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FIRST DETECTION OF X-RAY VARIABILITY OF η CARINAE

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ABSTRACT

Recent ROSAT Position Sensitive Proportional Counter (PSPC) observations for the first time unequivocally reveal the presence of a compact source of hard X-ray emission centered on the peculiar star η Carinae. These observations also show a dramatic change in the hard-band ($E>$ 1.6 keV) counting rate by about a factor of 2 in a 4-month interval. Thus, strong variability which is a characteristic of η Carinae in radio through IR and visible-band wavelengths is also observed at X-ray energies. The increase in hard X-ray emission could be the result of a tripling of the mass-loss rate in less than 4 months.

Subject headings: stars: activity — circumstellar matter —stars: individual (η Carinae) — stars: peculiar — X-rays: stars

1. INTRODUCTION

η Carinae is a well-known but little understood star located at a distance of 2600 pc in the OB association Trumpler 16 in the Carina Nebula. The star is best known for a dramatic outburst in the 1840's at which time the star ejected ~ 1 $M_\odot$ of material and brightened to $<0^m$ before declining by 8^m. The star has been classified as a Luminous Blue Variable (Davidson 1989), i.e. a massive, evolved single star near the Eddington limit which is subject to violent instabilities and periods of large mass loss. However, alternative models (Bath 1979, Gallagher 1989, van Genderen, de Groot and The 1994)

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have also been proposed. The star is difficult to study since it is surrounded by thick clouds of gas and dust ejecta which form a bright, oval-shaped nebulosity called the homunculus (Gaviola 1950). The homunculus in turn is embedded in an outer shell of material (Walborn 1976) which consists most noticeably of bright knots or condensations of gas and dust expanding away from η Carinae.

Although numerous X-ray observations of the Carina Nebula and η Car appear in the literature (Becker et al 1976, Bunner 1978, Forman et al. 1978, Seward et al. 1978, Seward and Chlebowski 1982, Chlebowski et al. 1984, Koyama et al. 1990) no strong evidence of X-ray variability has ever been reported. This is remarkable since the star is a known variable in every other region of the electromagnetic spectrum and in particular has varied continuously in the optical since the 1600's.

In this Letter we discuss ROSAT Position Sensitive Proportional Counter (PSPC) observations which show that the sources of hard and soft X-rays are spatially distinct and which provide the first direct evidence of X-ray variability in η Car. Our analysis shows that the variability arises from a point-like source of high-energy photons embedded in extended soft emission. The position of the variable source is consistent with the position of η Car. We explore simple models to describe the observed variation and briefly examine their implications.

II. OBSERVATIONS AND DATA REDUCTION

ROSAT PSPC observations of the Carina nebula region including η Car are listed in Table 1. A preliminary analysis of the Jun 92 segment of sequence 900176 has been published elsewhere (Corcoran et al. 1994). Sequences 200108 and 201262 were obtained from the ROSAT archive and analyzed along with our longer pointings. Data from all the sequences were reduced in the same way. Figure 1 shows PSPC images of η Car in 2 energy bands at 2 separate times. The O3 star HDE 303308 lies about $1'$ to the northeast of η Car and is barely resolved from η Car in the PSPC soft-band images. In each observation η Car was detected with a background-subtracted, vignetting corrected counting rate of about 0.3 counts s^{-1} in the total ROSAT band (0.2-2.4 keV). No short-term (minutes/hours) variation in counting rate was seen in any of the individual data sets.

η Car is obviously extended in the PSPC soft-band images, with an X-ray morphology similar to that described by Chlebowski et al. (1984). The maximum of the soft emission occurs to the northwest of the star (Fig. 2a). At energies above 1.6 keV, however, the X-ray emission appears pointlike with the maximum of the emission shifted so as to be coincident with the η Car (Fig. 2b). Chlebowski et al. (1984) previously deduced the presence of a compact source of hard X-rays near η Car from their analysis of *Einstein* IPC, SSS, HRI data, but were unable to conclusively identify the hard source in the *Einstein* data due to the limited spatial response of the IPC and the HRI's lack of energy resolution. The better spatial and spectral resolution of the PSPC data clearly show that the hard emission originates in a compact source very nearly coincident with η Car.

