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EXOSAT OBSERVATIONS OF THE X-RAY SOURCE 2S 0114+65

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ABSTRACT

The *EXOSAT* satellite made X-ray observations of the Be star binary system 2S 0114+65 on five occasions during the period 1983–1986. Several X-ray flares of a few hours' duration were observed. The hardness ratio shows an inverse correlation with intensity, indicating that the intensity variation is due to absorption. This implies density irregularities in the gas disk around the Be star on the scale of 10^{11} cm. An iron line emission at 6.4 keV was observed when the absorption was high. On one occasion the intensity showed quasi-periodic oscillations with a period around 2000 s.

Subject headings: stars: Be — stars: individual (2S 0114+65) — X-rays: sources

1. INTRODUCTION

The X-ray source 2S 0114+65 was discovered with the *SAS 3* satellite during observations with the rotation modulation collimator (Dower et al. 1978). The optical counterpart was identified by Margon & Brandt (1977) and Margon (1980) as LSI +65°010. This is an 11th magnitude B0.5 III star having a broad Hα emission in its optical line spectrum. The Hα emission indicates it to be a Be star. Extensive observations by the *Einstein, HEAO 1* and *OSO 8* satellites were reported by Koenigsberger et al. (1983). They found strong variability of the X-ray intensity and flaring. They also found an indication of a 14.93 minute periodicity in the X-ray flux. The energy spectra were determined and found to be hard, with absorption hydrogen column densities (N_H) several times 10^{22} atoms cm^{-2}. Based on the nature of the spectrum, Koenigsberger et al. concluded the X-ray–emitting system consists of a Be star and a compact star. Using a distance of 2.5 kpc we find that the maximum flare intensity is about 2×10^{35} ergs s^{-1}. Crampton, Hutchings, & Cowley (1985) made optical spectroscopic observations of LSI +65°010. Using radial velocity measurements they find an orbital period of 11.588 ± 0.003 days. They argued that the characteristics of the system are consistent with either a Be system or a supergiant X-ray binary.

In this paper we present the observations of the X-ray source 2S 0114+65 with the *EXOSAT* satellite. We present the results in § 2 and discuss some implications in § 3.

2. OBSERVATIONS AND RESULTS

The source 2S 0114+65 was observed five times by the *EXOSAT* satellite during 1983–1986 (see Table 1). The observations were carried out using eight medium energy (ME) detectors sensitive in the range of 1 to 10 keV (see Turner, Smith & Zimmermann 1981, for details). Of the eight detectors, four were pointed at the source while the other four monitored the background from a neighboring region of the sky offset from the source by 1° to 2°. The backgrounds, external plus internal, were steady during most of the observations except during the rising part of a flare in 1986. The source was detected in 1983 and 1986, but not in 1985. The average flux during each of the observations is given in Table 1. X-ray flares from the source were seen four times in 1983 and 1986. The 2–10 keV X-ray light curves of the observed flares are shown in Figures 1 to 4, with a time resolution of 100 s to 200 s. The flares vary in duration from about 2000 s to 8000 s. Variability is seen down to a time scale of about 100 s.

The hardness ratio, i.e., the ratio of the X-ray intensity between 5 and 10 keV to the X-ray intensity between 2 and 5 keV was determined during each flare and was found to be variable. Typical examples of it are shown in the lower panels of Figures 1 and 2. The hardness ratio in Figure 1 is for an integration time of 1000 s as the source was very weak in the 1983 observing (see Table 1), whereas it is only 100 s in Figure 2 when the source was very bright. An inverse correlation between the 2–10 keV intensity and the hardness ratio appears to be present in Figures 1 and 2.

