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ABSTRACT

X-ray emission line components from Mg, Si, S and Fe are unambiguously detected from Capella with the Solid-State Spectrometer onboard the Einstein Observatory. The X-ray spectrum is inconsistent with an isothermal corona, and requires components between 6×10^6 K and at least 24×10^6 K for an adequate fit. An inhomogeneous corona in which the X-ray emitting plasma is confined to magnetically-contained loops appears to be reconcilable with all of the experimental evidence.

Subject headings: stars: coronae - stars: individual - X-rays: spectra

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I. INTRODUCTION

X-rays from the nearby star system Capella (α Aur) were first detected by Catura, Acton and Johnson (1975), and confirmed by Mewe et al. (1975). The system is a G5III + G0III spectroscopic binary with a period of 104 days at a distance of 14 pc; the G5III primary has a mass of 3 $M_\odot$, a radius of 14 $R_\odot$, and is separated from the secondary by about 10^{13} cm (Wright 1954; Hoffleit 1964). Dupree (1975) tentatively identified L_α and O VI emission lines with the corona of the G5 primary, and additional ultraviolet emission lines observed by Vitz et al. (1976) suggested a chromosphere-corona transition region in this component qualitatively similar to that in the Sun. Haisch and Linsky (1976) modelled such a transition region for the star, predicting an average coronal temperature of 1.2×10^6 K. Those authors suggested that the higher temperature (8×10^6 K) emission observed by Catura, Acton and Johnson might have arisen from an active region (or regions) in the stellar corona, but point out that their calculation might well suffer from a variety of oversimplifying assumptions.

Recently Cash et al. (1978) have reported the detection of X-ray emission from temperature components near 10^7 K from Capella. Their data are well-fit by an isothermal corona (including the contribution of Fe-blend transitions expected near 0.85 keV), but cannot exclude deviations from isothermality: in particular, they remark that there can be no substantial contribution from temperatures less than about 3 times the average value calculated by Haisch and Linsky, but that their experiment was insensitive to possible large emission measures at temperatures in excess of 10^7 K.

We report here the confirmation of the Fe-blend feature at about 0.85 keV noted by Cash et al. and the unambiguous identification of Mg XI, Si XIII and S XV from Capella, obtained with the Solid-State Spectrometer (SSS) onboard the Einstein Observatory (HEAO-2). Multi-temperature modelling is required to adequately fit the SSS data, with the elemental abundances of the line-prominent species somewhat in excess of solar. We discuss the reasons why confinement of the X-ray emitting plasma to coronal loop structures provides a natural explanation for the X-ray data.

II. THE EXPERIMENT

The SSS consists of a cryogenically-cooled Si(Li) detector at the focus of the Einstein Observatory X-ray telescope. It subtends a 6 $\widehat{\mathrm{min}}$ diameter circular aperture, and is slightly defocussed so that a point source is blurred to a radius of approximately 1 $\widehat{\mathrm{min}}$. It exhibits a noise-limited spectral resolution of about 160 eV FWHM, which is approximately energy-independent over the range 0.5 - 4.5 keV. Each photon is pulse-height-analyzed into one of 128 bins, each of which has a 45 eV width.
The effective collecting area of the detector is approximately 100 cm^2 below 3 keV, and drops to about 10 cm^2 at 4.5 keV owing to the high-energy reflection cutoff of the telescope optics. A description of the entire observatory instrumentation may be found in Giacconi et al. (1979), and further details of the SSS system are given in Holt (1976) and Joyce et al. (1978).

The total background due to all non-source contributors is 0.28 sec^{-1} above 0.5 keV, and 0.19 sec^{-1} above 1 keV. Background is not measured simultaneously with each source observation, and must be estimated from data accumulated at other times. Uncertainties in the background exist at the 10% level, which can compromise the spectral fitting for very weak sources. Capella was observed at 4 times the background (i.e. the source contributing 3/4 of the total count rate).

A time-dependent buildup of ice (mostly H_2O) on the detector surface arises from the cryopumping of ambient outgassing material onto the 100 K detector. It is periodically "defrosted" by heating to 220 K, but observations typically have an accumulated ice buildup in excess of 10^{-4} cm (i.e.

the equivalent of $\gtrsim 10^{21}$ H-atoms-cm^{-2} of interstellar column density), which raises the effective low-energy instrument threshold to about 0.8 keV. Capella was observed for approximately 7000 sec (net) centered at 2000 UT on 2 Mar 1979 (JD 2443935.3, at a conventional phase of 73.2 d). As evidenced by Figure 1, there were no significant intensity variations during the exposure.

