Coordinated XTE/EUVE Observations of Algol

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Principal Investigator:

Robert A. Stern
Dept H1-12 Bldg 252
Solar and Astrophysics Laboratory
Lockheed Martin ATC
3251 Hanover St.
Palo Alto, CA 94304
(415) 424-3272

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1. Summary

We performed a coordinated RXTE observation of the prototypical eclipsing binary Algol in conjunction with EUVE and ASCA observations. Observing the X-ray spectrum of Algol with ASCA, EUVE, and RXTE provides critical, near-simultaneous constraints on the distribution of the hottest temperature plasma in the Algol system: this is required to unambiguously determine the coronal Fe abundance. After some initial shuffling of observatory schedules with the help of mission planners, the coordinated multiwavelength observation was successfully performed in February, 1996. Analysis of the data, including development of new, IDL-based global model fitting routines, was accomplished from mid-1996 to mid-1997. The results indicate that the initial estimates of [Fe/H] $\sim$ 0.3 dex (Stern *et al.* 1995) are confirmed, and the Algol high temperature plasma thus has an Fe deficiency relative to the (Anders and Grevesse 1989) solar abundance.

2. Technical Progress

The results of this investigation will be published (in CD ROM format) in the proceedings of the 10th Workshop on Cool Stars, Stellar Systems, and the Sun, Cambridge, 1997, ASP Conference Series, eds. J.A. Bookbinder & R.A. Donahue (San Francisco: ASP). A hardcopy version of this paper is appended to this report.

Multiwavelength EUVE/ASCA/RXTE Observations of Algol and the [Fe/H] Abundance

Robert A. Stern [1], James R. Lemen [1], Sandy Antunes [2], Stephen A. Drake [3], Fumiaki Nagase [4], Jürgen H.M.M. Schmitt [5] Kulinderpal Singh[6], Nicolas E. White[7]

Abstract.
EUVE, ASCA, and XTE observed the eclipsing binary Algol (Beta Per) from 1-7 Feb 96. The coordinated observation covered $\sim$ 2 binary orbits of the system, with a net exposure of $\sim$ 160 ksec for EUVE, 40 ksec for ASCA (in 4 pointings), and 90 ksec for XTE (in 45 pointings). We discuss results of modeling the combined EUVE, ASCA, and XTE data using continuous differential emission measure distributions, and provide constraints on the Fe abundance in the Algol system.

1. Introduction

The prototype eclipsing binary Algol (β Per; P = 2.87 d.), studied intensively in nearly all wavelength regions from IR to X-rays, is now beginning to reveal more of its multifaceted nature through both ASCA (Antunes, Nagase, and White 1994), and EUVE spectrometer observations (Stern *et al.* 1995). A key result in both of these investigations is that the highly ionized Fe X-ray line complexes or individual EUV lines are considerably weaker than expected (relative to the continuum or other spectral features) from models using the solar abundances of, e.g. Anders and Grevesse (1989). However, because these observations were performed many months apart, and because of Algol's inherent variability, a combined analysis of the earlier data is not possible. To remedy this, a coordinated EUVE/ASCA/XTE observation was undertaken to settle the issue of the Fe abundance in Algol's corona and place limits on the form of the differential emission measure (DEM) from 10^6–10^8 K, using the presence of the strong Fe L complexes and the line-to-continuum ratios of the Fe lines.

[1] Solar and Astrophysics Lab/Lockheed Martin

[2] Hughes/STX

[3] NASA/USRA

[4] ISAS

[5] MPE/Garching

[6] Tata Inst. of Fund. Res.

[7] NASA/GSFC

2. Observations

EUVE observed Algol for more than 2 binary orbits, with a net exposure time of $\sim$ 140 ksec. ASCA co-observed for a total of $\approx$ 40 ksec in four separate pointings, and XTE in 40 pointings for $\approx$ 90 ksec. The ASCA data were taken largely during quiescent periods, which will be helpful in the combined emission measure and Fe abundance analysis. The XTE data sampled a much larger portion of the EUVE observation, with concentrated periods of observation designed to overlap with the ASCA observations. The times of the coordinated EUVE/ASCA/XTE observations are indicated in Figure 1. Because of the late launch of XTE, the EUVE and ASCA observations were delayed by about 1 week: the high level of coordination and cooperation among the various observatories and schedulers made this last minute shift possible.

