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ABSTRACT

The GSFC Cosmic X-ray Spectroscopy Experiment on OSO-8 observed X Per for twenty days during two observations in Feb. 1976 and Feb. 1977. The spectrum of X Per varies in phase with its 13.9 min period, hardening significantly at X-ray minimum. Unlike other X-ray binary pulsar spectra X Per's spectra do not exhibit iron line emission or strong absorption features. Our data show no evidence for a 22 hour periodicity in the X-ray intensity of X Per. These results indicate that the X-ray emission from X Per may be originating from a neutron star in a low density region far from the optically identified Be star.

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I. INTRODUCTION

The nature of the X-ray binary pulsar X Per has remained enigmatic in spite of numerous observations in both X-ray and optical bandwidths. White et al. (1976) discovered that the X-ray emission for X Per pulses with a period of 13.9 min, which has since been confirmed (White, Mason and Sanford 1977; Canizares et al. 1977; Margon et al. 1977). White et al. (1976) also reported an X-ray intensity modulation with a period of either 22 or 11 hours which has not been confirmed. A precise determination of the X-ray position indicates that the X-ray emission is probably associated with the Be star X Per (Hawkins, Mason and Sanford 1975). If the identification is correct, it implies an X-ray luminosity of 5 x 10^{33} ergs/s between 2 to 10 keV. Optical observations of X Per by Hutchings et al. (1974,1977) show it may be a spectroscopic binary with a 580 day binary period. If this effect is due to the gravitational influence of an unseen binary companion, it would have a mass of > 16 solar masses (Hutchings 1977).

II. OBSERVATIONS

X Per was observed by the GSFC Cosmic X-ray Experiment on OSO-8 during Feb. 21 - Mar. 2, 1976, and Feb. 21 - Mar. 3, 1977. The observations were made with a xenon-filled proportional counter with $5^{\circ}.09$ FWHM circular collimation, which is tilted 5° from the satellite's negative spin axis. Therefore, the detector makes a small angle scan every satellite rotation (~ 10 s) allowing a nearly continuous sampling of off-source background. Counting rates are obtained every 160 ms. The energy range of the detector is 2 - 60 keV, which is divided into 63 pulse-height channels.

The integrated pulse-height spectra for our two observations of X Per are shown in Figure 1. Both these spectra were fit to several simple continua (thermal bremsstrahlung, power-law, blackbody) modified by photoelectric absorption, and both spectra were found to be best represented by thermal bremsstrahlung continua, as depicted in Figure 1 and tabulated with errors in Table 1. Both pulse-height spectra show a high energy excess relative to the best fit continua.

There is no evidence for the presence of iron line emission between 6.4 - 6.9 keV in the X Per spectra. The 90% confidence upper limit for the equivalent width of any line emission in the 6.4 - 6.9 keV energy range is 200 eV.

The 13.9 min periodicity in the intensity of X Per was very evident in our data. The 160 ms rates from X Per were folded on a number of trial periods. Each folded light curve was tested against the hypothesis of constant intensity and the true period was assumed to be the one resulting in the highest χ^2. The pulse periods for X Per in Feb. 1976 and Feb. 1977 were found to be 13.9228 $\pm$ .0008 and 13.9195 $\pm$ .0008 min., respectively. A discussion of the error analysis can be found in Becker et al. (1977b). The folded light curves for these two epochs are shown in Figure 2.

The spectral data were folded on the observed pulse period into ten bins. Each data set so obtained was fit to a thermal bremsstrahlung model. The best fit value for kT as a function of pulse phase has been plotted in Figure 2. In both 1976 and 1977 we find that the spectrum hardens markedly at the minimum of the pulsed light curve, with the best fit kT increasing to 20 keV from its average value of $\sim$ 13 keV. Since this increase in temperature occurs at intensity minimum, there is the possibility that the effect is due to incorrect background subtraction. We do not feel this is the case. Firstly, background is accumulated every satellite rotation and is selected with the same criteria applied to the on-source data. Secondly, the effect is not limited to the highest energy channels, but rather is apparent even if we only consider the energy range of 2 - 20 keV.