III. DATA ANALYSIS

The SSS is well-suited for the study of plasmas with temperatures near 10^7 K. Here the transitions to the ground state from helium-like ions of Mg, Si, S, Ar and Ca have large equivalent widths that are easily discernible with the SSS resolution. At lower temperatures (i.e. near 10^6 K) there is no appreciable flux above 1 keV, and approaching 10^8 K the line features have much lower equivalent widths while the continuum becomes relatively flat over the limited dynamic range available.

The general fitting procedure for suspected thermal sources is begun with an attempted fit to an isothermal source in collisional equilibrium (Raymond and Smith 1977; Raymond and Smith 1979) with elemental abundances fixed at solar values. In all steps in the fitting procedure, trial models are folded through the detector response and compared with the experimental data via the χ^2 test for statistical consistency. If the initial attempt with only the column density and temperature as the free parameters does not yield an acceptable fit (where we define acceptability such that the probability for obtaining a higher value of χ^2 than that provided by the best test model is >10%), we allow the abundances of the elements which might contribute significantly to also be free parameters. If we are still unable to obtain an acceptable source parameterization, additional degrees of freedom are removed with the assumption of additional isothermal components.

The SSS data from Capella could not be adequately fitted to an isothermal source with either solar or separately variable elemental abundances, nor could they be fitted with two isothermal components having solar abundances. An acceptable fit was obtained, however, with two isothermal components for which the abundances were not constrained to be solar. Only the abundances of Mg, Si, S and Fe were varied in the final analysis, as the fitting procedure was insensitive to changes in the proportions of the other elemental constituents. Table 1 lists the best-fit values of the parameters obtained, as well as the 90% confidence minimum and maximum values which they can have using the prescription of Cash(1976).

For the fits summarized in Table 1, higher values of emission measure are correlated with lower abundances (since the total emission must be the sum of continuum and line components), and with lower temperatures. Maximum abundance values for the two-temperature fit are not tabulated because, as discussed in the next section, the best-fit (and perhaps even the minimum) values are almost certainly overestimated. There is an additional uncertainty not specifically included in the tabulated results which arises from the correction for ice build-up on the detector; this affects only the Fe abundance, which could be systematically incorrect by as much as 25%.

The data plotted in Figure 2 are all background-subtracted. Background uncertainties may be significant above about 3 keV where there is little source flux detected, but the results of the fitting procedure are dominated by the higher statistical precision of the lower energy data; exactly the same best-fits and limits were obtained whether a dynamic range of 0.8 - 3.0 keV or 0.8 - 4.5 keV was used in the analysis.

IV. DISCUSSION

The present results indicate that the X-ray emission from Capella can no longer be acceptably described as an isothermal plasma. The SSS data require at least two "isothermal" components, with significant overabundances (relative to solar) of line prominent elements, for the simplest acceptable fits. As evidenced by Figure 2, the line features in the spectrum are furnished largely from the low temperature component. The higher temperature component is required predominently for the enrichment of higher ionization states in the lines, and appears to overestimate the continuum contribution above 3 keV. It would appear, therefore, that the apparent overabundances of the two-component fit represent the best compromise the fitting procedure could obtain in attempting to simultaneously match the lines while suppressing the high energy continuum excess.

There are, of course, a variety of physical effects which might contribute to anomalously high elemental abundances in the fitting procedure. An obvious source of addition line emission arises from the photoionization of cooler material by the X-ray continuum; the small apparent excess in the experimental spectrum near 2.35 keV relative to that expected from the low temperature component is particularly suggestive of photoionization of a cooler population of S. The line components would also appear overabundant if the electrons and ions have not collisionally equilibrated; if the electron temperature is higher, the absence of a low temperature continuum component would give the appearance of higher abundances in the line-emitting species. Lastly, any broad range of temperature components forced to be fit to a single temperature (or two temperatures) cannot possibly be reconciled consistently with the actual abundances in the plasma. There must be some level of contamination from all these effects, but their detailed modelling will not be attempted here. We note, however, that a qualitative estimate of their impact on the formal fits of Table 1 would suggest that a distribution of solar abundance components with a total emission measure of about 8×10^{52} cm^{-3}, which extends over about 5×10^6 K to 5×10^7 K but is peaked $\lesssim 10^7$ K, might best describe the spectrum we observe.