3. Results

3.1. EUVE Lightcurve

A lightcurve from the EUVE Deep Survey/Lexan filter ($\lambda \sim$ 70-170 Å) is shown in Figure 2. Note the nearly continuous variability of the Algol system in this wave band, which is similar to the coverage of the EUVE Short Wavelength (SW) spectrometer. The flare occurring at about midday on Feb 3 is relatively small by Algol standards, with an exponential decay time $\lesssim$ 4 hr. Folding the DS/Lexan data with the orbital period of Algol, 2.867 d, results in the lightcurve shown in Figure 3. Although parts of the Algol lightcurve are reproducible from orbit to orbit, successive orbits of the Algol system reveal numerous changes due either to small flares or evolution of activity patterns. For example, what appears to be a secondary eclipse during the first orbit ($\phi \sim 0.5$) is masked by what is probably a decaying flare during the second orbit. This lack of reproducibility on an orbit-to-orbit basis suggests caution in attempting a detailed model of EUV eclipses.

3.2. RXTE lightcurve

The RXTE observation was designed to provide $\sim$ one (spacecraft) orbit exposures, sampled throughout the EUVE observation. The RXTE PCA (Proportional Counter Array) data are strongly affected by instrumental background, which is highly variable during a given observation. Hence a correct background correction algorithm is crucial. Using the software developed by Keith Jahoda and provided by the RXTE GOF, we have obtained a background-corrected PCA lightcurve for the Algol observation. This is shown in Figure 4. Note that the RXTE and EUVE lightcurves are in rough correspondence, but the peak on the larger flare is missed by RXTE, and there are still likely some systematic effects present in the background subtraction.

3.3. EUVE/ASCA/RXTE Spectra and Continuous EM Model Fit

By filtering the EUVE spectrometer data, removing periods of high count rate ($\gtrsim$ 1 c/s), we obtain what may be termed a "quiescent" spectrum in the EUVE SW

