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X-RAY OBSERVATIONS OF X PERSEI

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ABSTRACT

We have used the *HEAO 2 Einstein Observatory* to confirm the identification of 4U 0352+30 with X Per. We have also analyzed the *HEAO 2* data in order to determine an additional point in the pulse period history of the X-ray source and to search for short binary periods. In addition, we have reanalyzed a majority of the historical X-ray observations and have obtained more refined values for the pulse period as a function of time. The period history possess significant scatter, but we find no evidence for a measurable long-term spin-up trend and hence set a lower limit to the spin-up time scale. This lower limit is consistent with the presence of a neutron star, but it does not rule out a degenerate dwarf. The period history was also searched for evidence of binary motion, and upper limits to $a_x \sin i$ were obtained.

Subject headings: stars: Be — stars: individual — X-rays: binaries

I. INTRODUCTION

The 835 s pulsating X-ray source (White *et al.* 1976; White, Mason and Sanford 1977) 4U 0352+30 (Forman *et al.* 1978) has been identified as a companion to the Be star X Per (Braes and Miley 1972; van den Bergh 1972; Brucato and Khristian 1972). We have now confirmed the identification with X Per with a high resolution imaging (HRI) detector observation using the *Einstein* (*HEAO 2*) observatory (Giacconi *et al.* 1979).

Despite the identification, the exact nature of the compact object remains a mystery. Arguments have been presented in favor of all three types of compact objects, i.e., degenerate dwarf, neutron star, and black hole. Thus, the very low ($\sim 5 \times 10^{33}$ ergs s^{-1}) X-ray luminosity and the long pulsation period are consistent with the degenerate dwarf hypothesis (Garavoglia and Treves 1976; Mushotzky *et al.* 1977). This interpretation was bolstered by a report of a 22 hr period in the X-ray luminosity by White *et al.* (1976) which, however, was not confirmed (see, e.g., Becker *et al.* 1978). The X-ray luminosity, the pulsations, and the previously reported measurements of the period derivative (White, Mason, and Sanford 1977), together with theories of disk accretion (see, e.g., Ghosh and Lamb 1979) are also consistent with the compact object being a neutron star. Finally, optical observations by Hutchings *et al.* (1974), Hutchings, Crampton, and Redman (1975), and Hutchings (1977) of the radial velocities of the Be star indicated a period of 580 days. If these variations are interpreted as due to orbital motion, then the resulting mass function implies that the compact object has a mass in excess of 16 $M_\odot$ and thus must be a black hole, although it is difficult to accept this interpretation since an uncharged black hole is not expected to pulse.

The best source of information concerning the nature of the compact object is timing of the X-ray pulsations. A careful study of pulse arrival times and pulse period variations can shed light on both the orbital period and the period derivative, knowledge of which are required if we are to understand this puzzling system. In this paper we report the result of such a study.

Observations from two different satellites will be discussed. First, we have reanalyzed the majority of the *Orbiting Astronomical Observatory* (*OAO*) *Copernicus* observations of the 4U 0352+30/X Per system which were originally reported by White, Mason, and Sanford (1977) and White *et al.* (1982). In addition, we include the results of a newer *Copernicus* observation taken in 1979. The source was also observed in 1980, but no pulsations were detected. The second satellite used was the *HEAO 2*/*Einstein.* 4U 0352+30 was observed 4 times, three for short periods with imaging instruments (twice with the IPC, once with the HRI) in the focal plane, and once for a longer time span of 82,000 s with the solid state spectrometer (SSS) in the focal plane. The HRI data were used to confirm the identification with X Per. The optical position from the SAO Star Catalog (1966) is

$$\alpha(1950) = 3^{h}52^{m}15\overset{s}{.}09, \qquad \delta(1950) = 30°54'0\overset{''}{.}7 ,$$

which should be compared to the *Einstein* position of

$$\alpha(1950) = 3^{h}52^{m}15\overset{s}{.}40, \qquad \delta(1950) = 30°54'1\overset{''}{.}9 .$$

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The optical position is within the 98% confidence contour (5″.05), based on the formal error associated with the X-ray position measurement. We note that for this observation, there was only one fiducial light measurement available, and thus the formal error on the X-ray position may be somewhat optimistic. The pulse period measurements presented here were obtained with the monitor proportional counter (MPC) during the SSS observation.