We have no unique explanation for the fact that the present data, in agreement with the previous X-ray results, demand a much higher coronal temperature than the 1.2×10^6 K calculated by Haisch and Linsky on the basis of the ultraviolet measurements. Haisch and Linsky suggested that the 8×10^6 K measured by Catura, Acton and Johnson might have represented the contribution from a minor active constituent in a cooler corona, much like a solar-active region. Cash et al. demonstrated that there could be no substantial coronal emission at temperatures below 3×10^6 K, so that perhaps the higher temperature component observed with the SSS represents the active component in a corona with a "quiescent" temperature of about 6×10^6 K. The high emission measure could still be confined to a relatively small fraction of the coronal volume, where the density is higher than the coronal average. Post-impulsive solar flare coronal X-ray emitting regions of comparable temperature exhibit cooling times < 1 hour, so that the relative constancy of the count rate in Figure 1 would argue either that a proliferation of newly created active regions must be replacing the ones which cool, or that the hot regions in Capella are longer-lasting. In any case, we appear to be observing an overall coronal configuration which is: a) quasi-stable (at least on a timescale of several hours), b) not isothermal, and c) much too hot to be gravitationally bound to the star.

Haish and Linsky were careful to point out all of the simplifying assumptions which led to their calculation of a 1.2×10^6 K isothermal corona, and have noted several qualifications which could invalidate their conclusions. In particular, they remark that the acoustic flux required to heat the corona even to 1.2×10^6 K is large compared with estimates for that generated in the photosphere, and that a different heating mechanism may be required. Rosner, Tucker and Vaiana (1978) have suggested that the heating of even the quiescent solar corona may be dominated by the conversion of magnetic energy via Alven mode dissipation and coronal current heating, and that quasi-stable loop structures may represent the basic building blocks of stellar coronae, in general. The loop structures may be long-lasting in a quiescent corona, or unstable if the heat input is variable (see Withbroe 1978 for the application of such a model to the cooling phase of solar flare). The X-ray temperatures observed would then arise from the superposition of such loops over the total coronal structure. It would appear that this sort of model could be naturally reconciled with all of the X-ray data. In addition, the high temperatures defined by the X-ray measurements (independent of the mode of energy input) would, in a homogeneous corona, have implied a mass loss considerably in excess of the approximately 10^{-8} $M_{\odot}$/yr suggested by the wind speed measurement of Dupree (1975); as the coronal loops can be in hydrostatic equilibrium, however, the self-consistent model demands that the hot material trapped in the loops will contribute little to the total stellar mass loss.

Finally, we remark that although we have not attempted to construct a quantitative loop model in this short communication, we can attempt a crude consistency check from scaling the solar coronal calculations of Rosner, Tucker and Vaiana. If we make the arbitrary assumption that the loop geometry scales linearly with stellar radius, both the observed temperatures as well as the total X-ray luminosities are consistent with loop magnetic fields which are an order of magnitude larger in the corona of Capella than in that of the Sun.

To summarize, the SSS exposure to Capella has provided direct evidence for:

1. X-ray line emission from Mg, Si, S and Fe
2. Significant deviations from isothermality in the stellar corona, with temperature components between 6×10^6 K and at least 24×10^6 K
3. Anomalously high apparent abundances (relative to solar) in the line-prominent elements if collisional equilibrium in two distinct components is assumed
4. Stability in the X-ray emission to $\lesssim$ 10% over a timescale of 4 hours.

We suggest that a natural explanation for all of the above follows from the suggestion of Rosner, Tucker and Vaiana that the coronae of late-type stars can be synthesized from magnetic loops, with the heat input to the contained plasma arising from the coronal magnetic field. The superposition of similar (but not identical) loops could then give rise to the broad temperature distribution which would explain the departures in the overall coronal emission from isothermality, and the apparent overabundances in the line-prominent species relative to those expected from collisional equilibrium. The relative constancy of the emission over hours suggests that our measurement of Capella was obtained in a stable, quiescent configuration, but the coronal loop scenario would not be inconsistent with the factor-of-4 variations reported by Mewe et al. (1975) at other times.

After the completion of this work we became aware of the conclusion of Ayres and Linsky (1979), based upon recent data obtained with the International Ultraviolet Explorer, that the X-ray emission from the Capella system was associated with the G0 secondary (rather than the G5 primary, as had been assumed in previous work). The SSS cannot provide direct evidence for or against this hypothesis, but, if correct, it would tend to strengthen the plausibility of the qualitative explanation we have made for the X-ray data. Ayres and Linsky suggest that the rapid rotation of the secondary should enhance the surface magnetic fields, implying a causal (rather than merely a consistent) relationship between the X-ray emission and a coronal loop geometry.

