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THE DISCOVERY OF 4.4 SECOND X-RAY PULSATIONS FROM THE RAPIDLY VARIABLE X-RAY TRANSIENT V0332+53

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ABSTRACT

Using the *EXOSAT Observatory* we have observed three outbursts from the transient X-ray source V0332+53 between 1983 November and 1984 January. We find that in addition to the rapid Cyg X-1–like variability previously reported by Tanaka *et al.* this source also displays stable pulsations with a period of 4.4 s. Doppler variations in the pulse period indicate that the pulsar is in a 34.25 day binary orbit with an eccentricity of 0.31. The times of periastron passage are close to those of the X-ray outbursts. The X-ray spectra and pulse profiles are quite similar to those seen from other X-ray pulsars. The rapid ~ 1 s variations are quantified in terms of the shot noise model previously applied to Cyg X-1 with the derived parameters found to be similar to those of Cyg X-1. It seems difficult to invoke the same mechanism to produce rapid fluctuations from both an accreting black hole and an accreting magnetized neutron star, and we conclude that two physically distinct processes can give rise to similar temporal variability. The rapid variations from V0332+53 may result from instabilities in the magnetosphere of a spherically accreting neutron star.

Subject headings: pulsars — stars: neutron — X-rays: sources

I. INTRODUCTION

The transient X-ray source V0332+53 was previously active for ~ 100 days in 1973 June when it reached a peak flux of $\sim 3 \times 10^{-8}$ ergs cm^{-2} s^{-1} (3–12 keV) before decaying to $< 5 \times 10^{-10}$ ergs cm^{-1} s^{-1} (Terrell and Priedhorsky 1984). Tanaka *et al.* (1983) using the *Tenma* satellite rediscovered V0332+53 at a flux 10 times lower than the peak value seen in 1973 and discovered flickering activity down to time scales of 0.1 s, reminiscent of that seen from the black hole candidate Cyg X-1. In this *Letter* we report the results of a series of subsequent observations of V0332+53 made by the European Space Agency's X-ray observatory *EXOSAT* (see Taylor *et al.* 1981 for details) that show this source to be a 4.4 s X-ray pulsar in a moderately eccentric $34^{d}25$ binary orbit about a B type star (Davelaar *et al.* 1983; Stella and White 1983; Parmar *et al.* 1984; White *et al.* 1984). We will concentrate here on the consequences of discovering "Cyg X-1"-like rapid fluctuations from an X-ray pulsar. Further papers will contain a more detailed consideration of the properties of V0332+53 and compare them with those of other OB star X-ray binary systems (Stella, White, and Rosner 1985; Davelaar *et al.* 1985).

II. THE OBSERVATIONS

A total of 14 *EXOSAT* observations of V0332+53 were made between 1983 November 20 and 1984 January 23 with each lasting typically 6 hr. During the first observation a Channel Multiplier Array (CMA) at the focal plane of an imaging telescope was used to obtain a position for the source at R.A. $03^{h}31^{m}14^{s}.5$ and decl. +53°00′17″ (1950) with an error radius of 10″. This error circle contains a $m_J = 12.1$ infrared object (Brand *et al.* 1983), that appears to be coincident with a $m_V = 15$ heavily reddened B star (Argyle 1983; Kodaira 1983; Bernacca, Ijima, and Stagni 1983; Honeycutt and Schlegel 1983). A further four observations by *EXOSAT* showed the 1–15 keV X-ray flux measured in the Medium Energy Proportional Counter array (ME) to decay over the following 10 days from 2.4×10^{-9} ergs cm^{-2} s^{-1} (1–15 keV) to less than 5×10^{-12} ergs cm^{-2} s^{-1} on 1983 December 1. On 1983 December 23 Williams *et al.* (1983) reported that the infrared counterpart had brightened in the *J* band by 0.8 mag. An *EXOSAT* observation on the following day confirmed the X-ray source to be again active at a level similar to the peak seen previously (Parmar *et al.* 1984). The quasi-simultaneous X-ray/infrared observation of an outburst secured the identification. *EXOSAT* observations over the following 10 days again showed the flux to decay in a manner similar to that of the preceding outburst. A third outburst was seen by *EXOSAT* from three observations made on 1984 January 19, 22, and 23 which gave fluxes of 7×10^{-10}, 9×10^{-10}, and 9×10^{-10} ergs cm^{-2} s^{-1}, respectively. The optical identification suggests a distance of between 1.5 and 5 kpc giving for the measured spectra discussed in § III a peak 1–15 keV luminosity of $\sim 7 \times 10^{35}$ $(d/1.5 \text{ kpc})^2$ ergs s^{-1}.