II. THE MPC OBSERVATION

The MPC has two parallel data streams. The first consists of eight logarithmically spaced pulse height channels covering the energy range from 1.1 to 20 keV which are read out every 2.56 s. The second is the time interval processor (TIP) which records the time intervals between photon detections in the 667 cm^2 argon gas-filled detector to microsecond accuracy but with no spectral information other than that the detected photons were in the 1.1 to 20 keV bandwidth. More detailed descriptions of the MPC and the TIP may be found in Gaillardetz *et al.* (1978), Grindlay *et al.* (1980), and Weisskopf *et al.* (1981).

For the principal analysis, the TIP data were converted to photon arrival times at the solar system barycenter, and pulse arrival time analysis was used to determine the best value of the pulse period. We selected an initial trial period and constructed a binned representation for a template by epoch folding the entire data set at periods at and near the value expected on the basis of earlier X-ray observations (Becker *et al.* 1978) and requiring that the χ^2 of a fit to an unpulsed source be at its maximum. We then generated a continuous, in pulse phase, representation for the template by Fourier analyzing the binned representation and keeping only those harmonics with amplitudes significantly larger ($> 3\,\sigma$) than the noise level expected on the basis of counting statistics. Sample pulse profiles were then obtained by epoch folding 4100 s sections of data at the trial period and requiring that the pulse be present at a high level of statistical significance. Pulse arrival times were subsequently determined by cross-correlating the sample pulse profiles with the template as a function of pulse phase. The measured phase were small, allowing a Taylor's expansion of the cross-correlation function and hence an analytic solution for the pulse arrival time. Errors were set by propagation of the errors due to counting statistics. The residuals of a fit of these arrival times to the hypothesis of a constant pulse period are shown in Figure 1. The χ^2 statistic for this fit was extremely poor, 92, for five degrees of freedom. Absorbing an extra degree of freedom by allowing for a period derivative did not significantly improve the fit. Allowing for binary motion with orbital periods ranging from 12,000 to 89,000 s also did not yield acceptable values for the χ^2 statistic.

The erratic behavior of the pulse arrival times was due, at least in part, to pulse shape variations. Figure 2 shows three of the sample pulse profiles, and the variation in pulse shape at the different times is clear. These variations could, of course, be due to a time-varying background signal or spectral changes coupled with an energy dependence of the pulse shape. As a check, pulse arrival time analyses were performed on the data for each energy channel separately with the background, calculated as a function of time, subtracted. (The background signal is determined from correlations between the anticoincidence veto and the eight channel counting rates when no known sources are in the field of view. These correlations are tabulated as a function of geographic latitude and longitude. Further discussion of background determination and rejection occurs in Grindlay *et al.* 1980 and Halpern and Grindlay 1983.) The erratic behavior of the arrival time residuals and the pulse shape variations were also manifest in these analyses, and so we

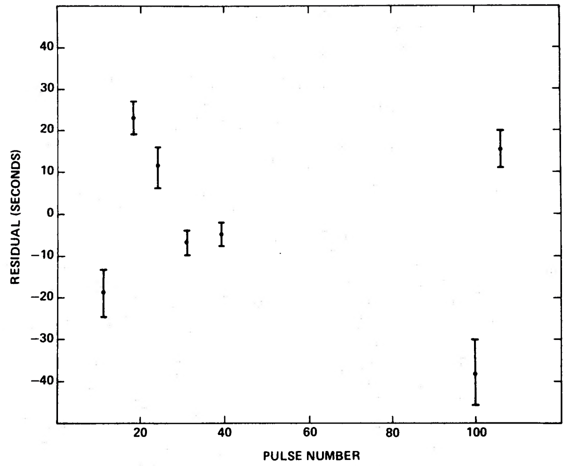

FIG. 1.—Residuals of a fit to a constant pulse period as a function of pulse number.