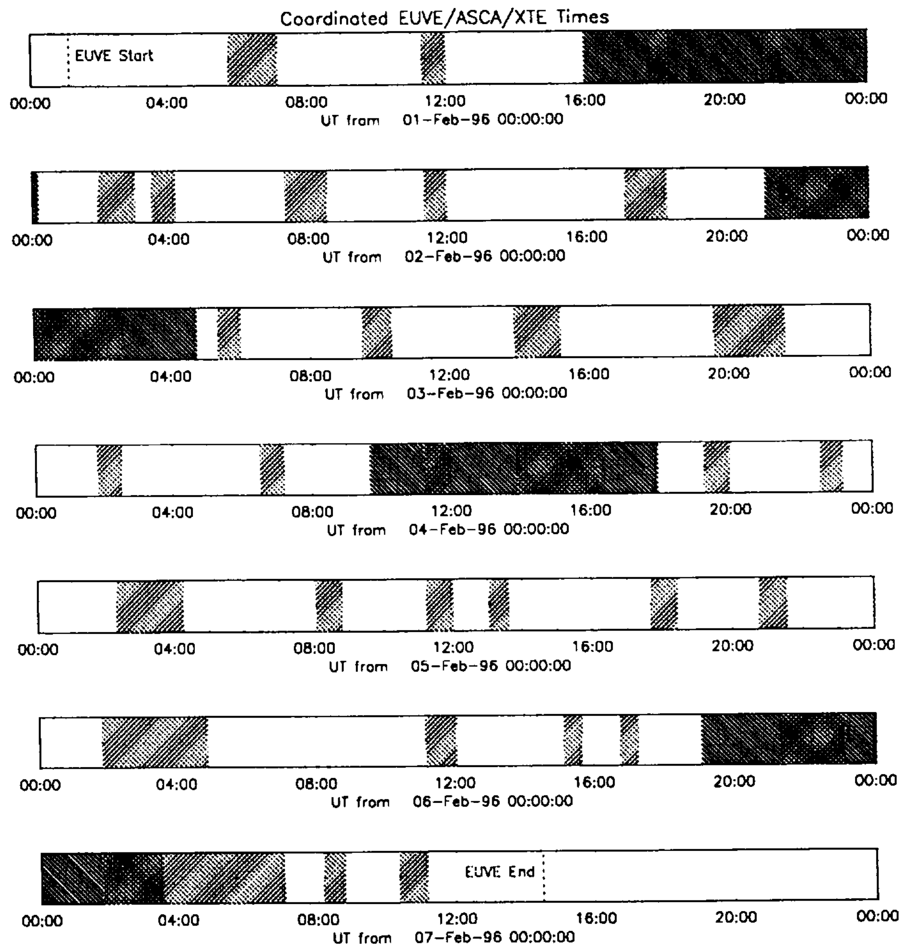

Figure 1. Times of coordinated EUVE, ASCA, and XTE observations. The EUVE observation start and end times are indicated by vertical dashed lines. The ASCA times are indicated by the four line shaded regions with the wider spacing, and the XTE observation times by the more numerous line shaded regions with the smaller spacing. The indicated observation periods include some times of SAA passes, earth occultations, etc.

and MW bands. Corresponding to this, we have selected the final ASCA observation, and the overlapping RXTE observations to match this "quiescent" data. We have developed a multiwavelength version (MULTI_FIT) of the EUVE_FIT software used to fit a spectrum to an emission measure (EM) distribution described by a sum of Chebyshev polynomials (see Stern *et al.* 1995). The ASCA and RXTE response matrices and effective areas were all computed using the data analysis software provided by their respective GOFs. The output FITS files were then read into IDL and converted into data structures for use by the MULTI_FIT software. The MULTI_FIT software was adapted to use the models produced by the SPEX software of Mewe, Kaastra and Liedhal (1995),

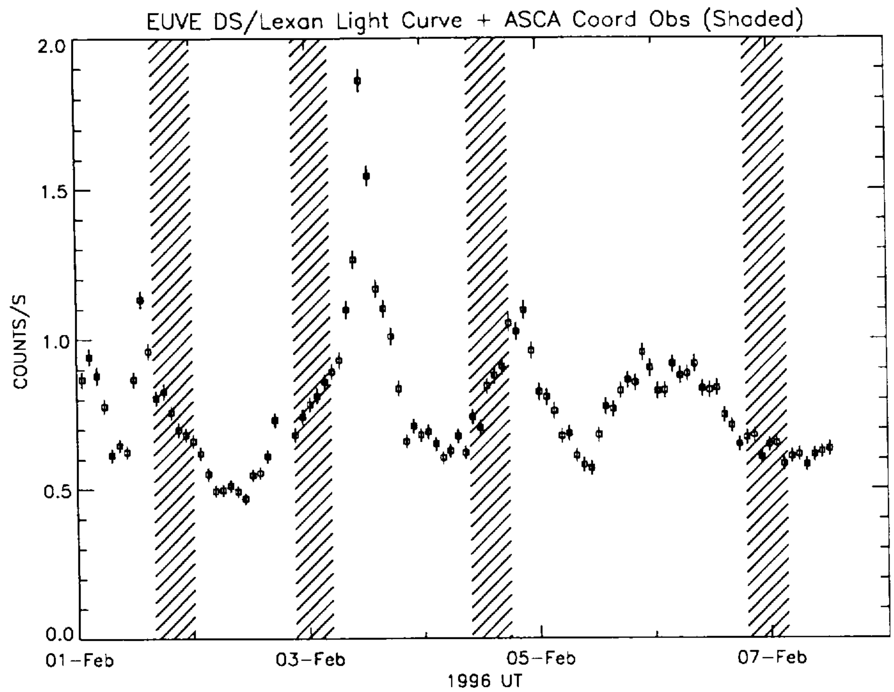

Figure 2. EUVE Deep Survey/Lexan lightcurve (50-170 Å). The times of the coordinated ASCA observations are indicated by the line-shaded regions.

with lines from each element separately calculated to allow for varying elemental abundances. In addition, the normalizations of the 3 instruments were allowed to vary independently to allow for intercalibration effects, but never were > 15% from their nominal values. A fixed absorption of $N_H \approx 4 \times 10^{20}$ was applied to the ASCA and RXTE data to account for known calibration problems with the ASCA SIS.

