Elsevier Editorial(tm) for Advances in Space Research
Manuscript Draft

Manuscript Number:

Title: Thermal and Nonthermal Contributions to the Solar Flare X-ray Flux
E2.3-0006-04

Article Type: Contributed Paper

Keywords: Sun; X-ray; spectra

Corresponding Author: Prof. K.J.H. Phillips NASA/Goddard Space Flight Center

Other Authors: Brian R. Dennis, PhD; Janusz Sylwester, PhD; Barbara Sylwester, PhD; Richard A. Schwartz, PhD; Anne Tolbert, PhD NASA/GSFC, SRC, Wroclaw, SRC, Wroclaw, SSAI, NASA/GSFC , SSAI, NASA/GSFC

Thermal and Nonthermal Contributions to the Solar Flare X-ray Flux

B. R. Dennis [a], K. J. H. Phillips [b], J. Sylwester [c], B. Sylwester [c], R. A. Schwartz [d], and K. A. Tolbert [d]

[a] *Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Code 682, Greenbelt, MD 20771, USA*

[b] *National Research Council Senior Research Associate, NASA Goddard Space Flight Center, Code 682, Greenbelt, MD 20771, USA*

[c] *Space Research Centre, Polish Academy of Sciences,ul. Kopernika 11, PL-51-622 Wroclaw, Poland*

[d] *SSAI, NASA Goddard Space Flight Center, Code 682, Greenbelt, MD 20771, USA*

Abstract

The relative thermal and nonthermal contributions to the total energy budget of a solar flare are being determined through analysis of *RHESSI* X-ray imaging and spectral observations in the energy range from ∼ 5 to ∼ 50 keV. With its ∼ 1-keV spectral resolution, intensities and equivalent widths of two line complexes, the Fe line group at 6.7 keV (mostly due to Fe XXV lines and Fe XXIV satellites) and the Fe/Ni line group at 8 keV (mostly due to higher-excitation Fe XXV lines and Ni XXVII lines) can be obtained as a function of time through a number of flares. With line and continuum intensities from the CHIANTI code, the thermal component of the flare emission can be more reliably separated from the nonthermal. The abundance of Fe can also be determined from RHESSI spectra. Comparisons of *RHESSI* spectra with those from the RESIK crystal spectrometer on *CORONAS-F* show very satisfactory agreement, giving much confidence in the intensity calibration of both instruments.

Key words: Sun, X-ray, spectra

1 Introduction

The *RHESSI* mission has been operating successfully since its launch on 2002 February 5, and has observed many thousands of solar flares. The instrument, which has been described by Lin et al. (2002), has nine cooled germanium detectors which enable flare spectra and images by modulation collimators to be obtained from the soft X-ray region (3 or 4 keV) to gamma-rays (17 GeV). Its relatively high resolution, ∼1 keV at energies less than 20 keV, enable line features in the spectrum at 6.7 keV (Fe line feature) and 8.0 keV (Fe/Ni line feature) to be observed. These line features are on a flare continuum which, at the flare impulsive stage, consists of a nonthermal component with relatively flat energy dependence and a thermal component with steeper spectrum.

This paper is concerned with analysis of flare spectra in the energy range $\sim 2-20$ keV, which has been observed by both *RHESSI* and the RESIK crystal spectrometer on the Russian *CORONAS-F* spacecraft. The $2-20$ keV range is of great interest since it is where the nonthermal component begins to be evident over the thermal component. We report on attempts to derive parameters for the thermal component as well as the absolute abundance of Fe in the flare plasma from line emission during a flare on 2003 April 26.

2 Theoretical X-ray Spectra in the 3.8 keV - 10 keV Range

We first briefly describe line and continuum emission from thermal solar flare plasmas in the range 3.8 keV - 10 keV. More details are given by Phillips (2004). The emission has been calculated for solar plasmas by Mewe et al. (1985) (MEKAL code) and Dere et al. (1997) (CHIANTI code). In analyzing *RHESSI* spectral data, we have used both codes, though most of the illustrations here are from CHIANTI. In the *RHESSI* range, the thermal spectrum consists of free–free and free–bound continua and two line features at 6.7 keV and 8 keV that, for flare temperatures $\lesssim 20$ MK, are made up of He-like Fe (Fe XXV) lines (transitions $1s^2 - 1snl$, $n \geq 2$, $l = s$, p etc.) and Fe XXIV dielectronic satellites. At higher temperatures, Fe XXVI and Ni XXVII lines contribute to both features. Illustrations of theoretical spectra in the 1 keV – 12 keV range at various temperatures are given in Figure 1.

