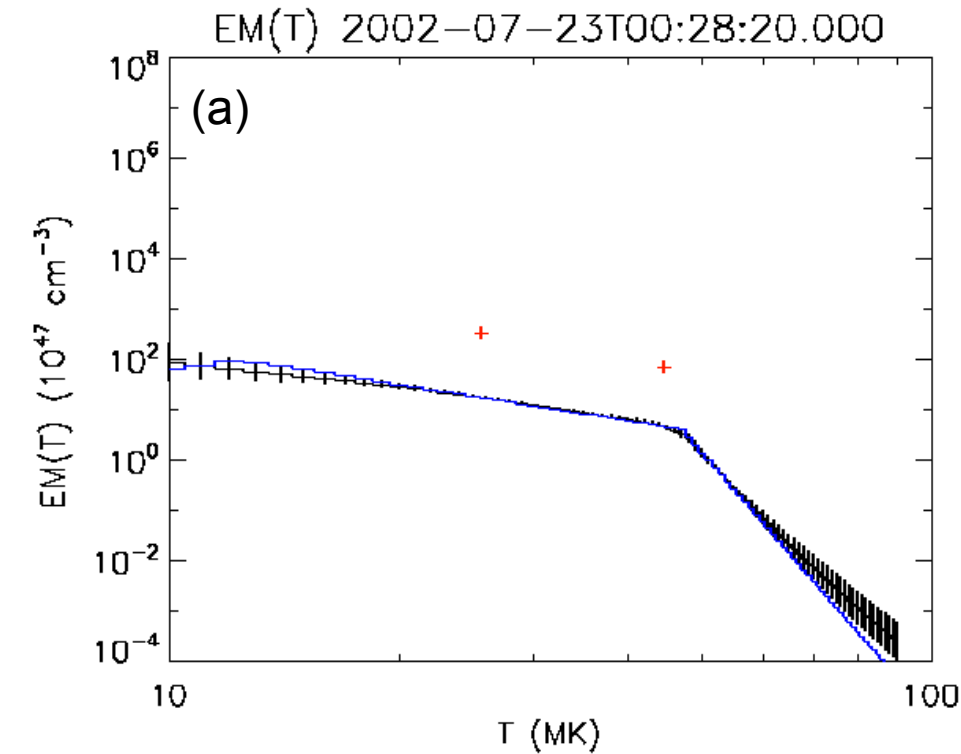
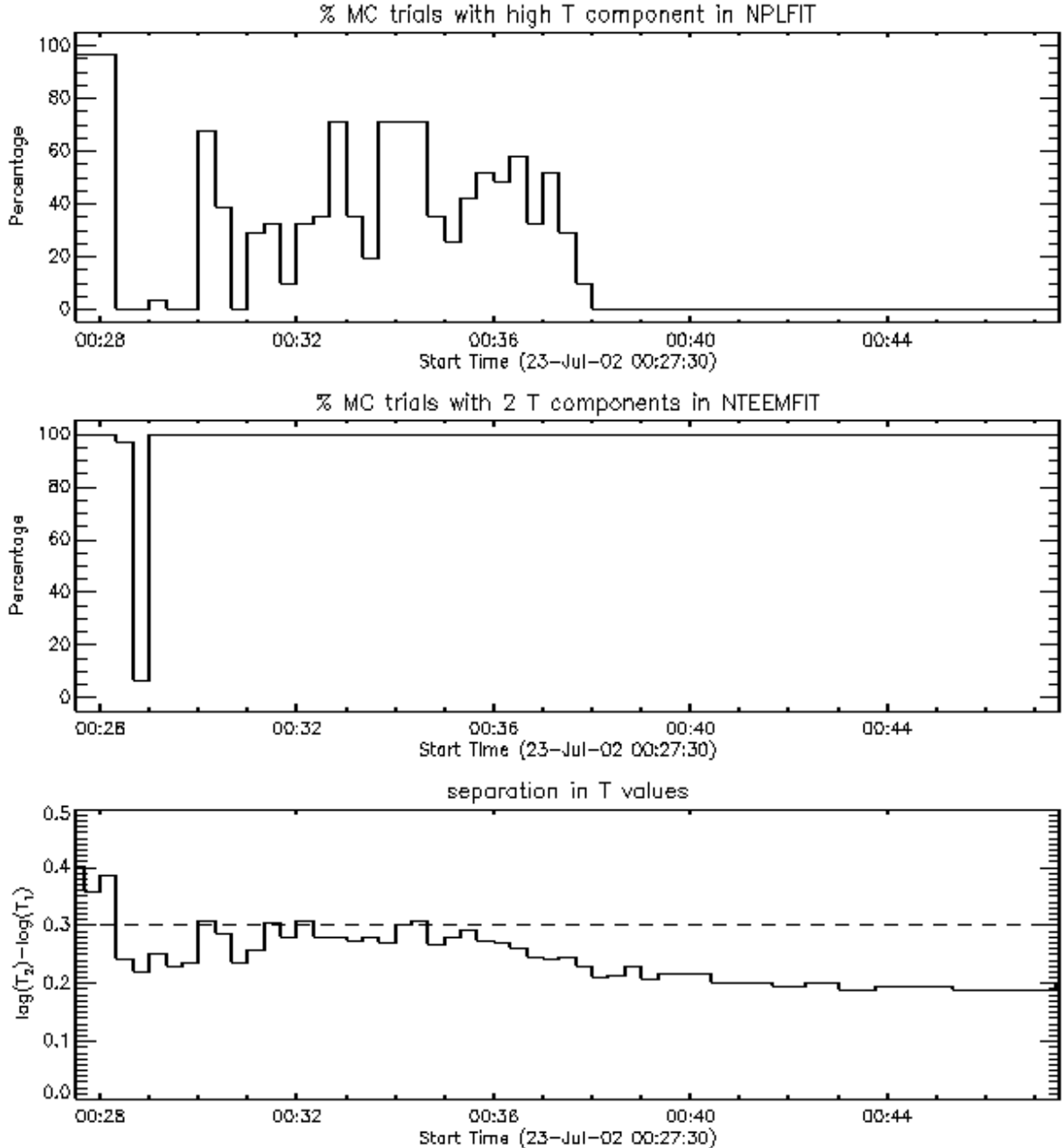