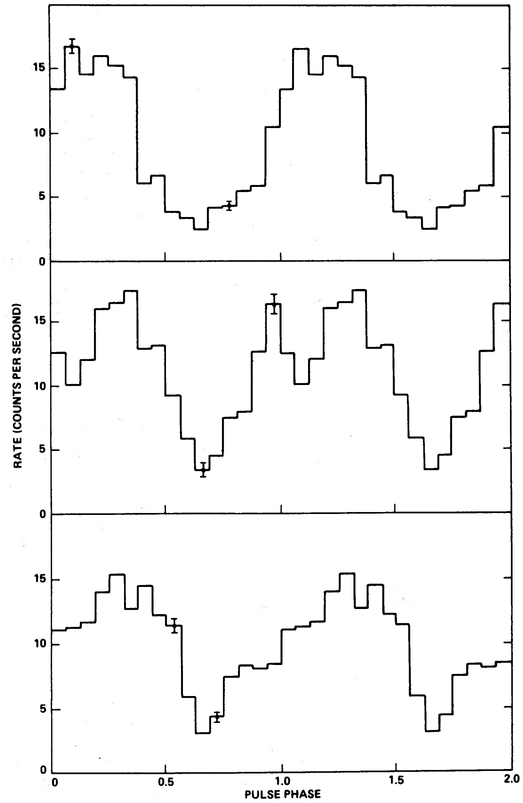

FIG. 2.—Three different sample pulse profiles. The background signal, which is nominally 17.5c s^{-1}, has been subtracted from the light curves.

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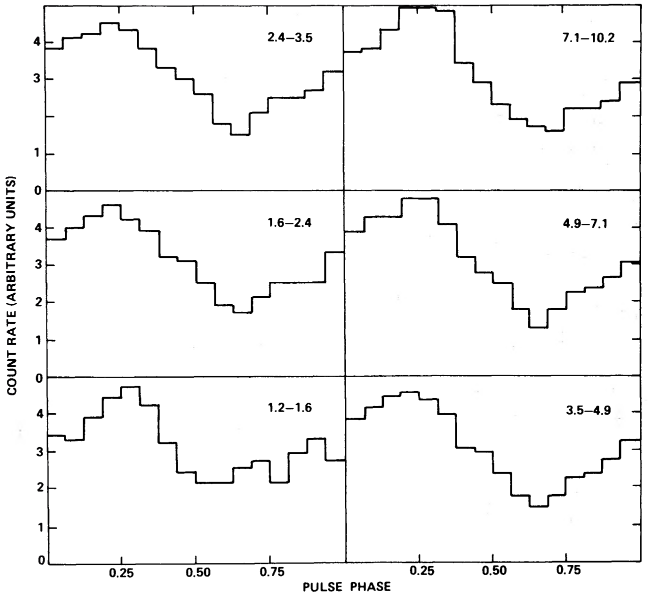

FIG. 3.—Time-averaged pulse shapes as a function of energy. Each light curve has been normalized to the same area under the curve.

conclude that the pulse shape variations are intrinsic to the source and occur over the entire bandwidth from 1.1 to 20 keV. The mean pulse shapes, normalized to constant area under the curve, are shown at different energies in Figure 3. The pulse shape variations limit the accuracy with which an arrival time analysis can be performed and may make it difficult, if not impossible, to search for short binary periods in future observations such as those which will be performed with the X-ray timing explorer.