With *RHESSI*'s spectral resolution, individual lines, in particular the Fe XXIV satellite structure at 6.6 – 6.7 keV, cannot be resolved. However, because the lines are all due to Fe and have a known dependence on temperature, and, as the continuum is well observed by *RHESSI*, we can find the Fe/H abundance. Spectral fits to the thermal spectrum, defined by the continuum slope and intensity, give temperature T and volume emission measure $EM = \int N_e^2 dV$ (N_e = electron density, V = emitting volume), which can be easily found, assuming an isothermal plasma. Other spectral fits, involving a multi-thermal plasma (i.e. two or more values of T) or a temperature distribution have been applied elsewhere in our analyses.

A convenient way of expressing the intensity of the two *RHESSI* line features

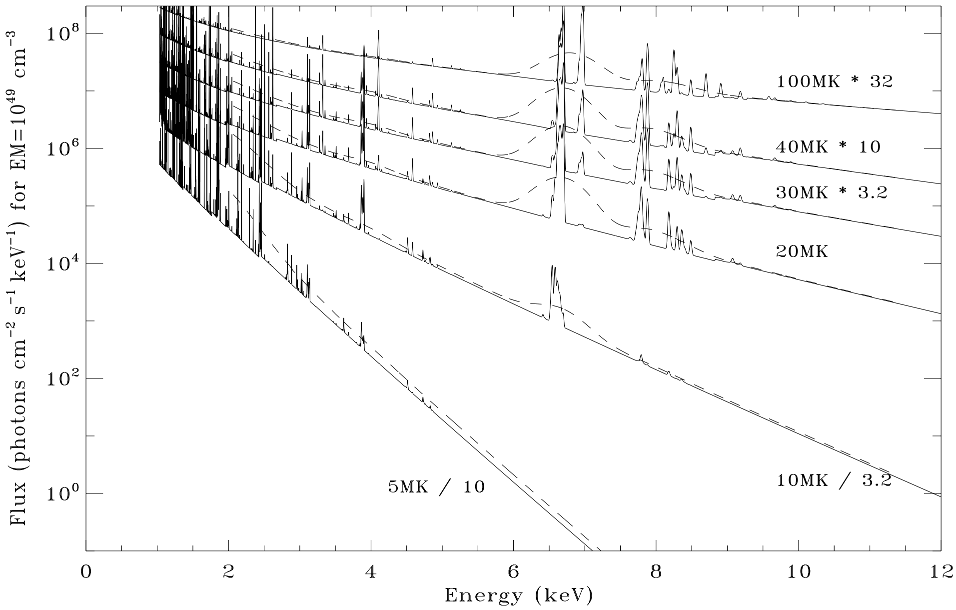

Fig. 1. CHIANTI X-ray line and continuum spectra for temperatures indicated. Solid lines: spectral resolution (FWHM) 0.05 keV; dashed lines: FWHM 0.8 keV. Coronal abundances (Feldman & Laming 2000) and ion fractions of Mazzotta et al. (1998) are assumed.

is through the equivalent width (energy width of a portion of the continuum at the line's energy with flux equal to that of the line feature). The variation of equivalent width with T is given in Figure 2 (solid line) based on CHIANTI. There is a fast rise of equivalent width with T for $T \lesssim 16$ MK.

3 RHESSI Observations

We illustrate our *RHESSI* flare thermal spectral analyses in the 4 keV – 10 keV range with observations made during an M2 flare with maximum at 03:08 UT on 2003 April 26. This flare was also observed by the RESIK instrument on *CORONAS-F*. There were several changes in the *RHESSI* attenuator state (see Smith et al. 2002), from A0 (no attenuator) to A1 (thin attenuator) to A3 (thick attenuator) and the reverse sequence.