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III. X-RAY PULSATIONS

The ME instrument was usually operated with half of the array offset to provide a background monitor, although during some of the later observations the array was co-aligned to give a total collecting area of 1400 cm^2. A FFT was applied to each series of 4096 data points accumulated with a time resolution of 0.625 s and the resulting power spectra summed. In Figure 1 typical summed power spectra are shown taken from the observations made on 1983 November 20 and 1984 January 23. In each case a strong peak is evident at 0.46 Hz, and a second peak at 0.23 Hz on 1984 January 23. The increase in the noise at the lower frequencies is caused by the stochastic variability (cf. Terrell 1972). The two peaks at 0.46 Hz and 0.23 Hz represent the fundamental and first harmonics of a stable 4.4 s modulation of the X-ray flux. The modulation had a peak-to-peak amplitude of typically 15% and was seen in all observations when the X-ray source was detected. Figure 1 shows that the pulse profile is dependent on the source luminosity with the 1.4–4.4 keV profile changing from a double pulse when the source is bright, to a single pulse when the source was 2.6 times fainter on 1984 January 23. The pulse becomes broader at higher energies such that when the pulse is double the two pulses become smeared together.

During the first outburst the period was decreasing at a rate of $\dot{P}/P$ of 1.6×10^{-10} s^{-1} from a value of 4.37534(15) s on 1983 November 20. During the second outburst a similar decrease was seen; however, the value of the pulse period at the start was 4.37532(20) s, consistent with that measured at the beginning of the first outburst such that the $\dot{P}$ reversed sense in the intervening time. This suggested a cyclic variation in the pulse period possibly caused by orbital motion. The three observations in late January again found the source in outburst with the pulse period on this occasion increasing with values of 4.37532(20) s, 4.37560(20) s, and 4.37560(20) s, respectively. An eccentric orbit when fitted to the nine pulse period measurements, assuming zero intrinsic change in the pulse period, gives an orbital period of $P_{orb} = 34^d.25 \pm 0^d.10$, $a_x \sin i = 48 \pm 4$ lt-sec, an eccentricity $e = 0.31 \pm 0.03$, a mass function of $f(M) \approx 0.1$ $M_\odot$, a periastron longitude $\omega = (313 \pm 10)°$, and a time of periastron passage T_0 at JD 2,445,652. ± 1. The outbursts occur close to the time of periastron passage although, due to incomplete coverage, a lag of several days cannot be ruled out. This solution is valid as