We have subjected the data to a Fourier analysis to determine the possible periods. The method used is generally known as the Lomb-Scargle method as adapted by Horne & Baliunas (1986) (see also Lomb 1976 and Scargle 1982). The low-frequency trends in the data were removed by subtracting the best-fit third-order polynomial prior to the power spectral analysis. Due to the high variability we were unable to detect any stable periodicity and in particular were unable to confirm the 14.9 minute periodicity found by Koenigsberger et al. (1983). However, quasi-periodic oscillations were observed in the flare of 1986 January 2 as shown in Figure 3. The period is around 2000 s, and the power spectrum diagram is shown in Figure 5. The background being monitored simultaneously did not show any significant power in the periodogram.

The energy spectrum of the X-ray emission during the flares was obtained. The spectral data were analyzed by fitting a power law multiplied by an absorption factor i.e.,

$$dN/dE = AE^{-\alpha}e^{-N_H\sigma(E)} ,$$

where N_H is the hydrogen column density and $\sigma(E)$ is the absorption cross section from Morrison & McCammon (1983). The data were fitted by convolving the above forms through the detector response function, and the quality of the fit was determined using the χ^2 statistical test. The best-fit constants α, N_H during each flare are given in Table 2 for fits to the spectrum between 2 and 10 keV. In two cases (see Table 2), the fits were better with an emission line around 6.4 keV; the equivalent widths are given in Table 2. Fits with a bremsstrahlung form of spectrum with absorption were tried but yielded very poor fits.

TABLE 1

SUMMARY OF X-RAY OBSERVATIONS OF 2S 0114+65

Satellite	JD 2,440,000+	Time (UT) hr	Average Flux (10^{-11} ergs cm^{-2} s^{-1})	Bandwidth (keV)
SAS 3	2625.5	...	9.0	2–10
OSO 8	2809.5	...	0.8	10–60
Einstein	3891.5	...	15.0	1.5–10
HEAO 1	2444.5	...	<2.1	2–20
	4462.5	...	Observed	2–20
EXOSAT	5543.5	0630–1422	0.7	2–10
	6429.5	0605–1423	<0.5	2–10
	6431.5	0700–0858	14.0	2–10
		0500–0552	7.7	2–10
	6432.5	0610–1003	16.0	2–10

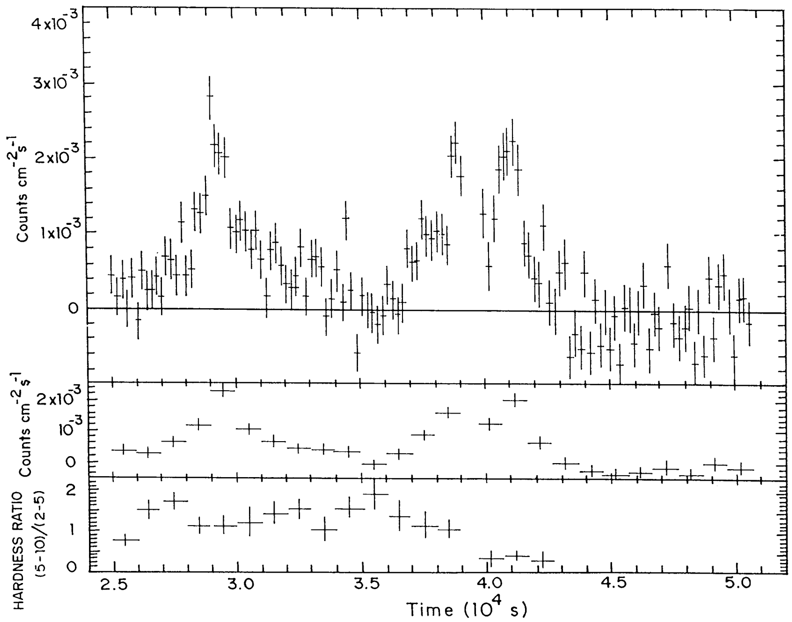

FIG. 1.—Background-subtracted count rates in the 2–10 keV energy range as observed from 2S 0114+65 in 1983 on July 28 are shown in the top two panels. The binning time for the top panel is 200 s and 1000 s for the middle panel. The hardness ratio from 1000 s integration is shown in the bottom panel. The anticorrelation of X-ray flares (*top; middle panels*) with the hardness ratio can be seen clearly.