RHESSI spectra were fitted with the *RHESSI* analysis software over the energy range 3–100 keV. In our investigations, we sometimes used the spectral output from individual detectors, while for some purposes data from seven of the nine detectors summed were more appropriate: in such cases, data from detectors 2 and 7, which have poorer spectral resolution, were omitted. A first-guess spectrum with appropriate parameters found from previous analysis was folded through the *RHESSI* spectral response matrix for each attenuator state, having subtracted a background spectrum.

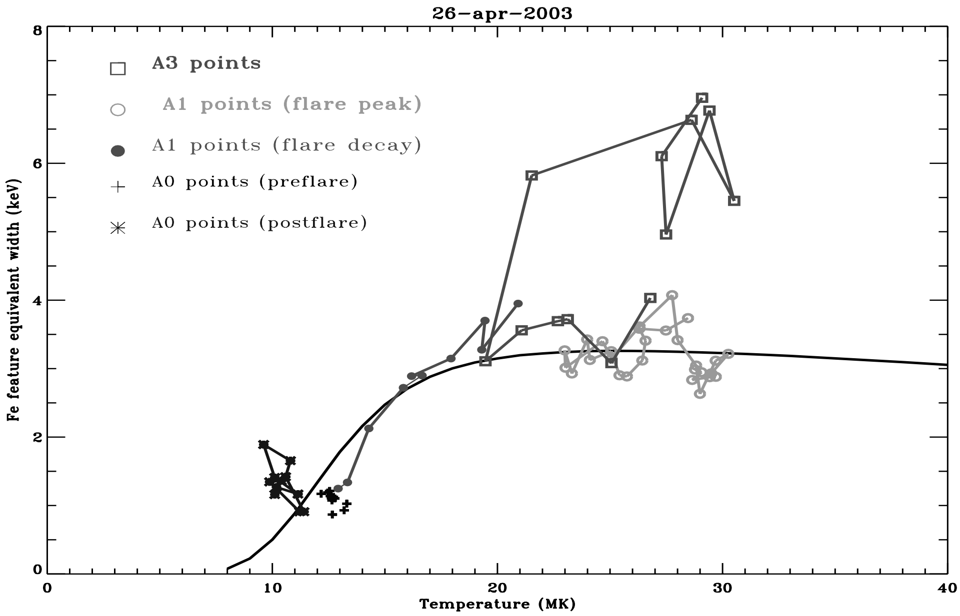

Fig. 2. Equivalent width (keV) of the Fe line feature plotted against T (smooth curve) as calculated from CHIANTI (assuming coronal abundances and Mazzotta et al. (1998) ion fractions). Observed *RHESSI* values in attenuator states A0, A1, and A3, for the flare of 2003 April 26 are shown as points connected by lines (see legend for line styles and plotting symbols).

The low-energy ($\sim$3 keV – 20 keV) part of the spectrum could generally be fitted during the A0 and A1 attenuator states with a thermal continuum and three line features with Gaussian profiles having a single value of T and EM. For higher-intensity spectra, the addition of a continuum with power-law dependence on energy E was found necessary to fit the spectrum at energies above $\sim$30 keV. An iterative process was used to refine the parameters of the first-guess spectrum, minimizing the value of χ^2. This procedure is adequate for spectra in the A0 and A1 attenuator states, but less so for A3 spectra, which are better fitted with two-component thermal continua: see Figure 3. Two of the three line features can be identified with the flare Fe line feature (energy $\sim$ 6.7 keV) and Fe/Ni line feature (energy $\sim$ 8 keV), and the third with an instrumental (Ge) line. Parameters from the final iteration describing the two thermal components of the continuum and the nonthermal continuum are given in the Figure. The fit to the observed spectrum over the 3 keV – 100 keV range gave $\chi^2 = 0.84$, and can be regarded as satisfactory.