III. OBSERVED VARIABILITY

Figure 1 shows PSPC images of η Car in different energy bands from the Jun 92 and Dec 92/Jan 93 observations. We saw a dramatic increase in hard-band ($E > 1.6$ keV) emission in the Dec 92/Jan 93 observation compared to the earlier dataset, with no significant change in the soft-band flux ($E < 1.0$ keV). The increase of the observed counting rate from the hard source in the Dec 92/ Jan 93 data is about a factor of 2. Figure 3 shows the net hard band (1.6 keV$< E <$ 2.4 keV) lightcurve for the Jun 92 and Dec 92/Jan 93 data. The Dec 92/Jan 93 hard band counting rate is about a factor of 2 larger than the Jun 92 hard band rate, with no significant evidence of variability within either data set.

IV. X-RAY SPECTRAL ANALYSIS

We extracted the spectrum of η Car from the PSPC data using a circular region of 1.75′ radius centered on η Car (excluding most of the X-rays from HDE 303308) as our source region and a circular annulus of inner radius 1.75′ and outer radius 3.75′ around η Car (excluding obvious point sources) as our background region. We found remarkably good agreement between the Aug 92 spectrum and the Jun 92 spectrum (Fig. 3). The Dec 92/Jan 93 spectrum showed a significant increase in emission at $E > 1.6$ keV, with no significant spectral change at lower energies.

We tried to model the spectra using a 2 temperature thermal model ("hot" plus "warm" components, with kT near 7.0 and 0.4 keV, respectively) with independent absorption (plus a constant ISM absorption) as suggested by Chlebowski et al. (1984). We found that we needed to include an additional "cool" component with $kT < 0.1$ keV in order to match the low energy emission detected in the PSPC. This "cool" component makes a significant contribution to the emission in the ROSAT band, but does not contribute substantially at higher energies. It would have been very difficult to detect the cool component in earlier observations since previous detectors were not very sensitive to such soft emission. Because the PSPC response drops rapidly above 2 keV, the PSPC spectra do not constrain the temperature of the "hot" component. Therefore we fixed the temperature of this component at 7 keV (Chlebowski et al. 1984).

The observed variation in X-ray emission could be produced by any combination of temperature, emission measure and/or absorbing column changes. For simplicity we considered 2 cases: one in which the emission measure of the hot component was allowed to vary with fixed absorbing column, and one in which the absorbing column was allowed to vary with fixed emission measure. In both cases the temperature of the hot component was held fixed at 7 keV, and the parameters of the cool and warm components and the value of the ISM absorption were also fixed. If we fix the absorbing column at the value derived by Chlebowski et al., 5×10^{22} cm^{-2}, then the emission measure of the hot component during the Dec 92/ Jan 93 observation needs to be a factor of 8 larger in order to match the observed increase at $E > 1.6$ keV. Parameters for this model fit are given in Table 2. On the other hand, if we hold the emission measure constant at log $EM = 57.81$ cm^{-3} (i.e. the value appropriate to the Dec 92/Jan 93 observation with $N_H = 5 \times 10^{22}$ cm^{-2}) but allow the absorbing column to vary, we find that the column needs to be increased in the Jun and Aug 92 observations by a factor of 2 (from 5×10^{22} to 10^{23} cm^{-2}) in order to match the spectrum above 1.6 keV at that time.

Thus, the PSPC spectra can be fit by a model in which the emission measure of the 7 keV material increased by a factor of 8 from Aug 92 to Dec 92, or one in which the column to the hot source decreased by a factor of 2 between Aug 92 and Dec 92. For variable emission measure model, the observed luminosity (uncorrected for absorption) of the hard component extrapolated into the *Einstein* band (0.2 - 4 keV) increases from 1.6×10^{33} to 1.4×10^{34} ergs s^{-1} in the Aug 92–Dec 92 interval. For a variable column density model, the observed luminosity of the hard component is 6.4×10^{33} ergs s^{-1} in Jun and Aug 92 and increases to 1.4×10^{34} ergs s^{-1} in Dec 92 (again in the 0.2 – 4.0 keV band). In either case, the observed luminosity from the "cool" and "warm" components alone is 2.6×10^{33} ergs s^{-1} in the 0.2 – 4.0 keV band. For comparison, Chlebowski et al. 1984 derived observed luminosities of 4×10^{33} and 5×10^{33} ergs s^{-1} for the soft and hard components, respectively, from the SSS spectrum. Note that the hard-band luminosities derived from the PSPC fits may be uncertain due to the extrapolation from the ROSAT to the *Einstein* band. The soft luminosity we derived from the PSPC spectra is probably more reliable due to the greater sensitivity of the PSPC at low energies and due to a more accurate correction of the spectrum for the diffuse soft background in which η Car is embedded.