We experimented with Chebyshev polynomials with nterms = 6 to 25, and allowing the elements Fe, Mg, S, and Si to vary. In general, the fits, though not formally accepted, provided good representations of the spectra. A sample of the best fit results is given in Table 1. As can be seen, changing the number of terms above ~ 10-13 did not have a significant affect on the fit, and the range of [Fe/H] values (relative to Anders and Grevesse 1989) was ~ 0.26-0.35. Attempting to place a formal confidence limit on this range is difficult, because of the dominance of systematic effects in the instrument calibrations and atomic codes.

For the purposes of illustration, we show the fit results for nterms = 11. The spectral fit in the EUVE SW and MW bands, the ASCA SIS and the RXTE PCA is shown in Figures 5-8 and the resulting EM distribution in Figure 9.

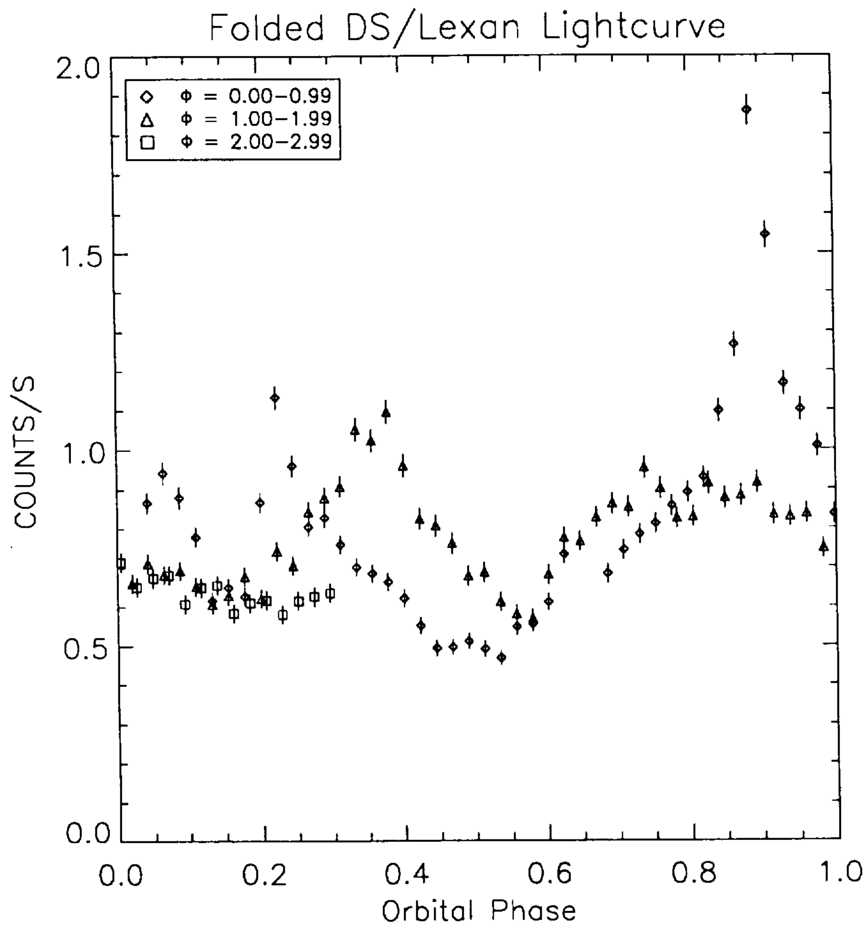

Figure 3. Phased lightcurve for DS/Lexan data. Different plotting symbols, indicated in the legend, refer to successive orbits.

4. Summary

The coordinated EUVE, ASCA, and XTE observations of Algol obtained in February 1996 offer a unique opportunity to determine the EM distribution and element abundances of the Algol system. Coordinated multiwavelength data indicate consistency with earlier ASCA and EUVE results, i.e., an [Fe/H] $\approx$ 30%. The simultaneous fitting of these results leaves no doubt that, unless the atomic physics data is wrong to the same degree in both the EUV and X-ray regions for the Fe L lines, the derived underabundances are real. The question of the photospheric Fe abundance of Algol is, however, still an unresolved problem.