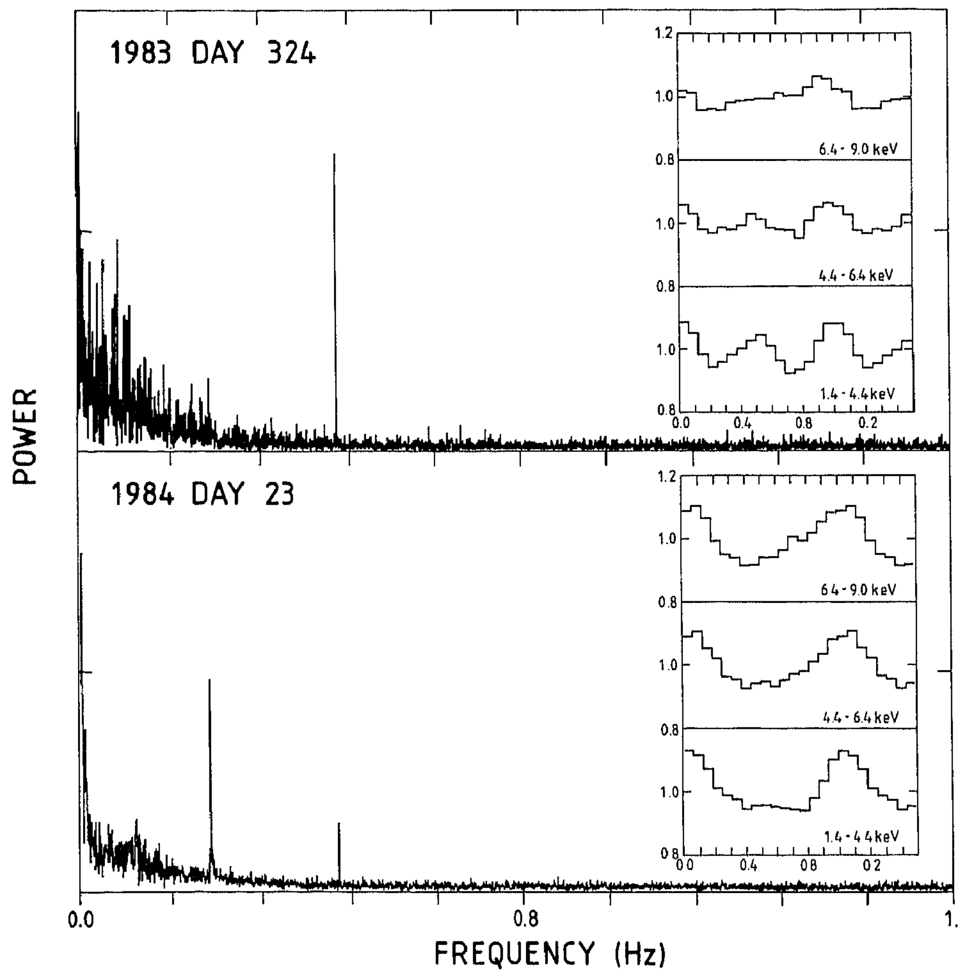

FIG. 1.—Power spectra for two *EXOSAT* observations of V0332+53 when the average flux was 2.4×10^{-9} ergs cm^{-2} s^{-1} (1983 November 20) and 9×10^{-10} ergs cm^{-2} s^{-1} (1984 January 23). The pulse profiles of the detected 4.4 s periodicity in three energy bands are shown as insets. The data used for the power spectra are from the 1.4–4.4 keV band only.

long as $\dot{P} < 3 \times 10^{-12}$ s s^{-1}; a value of $\dot{P}$ larger than this would be unusual for a 4.4 s pulsar with a luminosity of $\sim 10^{36}$ ergs s^{-1} (Rappaport and Joss 1977).

The ME spectral data are well described by a typical pulsar spectrum of a power law with an exponential cutoff at higher energies (cf. White, Swank, and Holt 1983). The spectrum evolved as the flux decayed by a factor of 10 during the first outburst with the power-law energy index, α ($E^{-\alpha}$), increasing from -0.5 ± 0.05 to -0.1 ± 0.05 and the high-energy cutoff energy decreasing from 15.7 ± 0.3 keV to 12.9 ± 1.2 keV. The cutoff e-folding energy of 11 keV did not change significantly as the flux declined. The equivalent hydrogen column density, N_H, varied between $(0.6 \pm 0.2) \times 10^{22}$ cm^{-2} and $(1.5 \pm 0.1) \times 10^{22}$ cm^{-2} with a tendency for N_H to increase as each outburst evolved. The uncertainties are 90% confidence.

IV. RAPID VARIABILITY

The total source variance, σ^2, is dominated by the stochastic flickering activity with $\sigma \approx 20\%$ the average count rate. The variance associated with the coherent pulsations contributes only $\sim 2\%$ to σ^2. The flickering activity is not strongly energy dependent, although the trend for a decrease in spectral hardness noted as the outbursts decayed is also present for the range of variability seen within each observation. An autocorrelation function (ACF) was computed from the 1–16 keV ME data binned into accumulation intervals of 15.6 ms and to exclude longer term trends for ~ 1800 intervals of ~ 22 s duration for the four brightest observations. The ACFs computed in each interval were then averaged with the resulting ACF shown in Figure 2 (cf. Stella, Kahn, and Grindlay 1984). The nearly exponential shape of the ACF is similar to the one obtained from data intervals of comparable length for Cyg X-1 (cf. Weisskopf, Kahn, and Sutherland 1975) and indicates the presence of shot noise–like variations with a characteristic decay time of 1.3 s. The slight slope changes visible for time delays of ~ 3 s and ~ 1 s are probably caused by the fundamental and the first harmonic of the periodic modulation. The linear decay of the ACF at very small time lags indicates activity on time scales of at least a few tens of milliseconds (see Priedhorsky *et al.* 1979 for a detailed discussion). A conservative estimate of the shortest time scale on which "edges" are positively detected in the data can be obtained from the smallest time delay for which the ACF slope is inconsistent with zero. At a 90% confidence level this gives a minimum time scale of at least 50 ms. Such a slope of the ACF cannot be due to high harmonic features in the pulsations as these would clearly appear in the power spectra (Fig. 1).