With observed fluxes of the continuum and Fe and Fe/Ni line features, the line equivalent widths can be evaluated (points in Figure 2) and the agreement with the theoretical curve examined. For observations in the A1 attenuator states, on the rise and decline of the flare, the observed equivalent widths of the Fe line feature approximately follow the theoretical curve, giving support for a coronal abundance of Fe in the flare plasma. However, the observed equivalent widths from the A3 attenuator state, analyzed with single-temperature fits (i.e. not

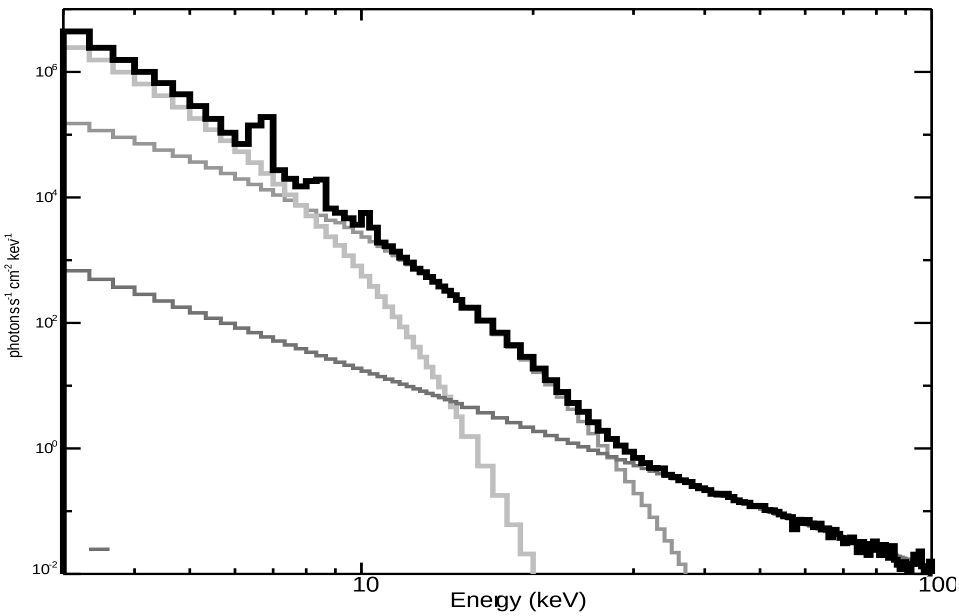

Fig. 3. *RHESSI* X-ray spectrum (*thick black histogram*) in A3 attenuator state near the peak of the flare on 2003 April 26, integrated over 03:07:44 – 03:09:24 U.T. This was fitted with a two-component thermal spectrum (T_1 = 29.4 MK, T_2 = 11.5 MK) and a nonthermal component with power-law energy dependence (grey histograms). Three line features were added with Gaussian profiles having centroid energies 6.70 keV, 8.36 keV, and 10.30 keV, identifiable with the Fe line and Fe/Ni line features and an instrumental feature.

the two-component fit as in Figure 3) vary widely, much more than is predicted by CHIANTI. This apparent discrepancy has been encountered in the analysis of several other spectra. The presence of a multi-thermal or two-component emission measure spectrum is likely to contribute to this discrepancy, but other possible explanations for this are also under investigation.

4 RESIK Observations and their Comparison with RHESSI

RESIK is a high-resolution crystal spectrometer (Sylwester et al., 2004) operating in the energy range 2.04 keV – 3.68 keV (3.37 Å – 6.09 Å) on the Russian *CORONAS-F* spacecraft launched on 2001 July 31. RESIK's spectral range includes diagnostically important lines of Ar, S, and Si ions, as well as 'trace' elements (K and Cl). Unlike many previous crystal spectrometers, it observes the continuum in solar flares with a background that is negligible for two of its channels (that in the other 2 channels can be accounted for in analysis software). Normally, RESIK operates in first order Bragg diffraction, but by changing the instrument's gain, third-order spectra (with wavelength ranges one-third their first-order ranges) can be obtained. The instrument has been precisely calibrated, with 20% uncertainties at most in the measured fluxes, making RESIK spectra suitable for comparison with those from *RHESSI*.