Acknowledgments. This work was supported by NASA Contracts NAS5-96052 (EUVE), PO# S-57785-Z (ASCA), PO# S-73068-Z (XTE) and the Lockheed Martin Independent Research Program.

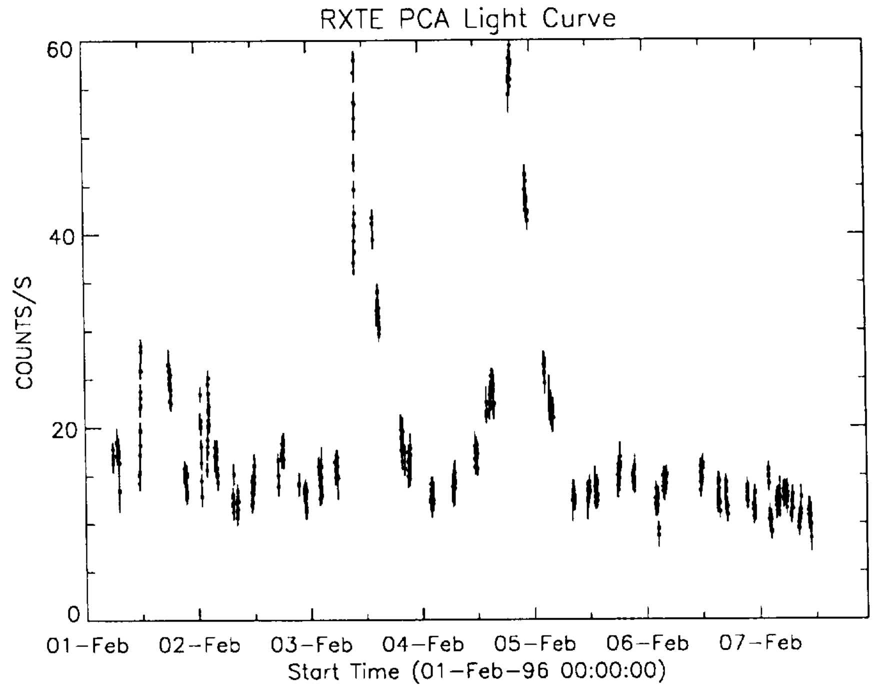

Figure 4. RXTE PCA Lightcurve for Algol observation.

References

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Antunes, A., Nagase, F., and White, N.E., 1994, ApJ, 436, L83.

Mewe, R., Kaastra, J., and Liedhal, D., 1995, SPEX code.

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Table 1. Chebyshev Polynomial Fit Results

Nterms	χ_r^2	NFREE	Fe	Mg	S	Si	O
6	1.39	741	0.26	0.48	0.08	0.29	N/A
10	1.34	737	0.27	0.44	0.08	0.28	N/A
15	1.35	732	0.26	0.42	0.09	0.28	N/A
20	1.36	727	0.27	0.44	0.08	0.28	N/A
25	1.37	722	0.27	0.44	0.08	0.28	N/A
11	1.52	737	0.26	0.73	N/A	0.41	N/A
11	1.49	737	0.35	0.90	0.20	N/A	N/A
11	1.39	737	0.31	N/A	0.18	0.40	N/A
11	1.48	737	0.31	1.1	N/A	N/A	0.