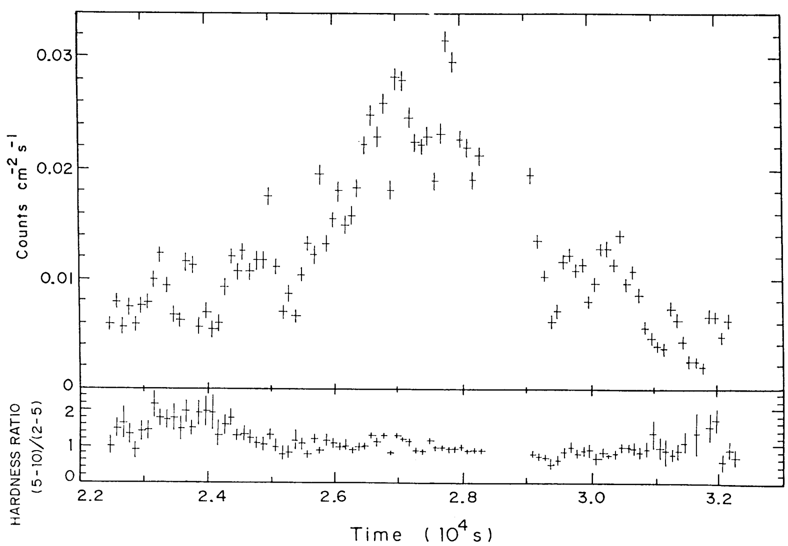

FIG. 2.—Source count rates (after background subtraction) in the 2–10 keV energy range as observed for 2S 0114+65 in 1986 on January 1 is shown in the top panel. The hardness ratio is shown in the lower panel. The binning time for both the panels is 100 s. The background monitors showed fluctuations in the rising part of the flare but were steady during the decaying part.

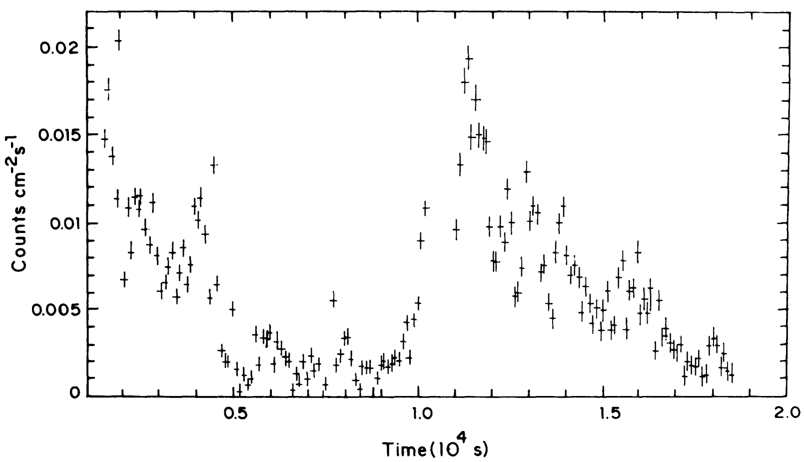

FIG. 3.—Background-subtracted source count rates in the 2–10 keV energy range as observed for 2S 0114+65 in 1986 on January 2. The binning time is 100 s.