We also examined our data for additional temporal variability and spectral-temporal correlation. Although the source was variable over time scales of hours, as illustrated in Figure 3, no evidence for a 22^h period or any other long period was found. A search for evidence of spectral variability by calculating the ratio of counts between 6 - 10 keV and 2 - 6 keV over two-hour samples did not yield any apparent correlation between spectral hardness and intensity.

III. DISCUSSION

The X-ray emission from X Per is strikingly different from those of other X-ray binary pulsars. X-ray spectra from most X-ray pulsars can be well represented by a power-law continuum of number index 1.0 - 1.2 with a high energy cutoff at 15 - 25 keV (Becker et al. 1977a; Becker et al. 1978; Ulmer 1975). In addition, it is typical for these sources to have strong iron line emission with equivalent widths exceeding 200 eV (Pravdo et al. 1977; Becker et al. 1978; Pravdo 1978). Lastly, many of these binary sources exhibit large variations in their low energy cutoffs due to varying amounts of photoelectric absorption. The spectra of X Per show none of these characteristics. Instead of a high energy cutoff, X Per appears to have a high energy excess relative to the best fit thermal bremsstrahlung model. This hard X-ray tail has been reported previously by Mushotzky et al. (1977) and is further confirmed by the Wisconsin experiment on OSO-8 (Bunner 1978). In fact, the spectra presented here are in good agreement with the earlier result by Mushotzky et al. (1977). White et al. (1976) have observed an absorption dip during which the neutral hydrogen column density increased by 4 x 10^{21} cm^{-2}, but this enhancement is small compared to the strong absorption events which characterize other binary systems.

X Per's low X-ray luminosity also distinguishes it from the catalog of other X-ray binary pulsars which are typically more luminous by $\sim$ 3 orders of magnitude. Rather, the X-ray luminosity of X Per is comparable to that observed from white dwarf binary systems such as Am Her (Swank et al. 1977). In this regard, the spin-up rate of X Per is a crucial measurement. Between 1972-1977, $\dot{P}/P$ was $-2.72 \pm .07 \times 10^{-3}$ min yr^{-1} (White, Mason and Sanford 1977). This rate is consistent with our two measurements and is the expected spin-up rate of an accreting neutron star with $L_x = 5 \times 10^{33}$ ergs/s, but is much too large for an accreting white dwarf of the same luminosity (White, Mason, and Sanford 1977; Lamb, Pines, and Shaham 1978).

There has been much speculation that the 22^h period in the X-ray intensity reported by White et al. (1975) defines the binary period of the system. We failed to detect this periodicity during two ten-day observations of X Per, and, therefore, suggest that 22-hours is not the period of the binary orbit.

Many of the unusual aspects of the X-ray emission from X Per can be understood if X Per is a neutron star in a low density region, i.e., distant from the Be star. This would explain the low luminosity and the lack of absorption dips. If there is a correspondingly small amount of material within the Alfven radius of the neutron star, it would also explain the absence of fluorescent iron line emission. Therefore, the X-ray behavior of X Per also argues against the X-ray emitting compact object being in a close 22 hour orbit about the Be star.

The high energy cut-off observed in other X-ray binaries has been attributed by some authors to Comptonization of the X-ray spectra by ionized material close to the neutron star (Illarionov and Sunyaev 1972; Ross, Weaver, and McCray 1978). If the emission from X Per comes from a neutron star with a mass accretion rate which is lower by 3 orders of magnitude than that for close binary systems, Comptonization would not be as important an effect. Therefore, the X-ray spectra from X Per, and in particular the hard X-ray tail, may be representative of the intrinsic emission processes near the neutron star undistorted by intervening material.