RESIK observed a number of flares in 2002 and 2003 for which there are *RHESSI* observations. During the 2003 April 26 flare, RESIK was in third-order diffraction mode for a short interval near the event peak (03:03 U.T. – 03:05 UT), but in first-order mode at other times. Figure 4 shows RESIK (all four channels) and *RHESSI* spectra at 03:00 UT (*RHESSI* in A0 attenuator state). The *RHESSI* spectra show a thermal continuum, with the Fe line (6.7 keV) and Fe/Ni (8.0 keV) line features while the RESIK spectra show He-like Ar (3.1 keV) and He-like and H-like Si (2.4 keV) lines. The RESIK continuum agrees with the *RHESSI* spectrum at around 3.5 keV to within about 20%, within the expected intensity calibration uncertainties of RESIK. The agreement between two quite different instruments is very gratifying, and adds to our confidence in the calibration of both instruments.

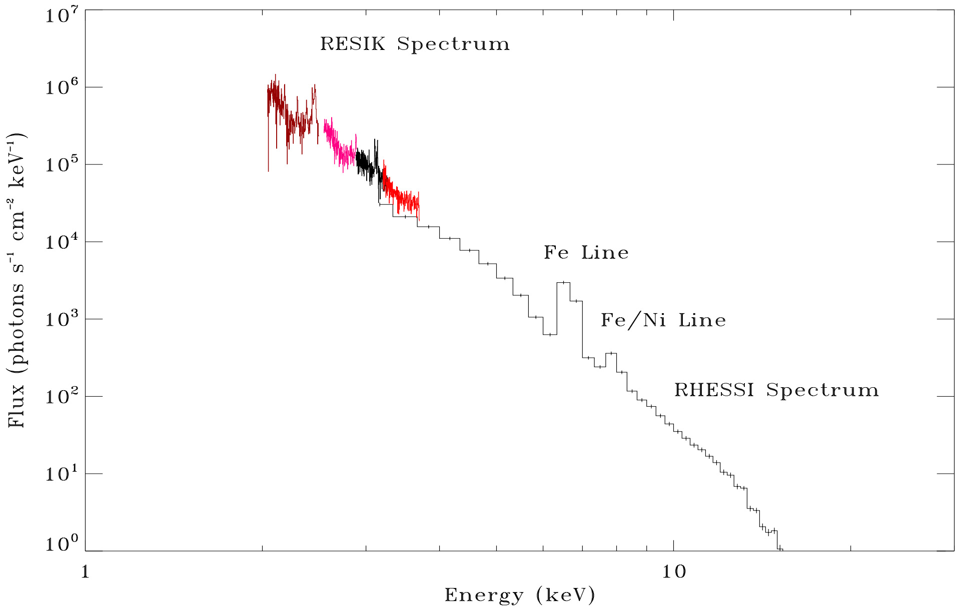

Fig. 4. Observed X-ray spectra for a time (03:00 U.T.) just preceding the main flare on 2003 April 26. RESIK spectra (four channels) cover 2.0 keV – 3.7 keV and include lines and continuum. Spectrum above 3 keV (histogram) is from *RHESSI* detector 4 (A0 attenuator) and shows the Fe line and Fe/Ni line features. The best-fit thermal spectral parameters for this spectrum are $T_e = 18.6$ MK, $EM = 2.1 \times 10^{47}$ cm^{-3}.

The Fe line was observed by RESIK in third-order diffraction when *RHESSI* was in its A1 attenuator state. The *RHESSI* spectrum gives the line flux as 7.83×10^4 photons cm^{-2} s^{-1}, while RESIK spectra integrated over the same interval gives nearly the same flux: 8.22×10^4 photons cm^{-2} s^{-1}.

5 Conclusions and Summary

Observations of several flares, including the one discussed in detail here, suggest that *RHESSI* can measure equivalent widths of the Fe line to an accuracy that allows a preliminary estimate to be made of the abundance of Fe: this is close to the coronal value (1.26×10^{-4}). There is good agreement – within about 20% – of *RHESSI* spectral fluxes and those from the *CORONAS-F* RESIK crystal spectrometer in the region of overlap, around 3 – 4 keV. There is also agreement between *RHESSI* and RESIK estimates of the Fe line flux.

Acknowledgements

K.J.H.P. acknowledges a National Research Council Senior Research Associateship award at the NASA Goddard Space Flight Center. B.S. and J.S. acknowledge support from grants 2.P03D.002.22 and BPZ-KBN-054/P03/2001 of the Polish Committee for Scientific Research. CHIANTI is a collaborative project involving Naval Research Laboratory, Rutherford Appleton Laboratory (U.K.), and the Universities of Florence (Italy) and Cambridge (U.K.). We thank E. Landi for providing updates of the CHIANTI database.