V. DISCUSSION

Due to the complexity of the η Car X-ray spectrum and the limited bandpass available to the PSPC, it is impossible to precisely determine the cause of the observed increase in hard X-ray flux from the ROSAT data alone. If the absorbing column to the hot component was a factor of 2 higher in the Jun - Aug 92 interval than in the Dec 92/Jan 93 interval, this implies a factor of 2 increase in the density of the absorbing material (assuming constant volume of absorbing material). Chlebowski et al. derived a total mass of gas in the absorbing shell of 3 $M_{\odot}$ for an absorbing column of 5×10^{22} cm^{-2}. This implies that the mass of the shell increased by an additional 3 solar masses from the time of the SSS observation to Jun 1992, after which time the additional mass was dissipated in an interval of 4 months. Given that the inner edge of the dust shell lies at 0.006 pc (Mitchell and Robinson 1978), such a large change in the gross properties of the extended absorbing shell in a time interval as short as four months seems unlikely. In addition, changes in the absorbing medium should have observable effects in other parts of the spectrum. No such effects have clearly been identified, although changes in the visible-band extinction have been seen recently (Hamann et al. 1994). Thus the observed variability is probably not due to an increase in the overall mass of the absorbing shell alone. In what follows, therefore, we assume that the observed X-ray variability is produced solely by a variation in the emission measure of the hot component.

Following Chlebowski et al., we assume that the hard X-rays are produced in a thin shocked shell formed by the collision of a spherically-symmetric, radiatively-driven stellar wind from η Car with the boundary of the inner dust shell at 0.006 pc from the central star, while absorption occurs in the cool gas and dust in the surrounding shell. Admittedly, this model is overly simplistic given the asymmetries in mass loss from η Car and inhomogeneities in the surrounding medium, but this model is useful to illustrate the magnitude of change in the physical conditions required to match the observed X-ray variability. If we assume that the width of the thin shocked shell is $\Delta R/R \sim 0.1$, then the volume of the hot gas is about 9×10^{48} cm^3. The emission measures we derived from the our modeling of the PSPC spectra imply that the density of the shell increased from 1.0×10^4 cm^{-3} to 3.0×10^4 cm^{-3} in the interval Aug 92 to Dec 92, assuming that the volume of the shell remained constant. For comparison, Chlebowski et al. derived a density of 1.5×10^4 cm^{-3} from the SSS spectrum. The density increase we derive requires a factor of 3 increase in mass loss rate from the central star, from $\dot{M} \sim 1 \times 10^{-4}$ $M_\odot$ yr^{-1} to 3×10^{-4} $M_\odot$ yr^{-1}, if all the hot gas is provided by the wind from the central star.

The assumed temperature of the hot component, 7 keV, fixes the velocity of the stellar wind at the shock interface at about 2300 km s^{-1}. This velocity is typical of terminal velocities from O-type stars but substantially higher than the wind velocity of 400–500 km s^{-1} derived by Hillier and Allen (1992) from analysis of the optical P Cygni line profiles from η Car. However, within 2″ of η Car, Hillier and Allen also observed Hα emission lines with full width zero intensity velocities of a few thousand km s^{-1}, which they attributed to electron scattering in the stellar wind. At 2300 km s^{-1}, the travel time from the stellar photosphere of η Car to the inner edge of the dust shell is about 2.8 years. If the variation in X-ray emission occurred inside the dust shell then the disturbance which gave rise to the X-ray variation occurred 2.8 years before the initial ROSAT pointing, if the disturbance travelled outward from the star at 2300 km s^{-1}. Assuming that the variation is entirely due to an increase in emission measure, the observed increase in hard X-ray emission which occurred in the Aug 92 - Dec 92 interval suggests that the mass-loss from the central star tripled in only 4 months.