The aperiodic nature of the short-term variability revealed by the autocorrelation analysis can be characterized in terms of a shot noise model consisting of sharply rising exponential shots (Sutherland, Weisskopf, and Kahn 1978). The fit obtained from the first 100 points of the ACF in Figure 2 gives $33\% \pm 4\%$ of the flux in shots with a 1.28 ± 0.03 s decay time and occurring at an average rate of 1.0 ± 0.1 s^{-1}. These values are comparable with those obtained from Cyg X-1 in the low state. Due to the small contribution of the coherent pulsations to the total source variance, the periodic signal only marginally affects the determination of the shot noise parameters. This model was applied separately to each observation of V0332+53, and within the errors the shot noise parameters were found to be independent of the source flux. For an

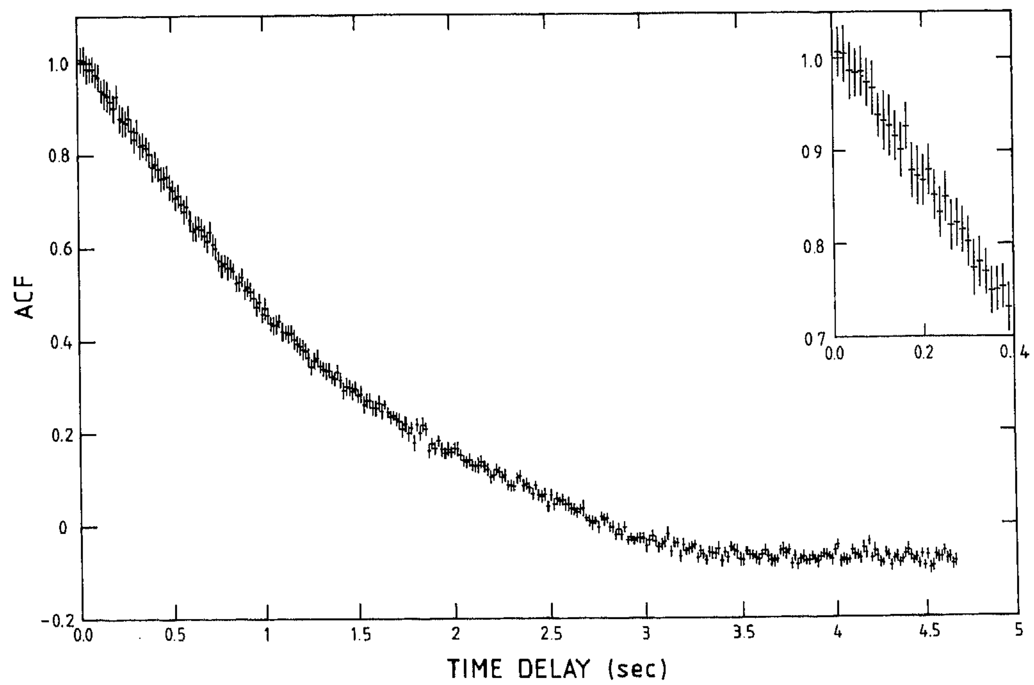

FIG. 2.—Average ACF of the high-resolution ME argon (1–16 keV) data from the four brightest *EXOSAT* observations of V0332+53. The almost linear decay of the ACF for time lags down to a few tens of milliseconds is shown in the upper right corner.

overall decrease by a factor of 3 in the source flux we exclude variations larger than 70%, 45%, and 20% (90% confidence level), respectively, in the shot noise rate, fraction, and decay time. A search for millisecond bursts (cf. Rothschild *et al.* 1974) failed to detect significant activity with an upper limit of 5×10^{-4} s^{-1} and 6×10^{-4} s^{-1} (90% confidence level) on the rate of occurrence of 7.8 ms and 15.6 ms bursts, respectively.