It remains for us to consider the nature of the 580 day periodicity in the velocity (± 35 km/sec) of the Balmer absorption lines of X Per (Hutchings et al. 1974; Hutchings 1977) and in the intensity of X Per (Guinan, McCook, and Dorren 1978). The cause of the velocity shifts is in doubt because the velocity of the He I absorption lines and the V emission peak show a much smaller variation over the 580 day cycle. Hutchings et al. (1974) first suggested that the Balmer line velocity changes are indicative of binary motion which imply the presence of an unseen companion of > 16 M_0 at an orbital radius of > 440 R_0. If this unseen companion is a compact object, it would have to be a black hole. Paczynski and Ziolkowski (1975) have suggested that the massive companion is a normal star which is obscurred by an optically thick gaseous disk. In either case, such an object would not emit pulsed X-rays.

Alternatively, Milgrom (1976) suggested that the He I velocity variations gave the true orbital velocity implying a secondary component mass of only 2 M_0. This model would allow the secondary to be a neutron star at an orbital radius of > 360 R_0.

Henrichs and van den Heuvel (1977) have suggested a third model in which the compact object is an eccentric close binary orbit with a 22 hour period. Apsidal motion of the elliptic orbit could then explain the 580 day period. As discussed above, however, the X-ray data do not support close, 22 hour orbit.

The X-ray data can be understood in terms of a wide binary system containing a Be star and a neutron star secondary with a 580 day period. If the mass loss from the Be star in X Per is comparable to that from other early stars such as the primary in Cen X-3, then the large inferred orbital radius in X Per directly yields the low luminosity. In this respect, the optical and X-ray data are self-consistent. The pulsations and the spin-up rate combine to provide strong evidence for a neutron star as the source of X-ray emission. If further optical studies continue to suggest the presence of a massive companion, we would have to conclude that X Per is, in fact, a triple system. A 580 day binary period for X Per should produce a periodic Doppler shift in the X-ray pulse period of approximately $\pm$ 0.0014 min which is comparable to the yearly spin-up rate. White, Mason, and Sanford (1977) searched for such a shift but were limited by the small number of available period determinations. An important observation for the future is the continued search for a 580 day Doppler shift in the X-ray pulse period of X Per.

THERMAL BREMSSTRAHLUNG FITS TO THE AVERAGE SPECTRA OF X PER BETWEEN 2-20 keV*

TABLE I

Date	Normalization	kT(keV)	$N_H (10^{22} cm^{-2})$	Intensity (2-20 keV) $(ergs\text{-}cm^{-2}\text{-}s^{-1})$	χ^2/Deg. of Freedom
Feb. 1976	.037	$12.2\pm.8$	$1.1\pm.2$	6.5×10^{-10}	42/32
Feb. 1977	.028	13.0	1.0	5.4×10^{-10}	70/32

*Errors for Feb. 1976 data are 90% confidence limits. Errors for Feb. 1977 data are not given because the fits were not statistically acceptable. The thermal bremsstrahlung model utilized the Gaunt factor computer approximation of Kellogg, Baldwin, and Koch (1975).

FIGURE CAPTIONS

Figure 1 - The PHA spectra of X Per in Feb. 1976 and Feb. 1977 from OSO-8 data. The models superimposed over the data are the best fit thermal bremsstrahlung continua.

Figure 2a,b- The pulsed light curves of X Per in Feb. 1976 and Feb. 1977.

2c,d- The best fit temperature for thermal bremsstrahlung continua for X Per spectra as a function of the pulse phase. The errors are 1 sigma limits.

Figure 3 - The intensity of X Per during observations by OSO-8 in Feb. of 1976 and 1977 in two hour averages.