η Car (and other LBVs) can show orders of magnitude increase in mass loss on short timescales, so a factor of 3 increase in mass loss rate occuring in less than 4 months is probably possible. Meaburn et al. (1993) interpreted a jet-like feature associated with η Car as evidence of non-isotropic mass ejection events which occurred about 130 and 100 years ago. Duncan et al. (1995) detected a three-fold increase in the radio flux density from η Car in the interval Jun 1992 – May 1994 and suggested that the change in the radio flux was produced by a tripling of the UV flux from η Car. While the similarity in magnitude and timescale of the radio and X-ray variations is intriguing, no firm connection between the X-ray and radio phenomena can be made at the present time. A simultaneous increase in the X-ray and UV luminosity could result from the dissipation of a common absorbing medium which obscures both the UV and X-ray sources. However, as discussed above, it is difficult to produce the requisite change in the absorbing medium if the medium is distributed in a distant massive shell around η Car. From the radio data Duncan et al.

calculate an increase in number of UV ionizing photons of $10^{47.9}$ photons s^{-1}. For comparison, the increase we derive in number of X-ray photons for the increased emission measure model is about $10^{43.4}$ photons s^{-1}. For the increased emission measure model, the total amount of additional mass in the hot shell is about 1.5×10^{-4} $M_{\odot}$. This is about a factor of 300 smaller than the minimum mass of ionized material Duncan et al. needed to explain the radio outburst.

X-ray variability has been seen in other massive stars. Most recently, Berghofer and Schmitt (1994) reported an increase in the hard band (0.6–2.4 keV) PSPC count rate from the O supergiant ζ Ori which occurred over a 2 day interval. They attributed the observed variation to an expanding shell of shocked gas moving through the stellar wind. However for ζ Ori the observed PSPC hard–band count rate increased by only 30% or so, less than the factor of 2 increase exhibited by η Car.

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Table 1.
ROSAT PSPC Observations Near η Car by Time

Seq No	Target	Pointing Dates	Total Exposure Time	PI
200108	HD 93129A	Dec 91	1641	W. Waldron
900176	η Car	Jun 92	24338	J. Swank
201262	HD 93250	Aug 92	5668	A. Pauldrach
900176	η Car	Dec 92/Jan 93	13083	J. Swank

Table 2.
Best Fit Spectral Model Assuming Variable Emission Measure for the Hot Component

	Pre-Dec 92[a]	Dec 92–Jan 93[a]
NH (ISM)	0.2	0.2
kT_{H}[b] (keV)	7.0	7.0
log EM_{H} (cm^{-3})	56.89±0.20	57.81±0.06
log NH_{H} (cm^{-2})	22.7	22.7
kT_{W} (keV)	0.46±0.10	0.46
log EM_{W} (cm^{-3})	56.50±0.40	56.50
log NH_{W} (cm^{-2})	21.5±0.2	21.5
kT_{C} (keV)	<0.10	<0.10
log EM_{C} (cm^{-3})	57.81±0.50	57.81
log NH_{C} (cm^{-2})	<20.9	<20.9
log Flux[c] (ergs cm^{-2} s^{-1})	−12.35	−11.60