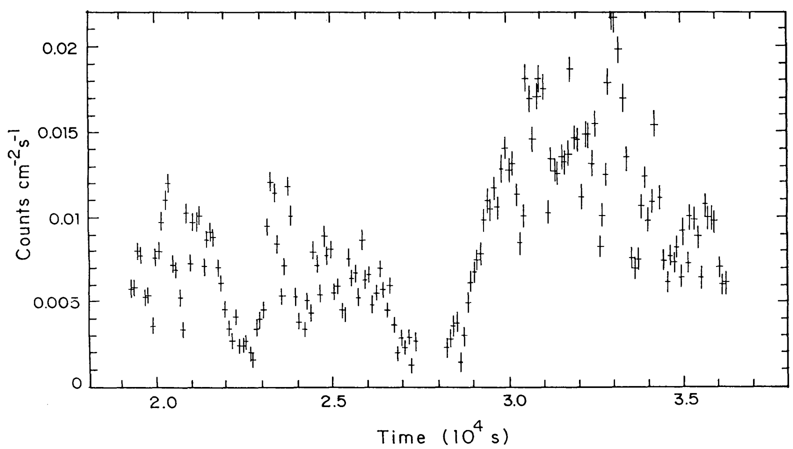

FIG. 4.—Background-subtracted count rates in the 2–10 keV energy range as observed for 2S 0114+65 in 1986 on January 2. The binning time is 100 s.

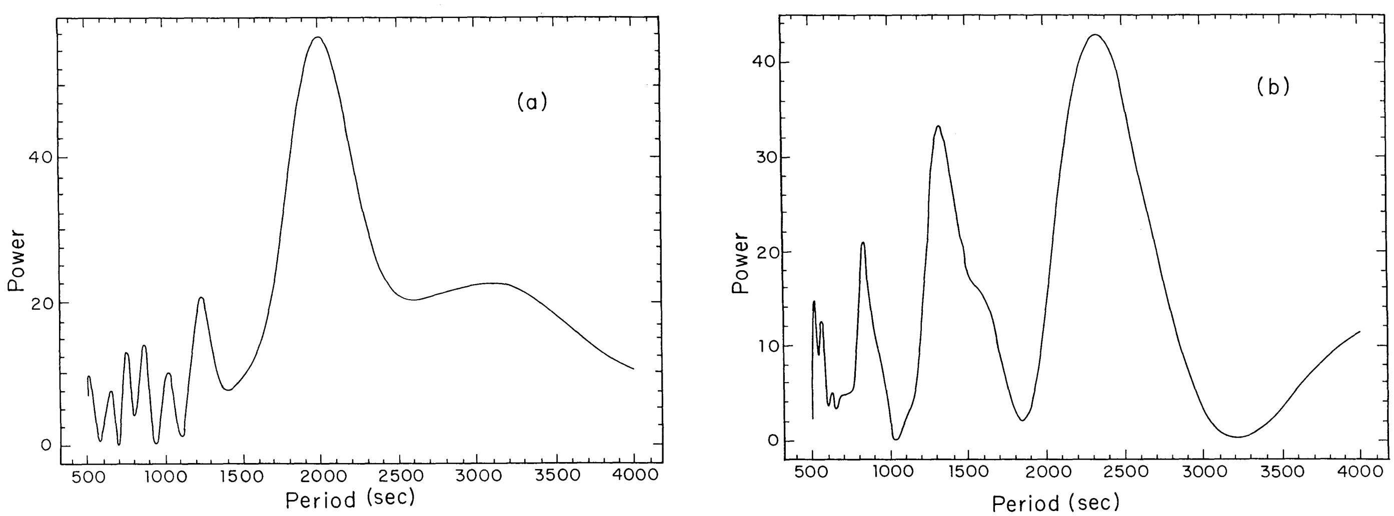

FIG. 5.—Periodograms obtained by Fourier analysis (as described in the text) of the flares of 1986 January 2 (Fig. 3). Panels (*a*) and (*b*) correspond to the two flares in Fig. 3. The most significant peak in both the panels has a slightly different period, viz., 2000 s in (*a*) and 2350 s in (*b*).