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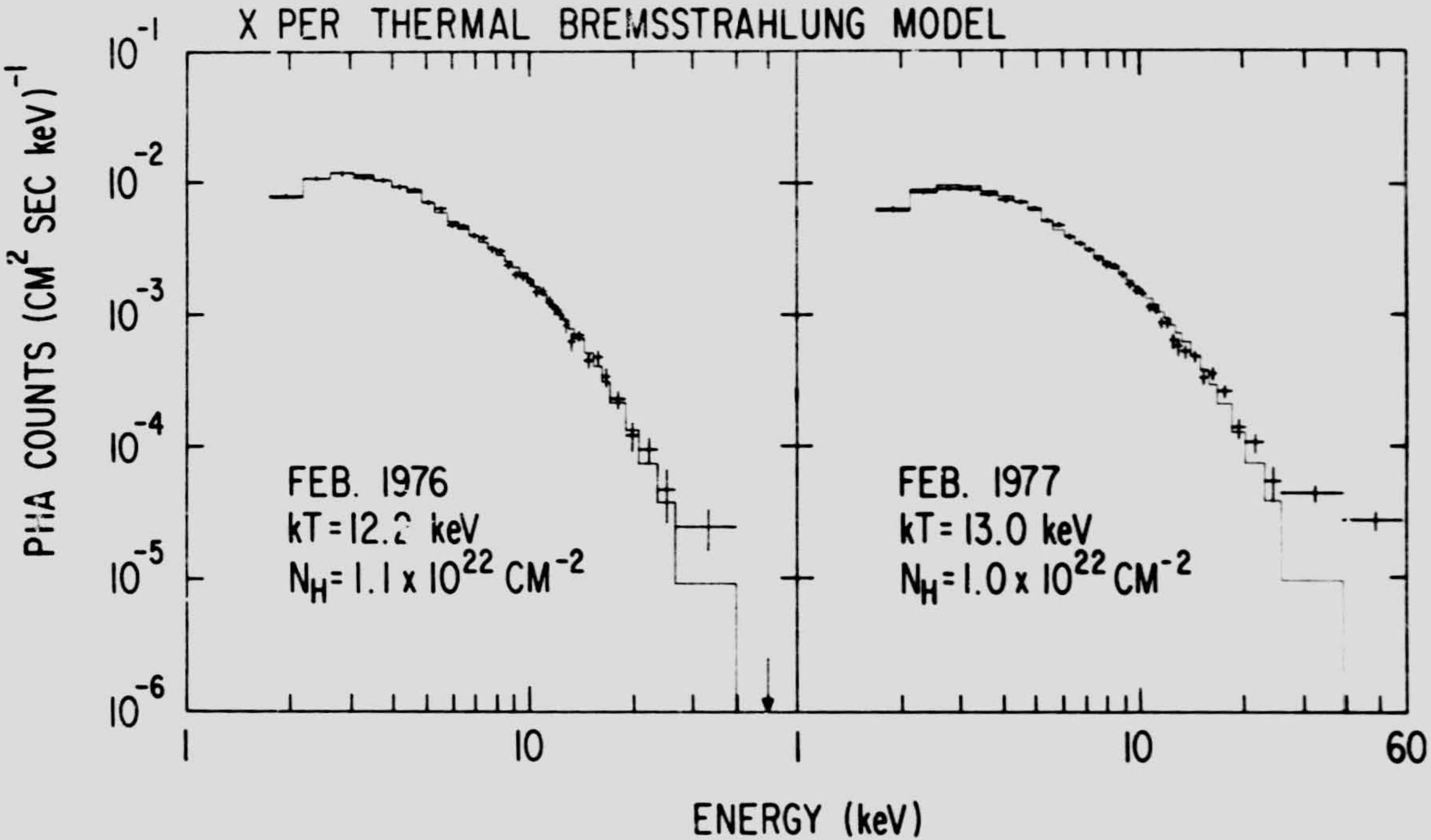
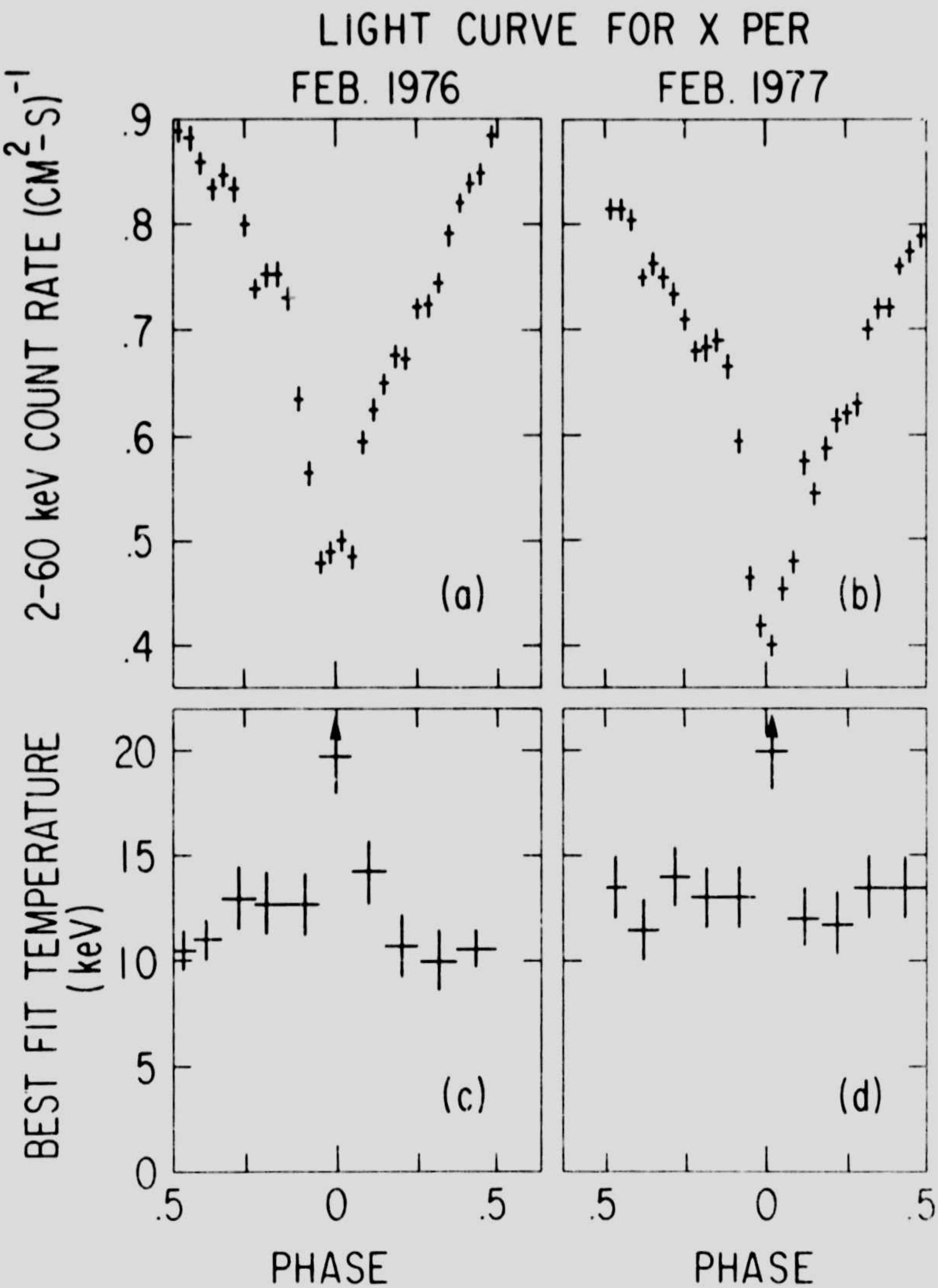
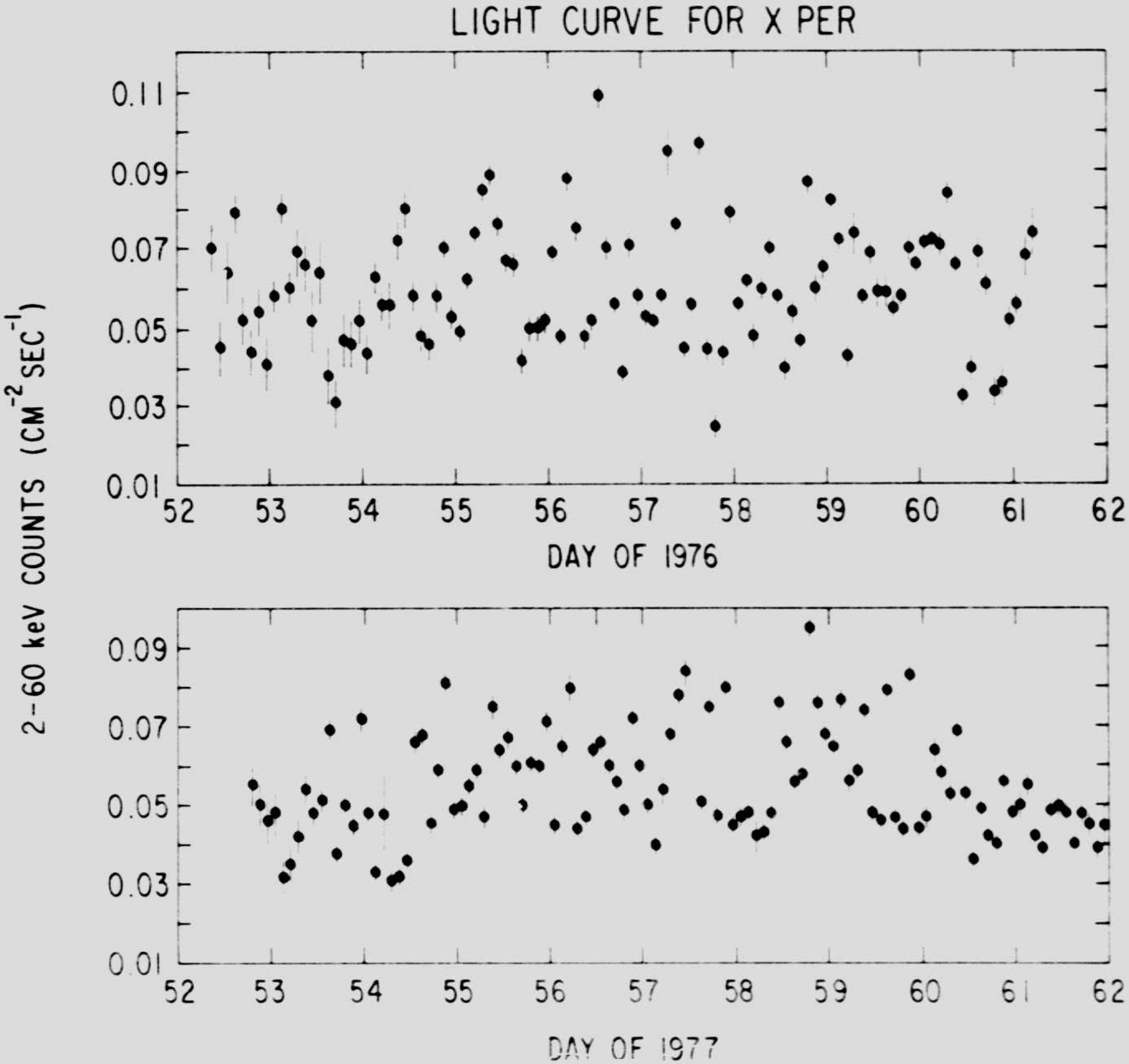

X PER THERMAL BREMSSTRAHLUNG MODEL
PHA COUNTS (CM² SEC keV)⁻¹
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
FEB. 1976
kT = 12.2 keV
N_H = 1.1 x 10²² CM⁻²
FEB. 1977
kT = 13.0 keV
N_H = 1.0 x 10²² CM⁻²
1
10
1
10
60
ENERGY (keV)


LIGHT CURVE FOR X PER
FEB. 1976
FEB. 1977
2-60 keV COUNT RATE (CM^2-S)$^{-1}$
.9
.8
.7
.6
.5
.4
(a)
(b)
BEST FIT TEMPERATURE (keV)
20
15
10
5
0
(c)
(d)
.5
0
.5
PHASE
PHASE



LIGHT CURVE FOR X PER
2-60 keV COUNTS (CM^{-2} SEC^{-1})
0.11
0.09
0.07
0.05
0.03
0.01
52
53
54
55
56
57
58
59
60
61
62
DAY OF 1976
DAY OF 1977