[a] Parameters without error bars fixed at tabulated value

[b] Subscripts H, W and C designate hot, warm and cool components, respectively

[c] Flux in (1.6 – 2.4) keV band uncorrected for absorption

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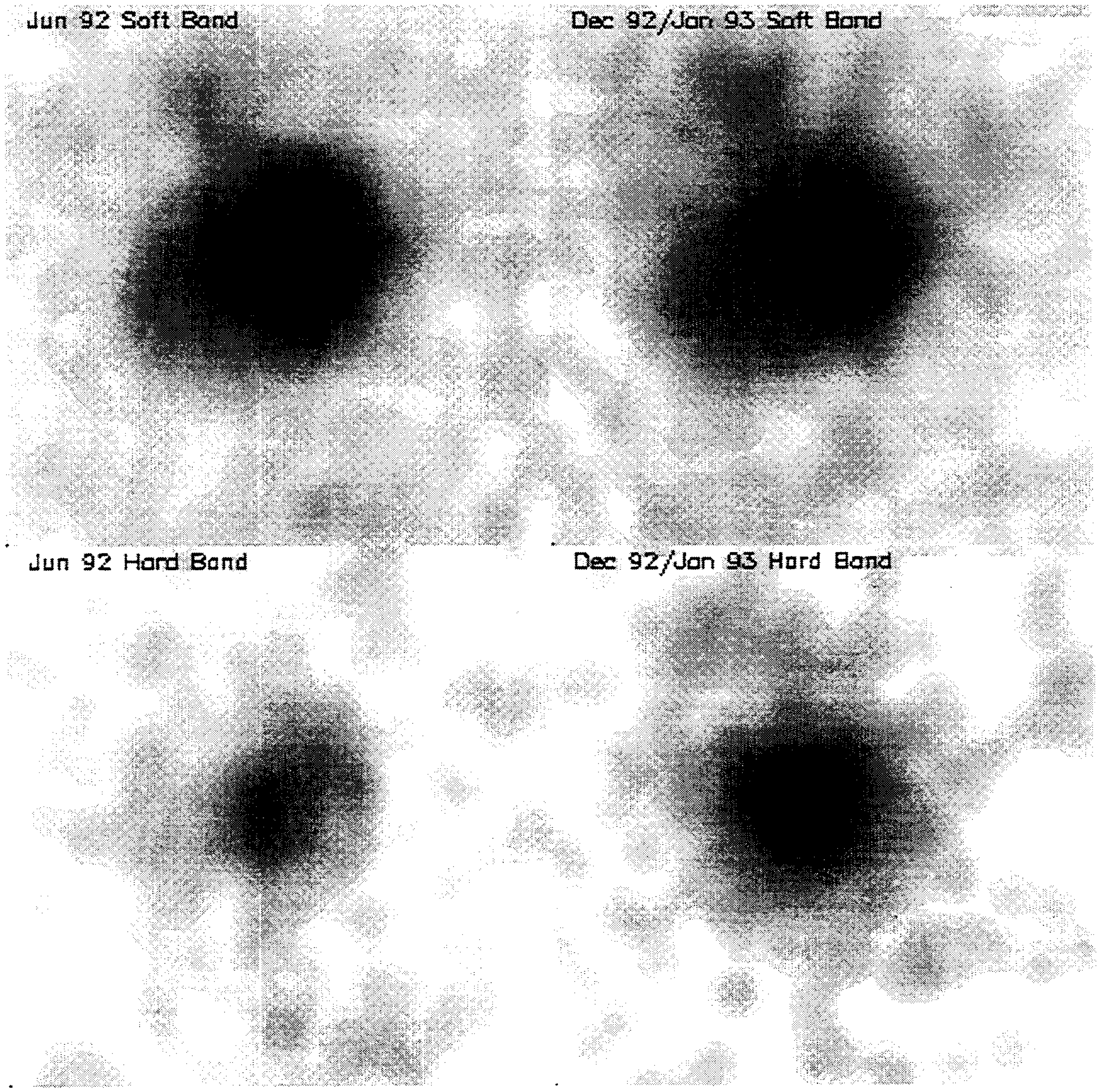


Jun 92 Soft Band
Dec 92/Jan 93 Soft Band
Jun 92 Hard Band
Dec 92/Jan 93 Hard Band