TABLE 2

SPECTRAL CHARACTERISTICS OF FLARES OBSERVED BY *EXOSAT*

JD 2,440,000+	TIME hr (UT)	PHOTON INDEX (α)	N_H (10^{22} cm^{-2})	Fe LINE Energy (keV)	Fe LINE Equivalent Width (eV)	χ^{2} [a]	AVERAGE FLUX[b]
5543.5	0630–1422	1.60 ± 0.60	8.2 ± 4.5	6.9 ± 1.4	527 ± 400	1.10	0.7
6431.5	0700–0858	1.25 ± 0.17	2.1 ± 0.7	...	...	1.35	14.0
6432.5	0050–0320	2.47 ± 0.30	9.4 ± 1.9	6.4 ± 0.4	526 ± 228	1.09	7.7
	0320–0552	1.01 ± 0.16	1.8 ± 0.9	...	...	0.95	
	0610–0800	0.93 ± 0.07	1.2 ± 0.5	...	...	1.00	16.0
	0800–0957	0.98 ± 0.01	1.5 ± 0.4	...	...	1.50	

[a] χ^2 per degree of freedom.

[b] Average flux in the energy range 2–10 keV and in units of 10^{-11} ergs cm^{-2} s^{-1}.

3. DISCUSSION

Table 1 lists the observations of the X-ray source 2S 0114+65 made before the *EXOSAT* observations. The fact that it is observed in most of the observations indicates that the source is "alive" quite often, unlike many other Be star X-ray sources which show extended periods of quiescence. Variability in the energy spectrum parameters of 1986 January 2 is remarkable. The value of N_H is quite high and is clearly associated with the gas envelope of the Be star. The general picture which is accepted is that a compact star (neutron star or white dwarf) is orbiting around the Be star and is fed by accretion from the gas envelope to produce the X-radiation. Since the compact star is embedded in the envelope, the X-radiation has to escape the gas envelope. The observation of the fluorescence iron line at 6.4 keV when N_H is large confirms this picture.

The most interesting result of the present observations is the inverse correlation of the hardness ratio and X-ray intensity in the flares. Table 2 shows the large variation in the column density, the higher values being associated with Fe fluorescence line emission. This implies that the hardness ratio variations are most likely due to a change in the absorption column density. Assuming this, it implies that the gas envelope is not uniform in density but has inhomogeneities. Crampton et al. (1985) give the mass of the primary Be Star as 18 $M_\odot$, which together with the orbital period of 11.6 days yields a velocity of about 330 km s^{-1} near the compact star which is at a distance of about 4×10^{12} cm from the Be star. If we use the flare durations of 2000–8000 s, the dimension of the inhomogeneities is between 7×10^{10} and 3×10^{11} cm. If we assume the size of the inhomogeneities of about 10^{11} cm in the radial direction also, then using $N_H \sim 2 \times 10^{22}$ cm^{-2}, the density of the gas in the envelope is of the order 2×10^{11} atoms cm^{-3}, which is similar to the value derived from other considerations.

The quasi-periodic oscillations seen in one of the flares are similar to those seen in the Be star X-ray source EXO 2030+375 (Parmar et al. 1988). The origin of these oscillations is unknown.

The question of whether the compact object in the Be star system 2S 0114+65 is a neutron star or a white dwarf is not answered yet. A comparison of 2S 0114+65 can be made with other Galactic Be star binary systems containing neutron stars, viz. A1907+09 and 4U 0115+63. These binary systems have similar orbital periods (8.4 days for A 1907+09 and 24.3 days for 4U 0115+63) but peak luminosities of the order of 10^{37} ergs s^{-1}. This would suggest that if the compact object in the 2S 0114+65 system were a neutron star it should show a similar luminosity. But the observed peak X-ray luminosity of about 10^{35} ergs s^{-1} implies that the compact object in this system is a white dwarf. However, the dependence of peak X-ray luminosity on the distance between the Be star and the neutron star needs to be understood more before this assertion can be made.

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Note added in proof.—Our attention is drawn to the brief analysis of the *EXOSAT* data of 2S 0114+65 by M. H. van Kerkwijk and L. B. F. M. Waters given in the Proceedings of the 23d ESLAB Symposium, Volume 1, edited by J. Hunt and B. Battrick (ESA SP 296, p. 473 [1989]). Our analysis is more extensive, with new results and conclusions.