Fig 7. More data. Plot (a) above is for the time of the highest T value, but the two temperatures are close (23 and 44 MK), and are not resolved. The top right plot, (b) is four minutes later, where the T's are separated slightly more (18 and 36 MK), and the two peaks are resolved. Plot (c) is in the flare decay phase, and the temperatures are not well-separated again (16 and 25 MK).



What this tells us is that given a model that allows us to have a continuous function for EM(T), we see a separate high-T (“superhot”) component for this flare wherever we would expect one.

Fig 8. The top panel shows the percentage of Monte Carlo trials which resulted in the separate high T component for each time interval. The percentage is nearly 100 early in the flare where the separation of the T values is larger than a factor of 2, zero where the T's are separated by less than a factor of 2, and middling when the separation is about a factor of 2.

The middle panel shows the percentage of MC trials for which a two-temperature delta function model is the best fit – pretty much 100 everywhere except for the one time interval that really badly wants a third T.

The bottom panel is the separation in Log(T) of the two temperature components in the delta-function model, with a dashed line drawn at a value of Log(2.0).

Conclusions:

- For the X-class flare of 23-Jul-2002, we find that for EM(T) models that consist of separate delta-function components, a two-temperature model fits the continuum thermal emission best for almost the entire flare time interval.
- Tests using an EM(T) function that is a continuous function consisting of an arbitrary number of power law components show that the expected temperature resolution for a RHESSI detector is about a factor of 2. That is, if there are two separate delta-function T components with more than a factor of 2 difference, then the power law EM(T) will have separate peaks. If the difference is less than a factor of 2, then no separate peaks.
- For the flare data, the separate high-T component does show up in the power law EM(T) when the T separation is large. This can be considered to be evidence for a separate superhot component in the 23-Jul-2002 flare. For more evidence, including the possibility of separating the components spatially, see the dissertation talk by A. Caspi, 320.01D on Thursday.
- Future work will include reconciliation of the line emission with the continuum emission, and quantitative comparison with GOES data.