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TABLE 1

SPECTRAL FITTING PARAMETERS

	T ($\times 10^6$ K)		LOG EM		*ABUNDANCES			
	T_1	T_2	EM_1	EM_2	Mg	Si	S	Fe
90% confidence minimum	4.3	24	---	52.0	1.1	1.9	2.9	0.4
best-fit	5.9	46	52.6	52.1	2.2	3.8	6.2	1.6
90% confidence maximum	6.6	100	53.0	52.2	---	---	---	---
single-temperature+	7.4 ± 0.8		52.9 ± 0.1		0.6	1.1	2.5	0.4

*Abundances are relative to solar, with all other abundances fixed at solar in fitting procedure.

+Single-temperature fit is not acceptable.

FIGURE CAPTIONS

Figure 1 - Chronology of the SSS exposure to Capella. Each data point represents the background-subtracted number of X-rays above approximately 1 keV accumulated in 100 s. The gaps in coverage represent earth-eclipse or high-background regions which are excluded from further analysis. Although there is a slight indication of an increasing trend at the beginning of the exposure, a χ^2-test of these data indicates consistency with the hypothesis of a constant source intensity.

Figure 2 - The raw data from the entire Capella exposure compared with four trial models folded through the detector response: a) the best-fit blend of temperature and abundances given in Table 1, b) exactly the same model as in a) but with the Fe abundance reduced from 1.6 to 0.0, c) the lower temperature best-fit component only, d) the higher temperature best-fit component only.

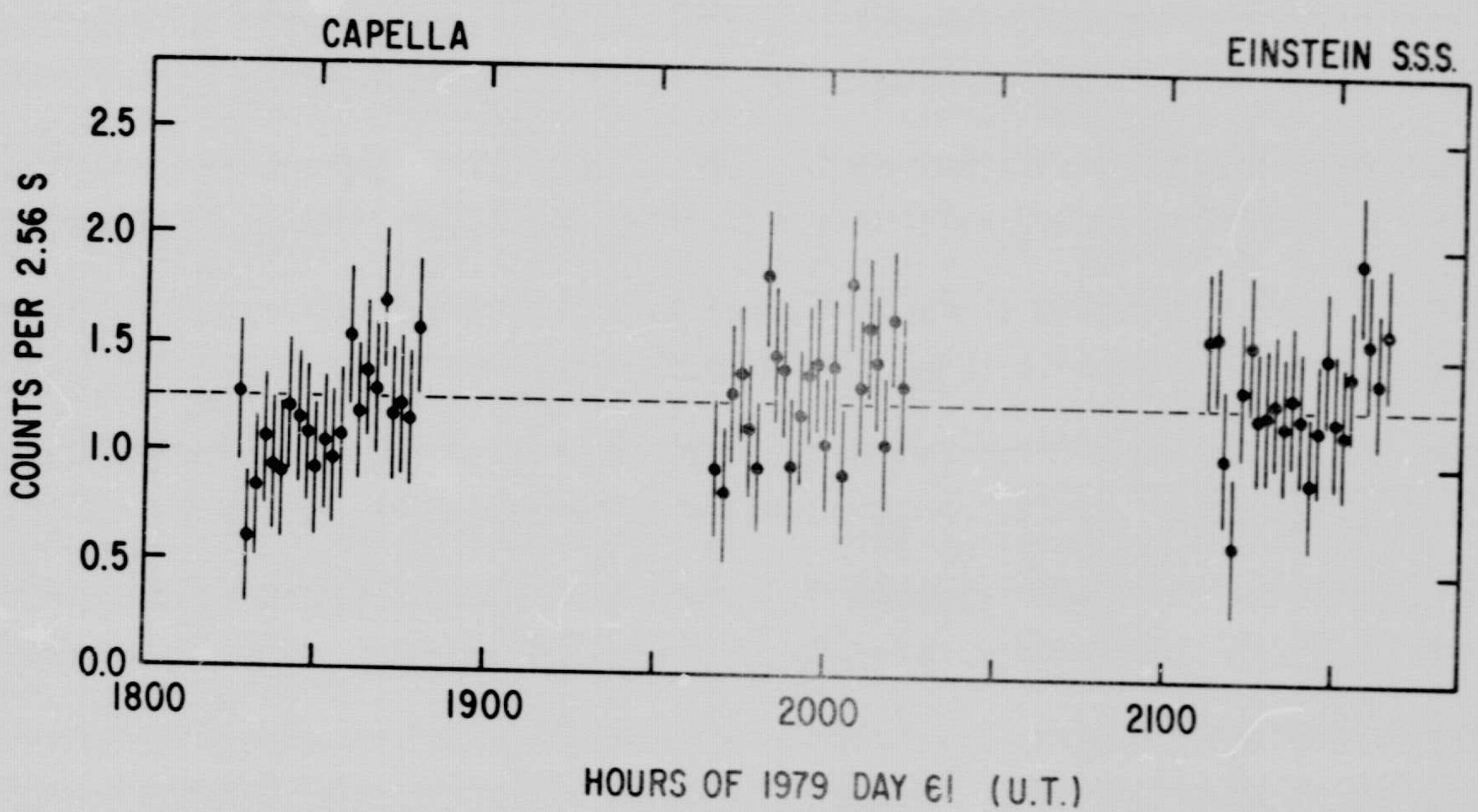
CAPELLA
EINSTEIN S.S.S.
COUNTS PER 2.56 S
2.5
2.0
1.5
1.0
0.5
0.0
1800
1900
2000
2100
HOURS OF 1979 DAY 61 (U.T.)