Fig 1

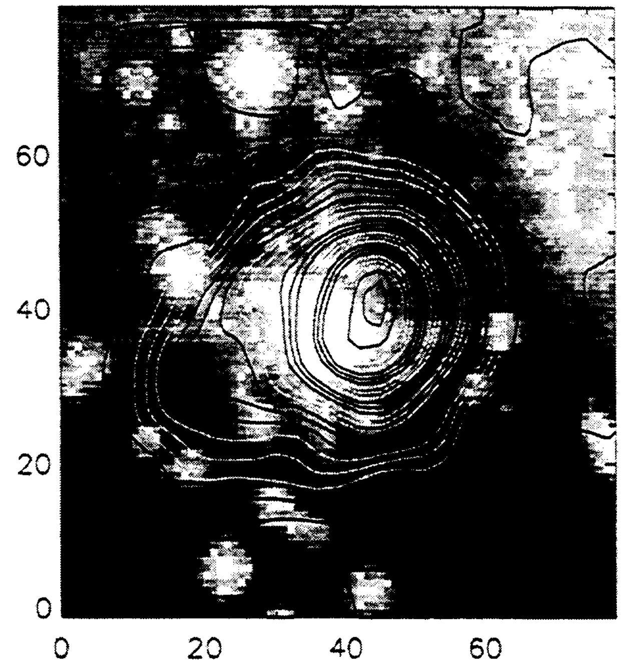


Fig 2a

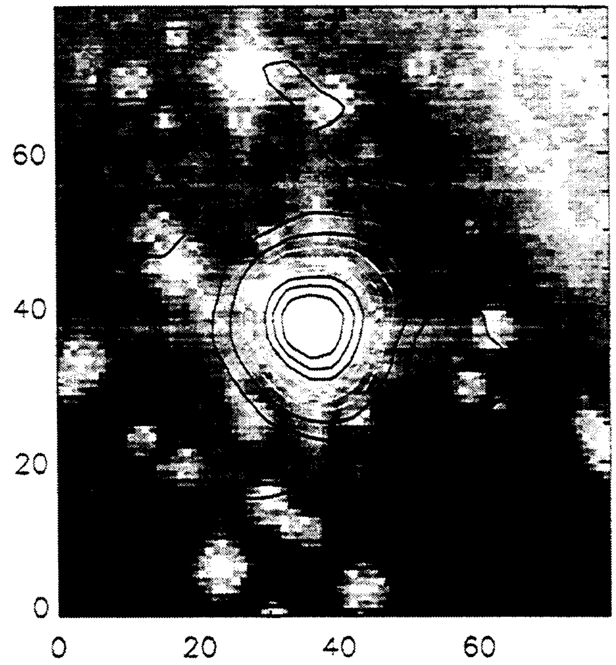
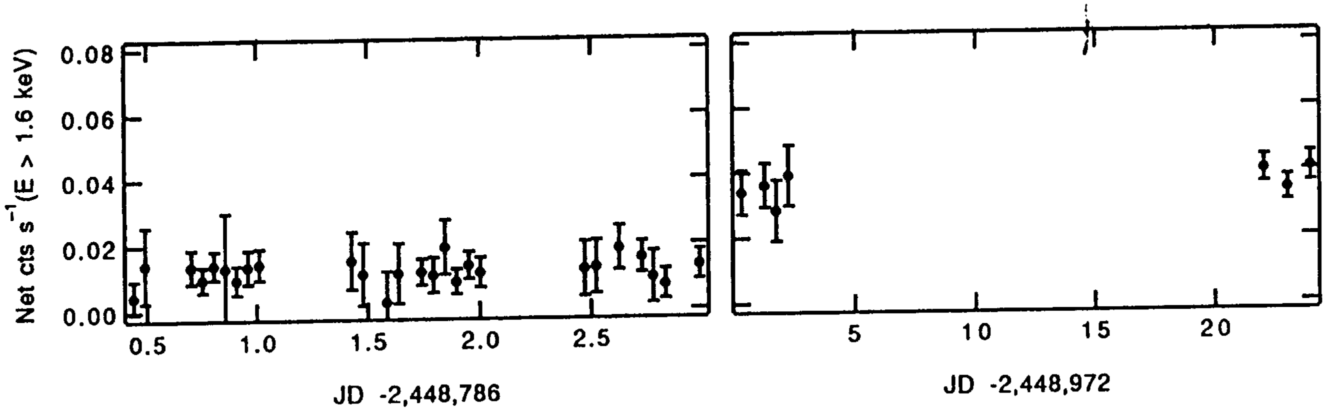