TABLE 1

PULSE PERIOD MEASUREMENTS OF X PERSEI

Midpoint of Observation JD 2,444,000+	Satellite	Period (minutes)	Comments
1619.3	*OAO*	13.9298 ± 0.0024	1
1675.1	*OAO*	13.9277 ± 0.0045	1
2082	*OAO*	13.9315 ± 0.0019	2
2429.0	*OAO*	13.92242 ± 0.00060	1
2769.8	*OAO*	13.9204 ± 0.0016	3
2789.3	*OAO*	13.9272 ± 0.0016	3
2807.8	*OAO*	13.91890 ± 0.00011	1
2832	*OSO*	13.9228 ± 0.0008	4
2884	*SAS 3*	13.9233 ± 0.0017	5
3040	*OAO*	13.9188 ± 0.0011	2
3154.8	*SAS 3*	13.960 ± 0.050	5
3161	*OAO*	13.92097 ± 0.00070	2
3187.5	*OAO*	13.9834 ± 0.0011	1
3200	*OSO*	13.9195 ± 0.0008	4
3414	*OAO*	13.91662 ± 0.00048	1
3532	*OAO*	13.9195 ± 0.0006	4
3567	*OSO*	13.9213 ± 0.0013	4
3888	*OAO*	13.9242 ± 0.0012	6
3915	*HEAO 2*	13.9273 ± 0.0036	6

COMMENTS.—(1) Remeasured, this work. (2) White, Mason, and Sanford 1977. (3) Margon *et al.* 1977. (4) White *et al.* 1982. (5) Canizares *et al.* 1977. (6) This work.

III. THE *OAO Copernicus* OBSERVATIONS

The X-ray observations of the 4U 0352+30/X Per system with the *Copernicus* satellite have been discussed previously in White *et al.* (1976), White, Mason, and Sanford (1977), and White *et al.* (1982) and will not be repeated here. We have reanalyzed these observations using pulse arrival time analysis as discussed in the previous section but with a sample length of 16,000 s due to a reduced sensitivity resulting from the lower counting rate. With this sample length fits to a constant pulse period were acceptable. The remeasured pulse periods, together with other historical measurements and including the MPC/TIP observation, are listed in Table 1. The error in the latter measurement was based on the scatter of the residuals shown in Figure 1 and thus reflects the larger uncertainty introduced by the pulse shape variations.

IV. PULSE PERIOD VARIABILITY

The period measurements listed in Table 1 are plotted as a function of time in Figure 4. (The *SAS* point with the large uncertainty has been excluded from the figure.) We fit these period measurements (excluding the *SAS* point whose statistical weight is negligible) first to a model which includes a period derivative. This fit was totally unacceptable, Pearson's χ^2 being 220 for 16 degrees of freedom. We then included terms which allowed for circular binary motion and varied the orbital period from 30 to 2000 days. Although this led to significant reductions in the χ^2 statistic, in no instances were the fits acceptable, with a minimum χ^2 of 51 for 13 degrees of freedom. In particular, there was no significant minimum in the χ^2 statistic at a binary period of 580 days.

Clearly, there are statistically significant variations in the pulse period as a function of time. No obvious trends appear in Figure 4, although it might be possible to argue for the existence of a spin-down episode, over the time spanned by the last two points, following a longer period of general spin-up. The pulse period variations may be due to period noise produced by fluctuating accretion torques (Lamb, Pines, and Shaham 1978), a period derivative, and Doppler shifts due to binary motion. If only the former two are taken into account, we can obtain an upper limit to the period derivative by performing an unweighted least-