Fig. 1

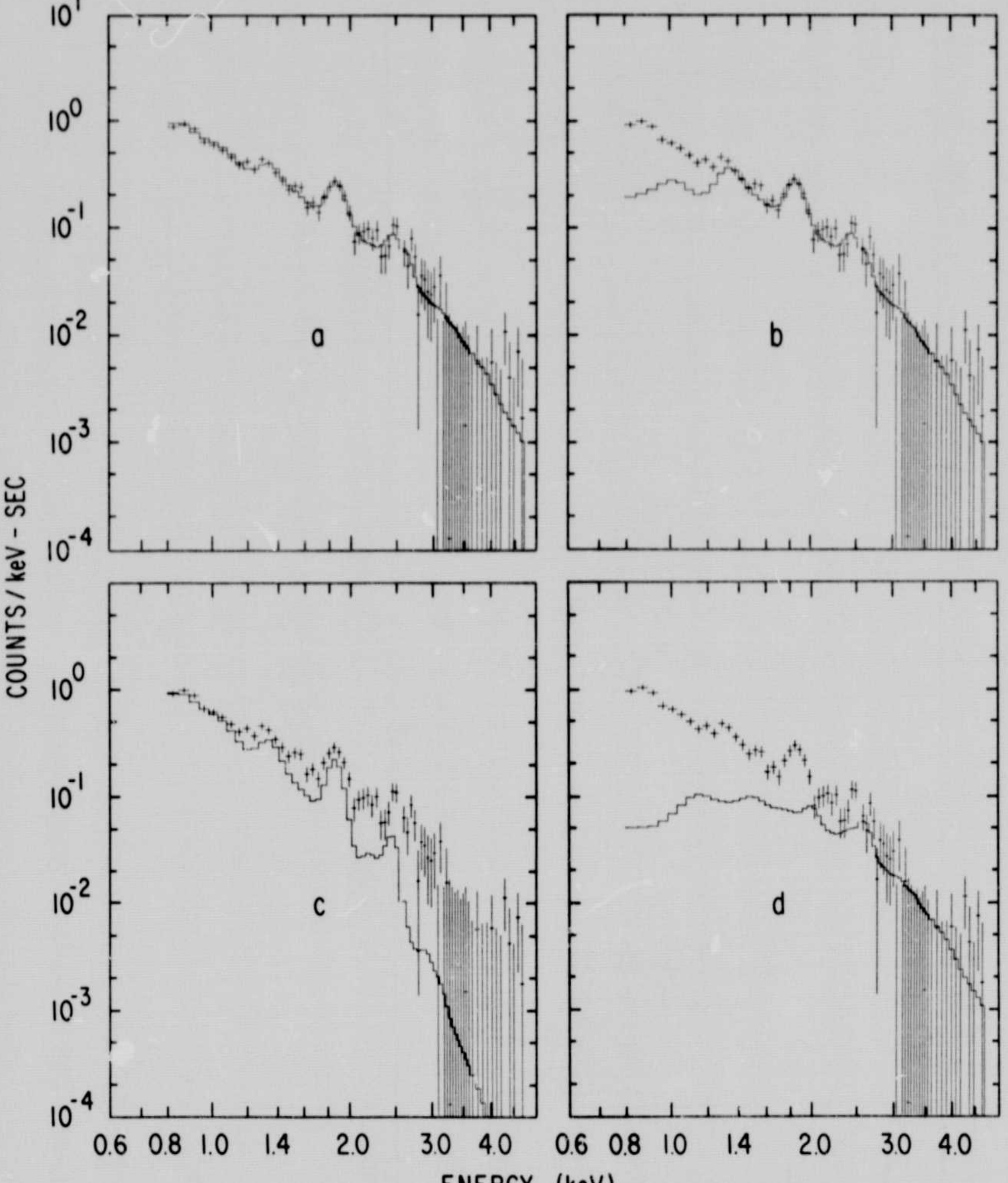

Fig. 2

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