Fig 2b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0.04
0.02
0.00
0.5
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2.5
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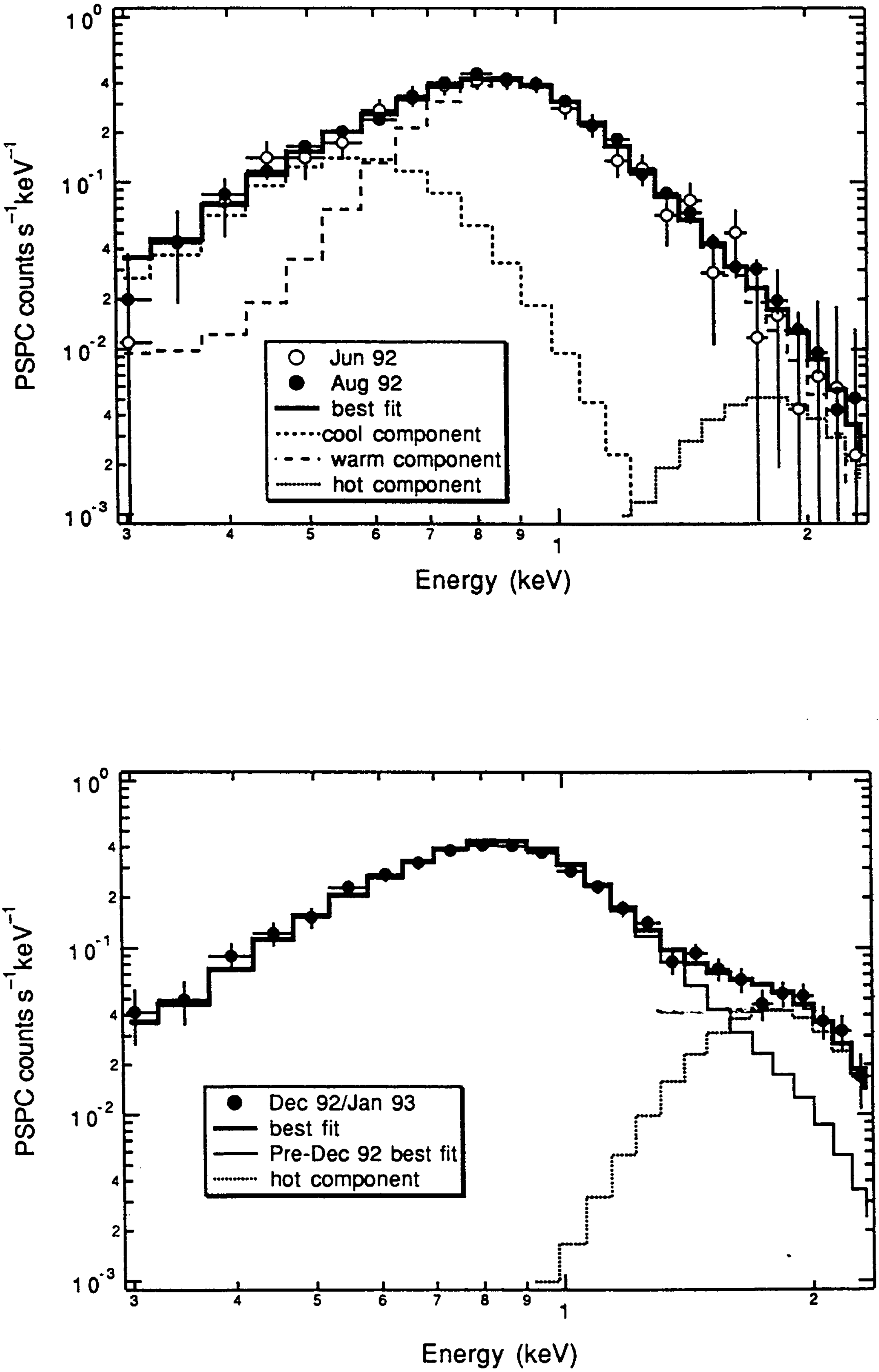
5
10
15
20
JD -2,448,972

Fig 3


PSPC counts s^{-1} keV^{-1}
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2
10^{-1}
4
2
10^{-2}
4
2
10^{-3}
3
4
5
6
7
8
9
1
2
Energy (keV)
○ Jun 92
● Aug 92
best fit
cool component
warm component
hot component
PSPC counts s^{-1} keV^{-1}
10^{0}
4
2
10^{-1}
4
2
10^{-2}
4
2
10^{-3}
3
4
5
6
7
8
9
1
2
Energy (keV)
● Dec 92/Jan 93
best fit
Pre-Dec 92 best fit
hot component

4a

4b

Fig 4