V. DISCUSSION

The discovery of 4.4 s X-ray pulsations together with a rapid stochastic flickering represents a previously unrecognized combination of time variability from a cosmic X-ray source. Apart from the rapid flickering, V0332+53 seems to be a typical transient binary X-ray pulsar associated with a B star companion similar, e.g., to 4U 0115+63 or A0538−66 (Rappaport and van den Heuvel 1982 and references therein). The stability of the 4.4 s X-ray pulsations and the general similarity of the properties to those seen from other X-ray pulsars (cf. White, Swank, and Holt 1983) strongly suggests that this system contains an accreting magnetized neutron star. Prior to this work rapid ~ 1 s stochastic variability had been considered a temporal signature of an accreting black hole based on the fact that such fluctuations were a distinctive feature of Cyg X-1. The discovery of rapid fluctuations from an X-ray pulsar does not invalidate the black hole candidacy of Cyg X-1 which is founded on the 10 $M_\odot$ spectroscopic estimate for the mass of the X-ray source (Rhoades and Ruffini 1974).

Discussion of the physical origin of the millisecond activity in black hole candidates has focused on phenomena occurring close to the last stable orbit of material accreting onto a black hole, a region which has no equivalent in neutron star accretion (Shakura and Sunyaev 1973; Leach and Ruffini 1973). The relationship of this millisecond activity to the characteristic 1 s shot noise activity of Cyg X-1 is controversial (Weisskopf and Sutherland 1978), although it seems plausible that the latter is caused by instabilities in the inner radiation pressure dominated region of the accretion disk where the bulk of the energy is released (Galeev, Rosner, and Vaiana 1979; Kahn 1980). The similarity of the shot noise parameters derived for V0332+53 and Cyg X-1 might suggest a common origin. However, in the nonpulsing bright Population II low-mass X-ray binaries where it seems probable that the surface magnetic fields are low enough and the luminosities high enough for a radiation pressure–dominated zone to form, the observed spectra are much softer and the time scale of the variability generally one order of magnitude longer than that observed from V0332+53 (cf. Lamb and Sanford 1979; Stella, Kahn, and Grindlay 1984). This suggests that while the observed aperiodic variability of Cyg X-1 and V0332+53 are similar, their physical origins are completely different.

The low 15% peak-to-peak amplitude of the X-ray modulation suggests that the inflowing material is either not effectively funnelled onto the magnetic pole or the main beam does not pass through our line of sight. In either event it is unlikely that instabilities in the accretion column are responsible for the aperiodic variability (see, e.g., Bonazzola 1982). The captured stellar wind material is also not likely to directly transmit fluctuations into the accretion flow since a time scale of 1 s gives a size two orders of magnitude less than the accretion radius ($\sim 10^{10}$ cm). For a shot rate of 1 s^{-1}, this requires a peculiar low-density wind containing a few high-density blobs.

Low-amplitude pulsations are typical of the lower luminosity $\lesssim 10^{36}$ ergs s^{-1} stellar wind accreting X-ray pulsars in wide orbits about Be star companions (White, Swank, and Holt 1983). In these cases the captured specific angular momentum is low and the flow effectively spherically symmetric with the material penetrating the magnetosphere in blobs via the Rayleigh-Taylor interchange instability. The dimension of the blobs will depend on the uncertain wavelength of the modes responsible for transporting the material into the magnetosphere (cf. Lamb 1984). The strength of any modulation of the X-ray flux will be a function of the fraction of the material that is stripped onto the field lines before it can free fall to the surface. The observed properties of V0332+53 are qualitatively consistent with this picture if the wavelength of the mode is long with only one large blob per second falling through the magnetosphere. The growth time scale of the interchange instability is of the order of the magnetospheric radius divided by the free fall time (Arons *et al.* 1984) and is consistent with a ~ 1 s characteristic time scale.

Two black hole candidates, GX 339−4 and Cir X-1 have been suggested, in part, on the basis of the detection of rapid variability. In both cases high reddening prevents a spectroscopic estimate of the X-ray source mass. The discovery of stable X-ray pulsations from a rapidly varying source emphasizes that rapid variability should only be used to identify black hole candidates when it is considered in conjunction with spectral indicators (cf. White and Marshall 1984) and, preferably, a direct estimate of the mass of the X-ray source.

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