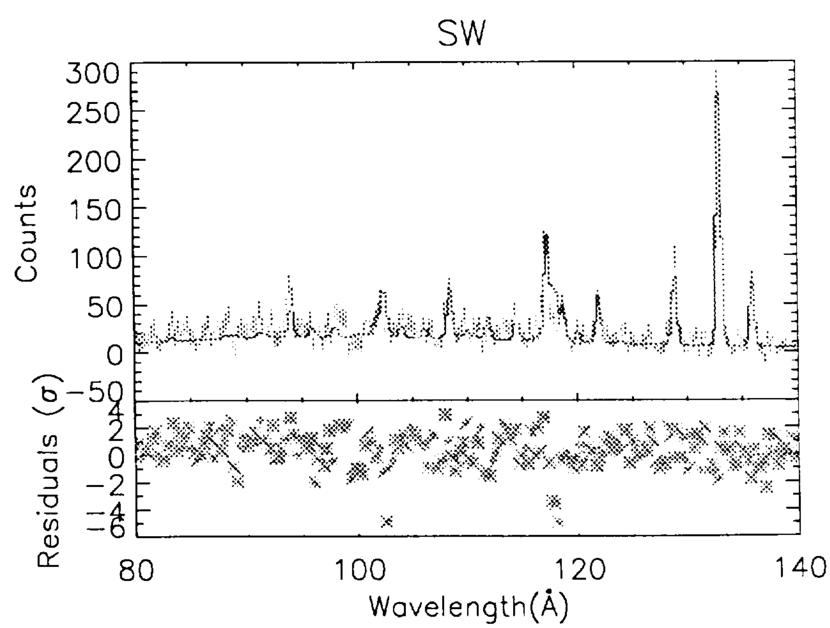

Figure 5. EUVE SW Spectral fits and residuals.

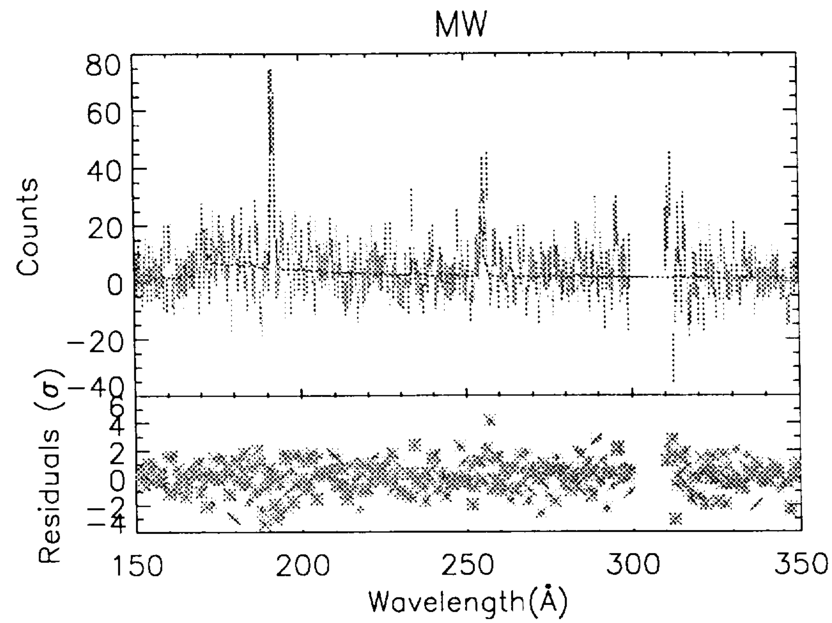

Figure 6. EUVE MW Spectral fits and residuals.

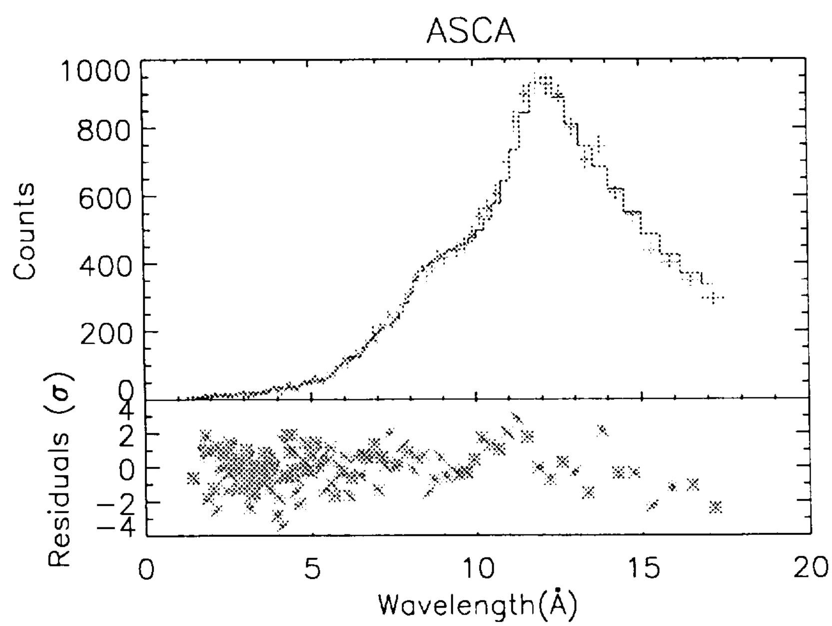

Figure 7. ASCA SIS Spectral fits and residuals.