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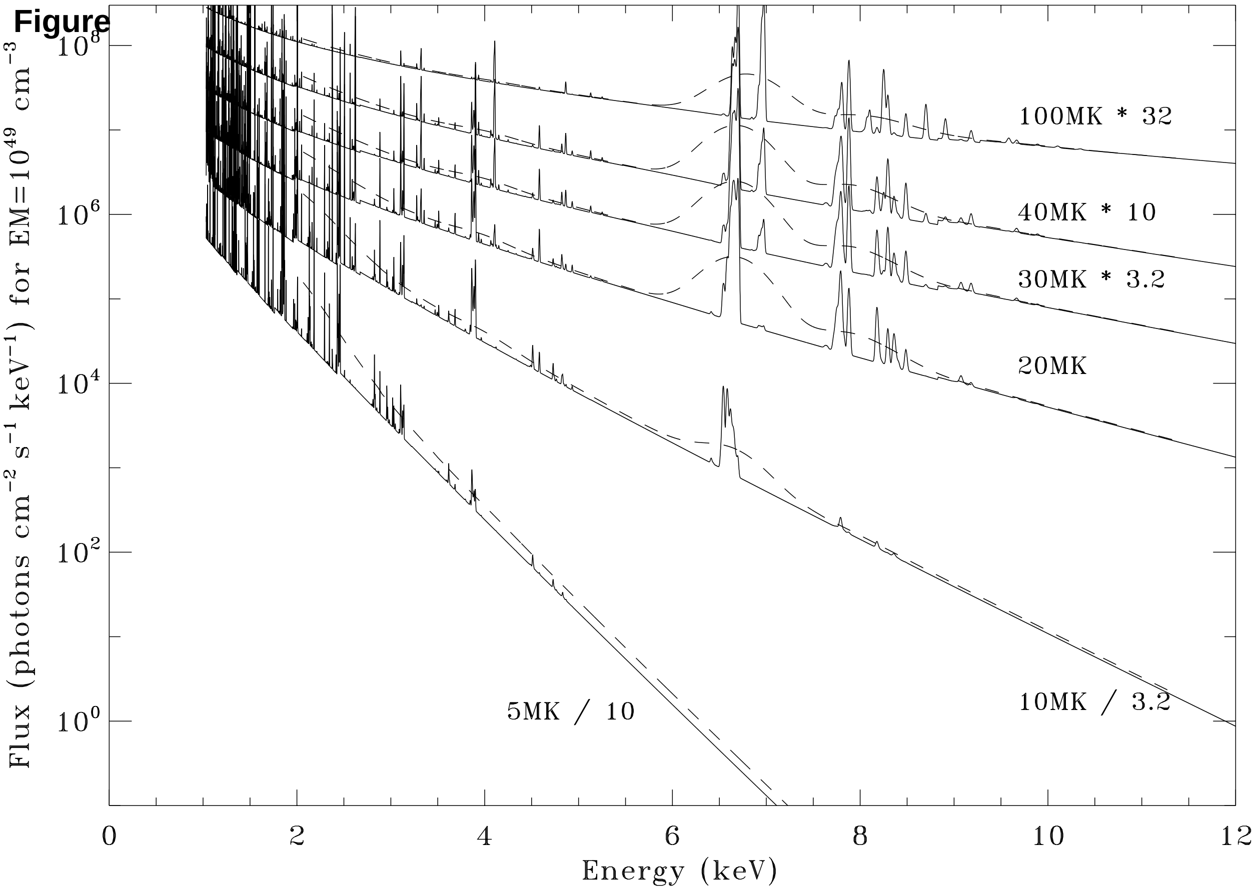
Figure



100MK * 32
40MK * 10
30MK * 3.2
20MK
10MK / 3.2
5MK / 10
Flux (photons cm^{-2} s^{-1} keV^{-1}) for EM=10^{49} cm^{-3}
10^8
10^6
10^4
10^2
10^0
0
2
4
6
8
10
12
Energy (keV)