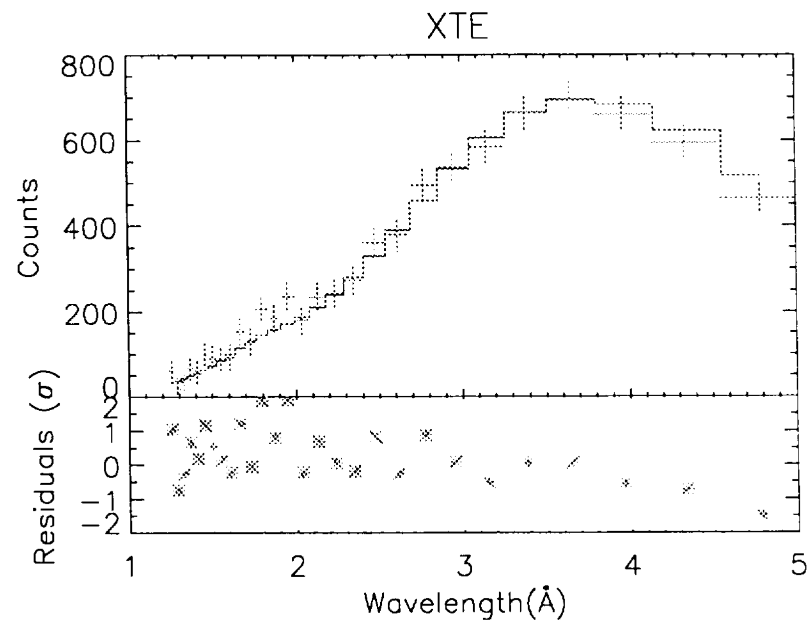

Figure 8. **RXTE PCA Spectral fits and residuals.**

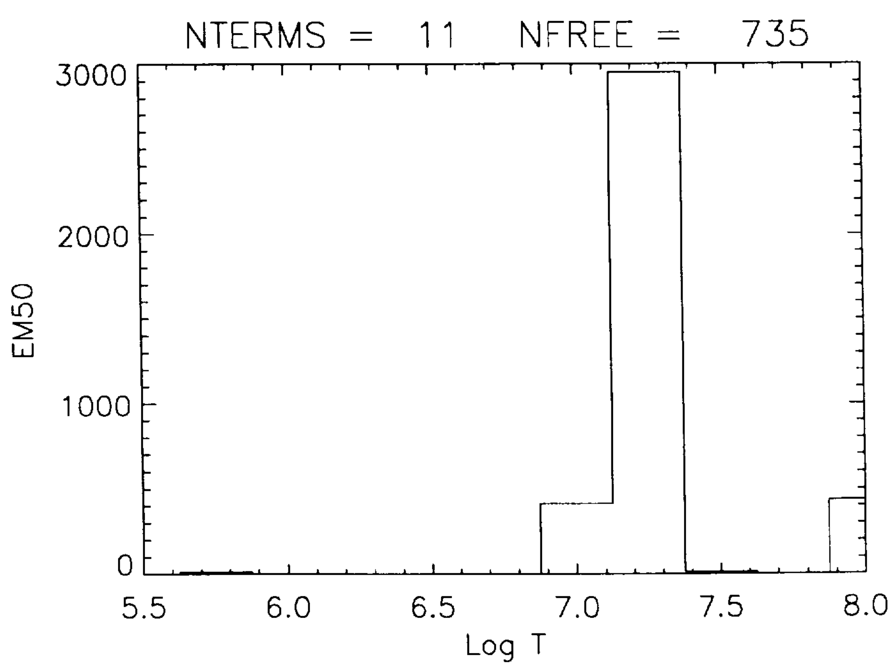

Figure 9. **DEM for Nterms=11 Chebyshev Polynomial fit.**