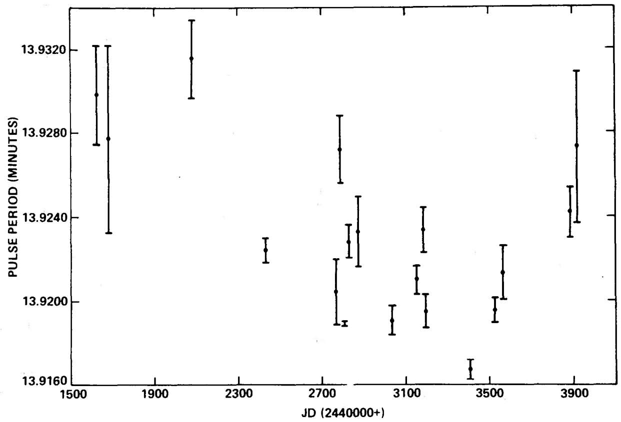

FIG. 4.—Pulse period measurements as a function of time

squares fit to the period measurements and basing the uncertainty on the scatter about the best fit line. The results of this fit yield $|\dot{P}| < 4.23 \times 10^{-9}$ s s^{-1} (95% confidence), which in turn implies a minimum spin-up scale, $|P/\dot{P}|$, of 6300 yr. This limit is consistent with that expected for such a low luminosity accreting neutron star, but does not rule out a degenerate dwarf. The existence of a long-term spin-up trend is not yet established nor ruled out for 4U 0352+30, and this X-ray source cannot yet be used to test accretion torque models (see Ghosh and Lamb 1979). The rms scatter, ΔP, of the period measurements about the best fit line is given by $\Delta P/P = 2.5 \times 10^{-4}$. Varying the period derivative about its best fit value leads to $\Delta P/P < 4.0 \times 10^{-4}$ (68% confidence) and 6.6×10^{-4} (95% confidence). If the entire scatter is attributed to period noise caused by fluctuating accretion torques, the magnitude of the period fluctuations, $\Delta P/P$, is perhaps slightly larger but still roughly comparable to that observed in other X-ray binary systems such as Cen X-3 (Lamb, Pines, and Shaham 1978).

On the other hand, if the observed period fluctuations are attributed entirely to Doppler shifts due to binary motion, then we can set an upper limit to the size, $a_x \sin i$, of the X-ray source orbit through the relation

$$a_x \sin i < \sqrt{2}(\Delta P/P)(P_{\rm orb}/2\pi)\,. \tag{1}$$

Here $a_x \sin i$ and the orbital period, $P_{\rm orb}$, are measured in seconds. In Figure 5, we show the upper limit to $a_x \sin i$ as a function of orbital period obtained from inequality (1) using $\Delta P/P = 2.5 \times 10^{-4}$ (see above). This value for $\Delta P/P$ also corresponds to an upper limit on the amplitude, K_x, of the X-ray source radial velocity of 110 km s^{-1}, independent of orbital period. Since our determination of $\Delta P/P$ is somewhat uncertain, the reader should keep in mind that the upper limits to $a_x \sin i$ and K_x are proportional to $\Delta P/P$, while the corresponding upper limits to the X-ray mass functions, f_x, as a function of orbital period are proportional to $(\Delta P/P)^3$. We also show in Figure 5 the upper limit to $a_x \sin i$ quoted in White *et al.* (1982) and Rappaport and van den Heuvel (1982). The X-ray data, analyzed in this fashion, provided no useful constraints on the orbital parameters of the 4U 0352+30/X Per system at an orbital period of 580 days. However, it is important to note that the period history of 4U 0352+30 is *not* formally consistent with a 580 day orbital period, with fits using Pearson's χ^2 near this period leading to a minimum value of $\chi^2 = 150$ for 13 degrees of freedom.

V. SUMMARY AND CONCLUSIONS

Using the *HEAO 2/Einstein* satellite we have confirmed the identification of 4U 0352+30 with the Be star X Per. We have also obtained an additional point in the period history of this X-ray source and discovered pulse shape variations on time scales of thousands of seconds. No evidence for binary periods between 12,000 and 80,000 s was obtained, although the search is complicated by the pulse shape variations. High sensitivity observations over many days will be required to firmly establish whether or not such short binary periods are present.

We have reanalyzed the majority of the historical observations of this source and decreased the statistical uncertainty in most of the pulse period measurements. The historical data show clear evidence for pulse period variability on time scales between 30 and 2000 days, but with no direct evidence for binary motion. Neglecting effects due to binary motion we were able to set a lower limit to the spin-up time scale of 6300 yr, a value which could be expected from accretion onto a low luminosity neutron star. However, this lower limit does not rule out the much longer time

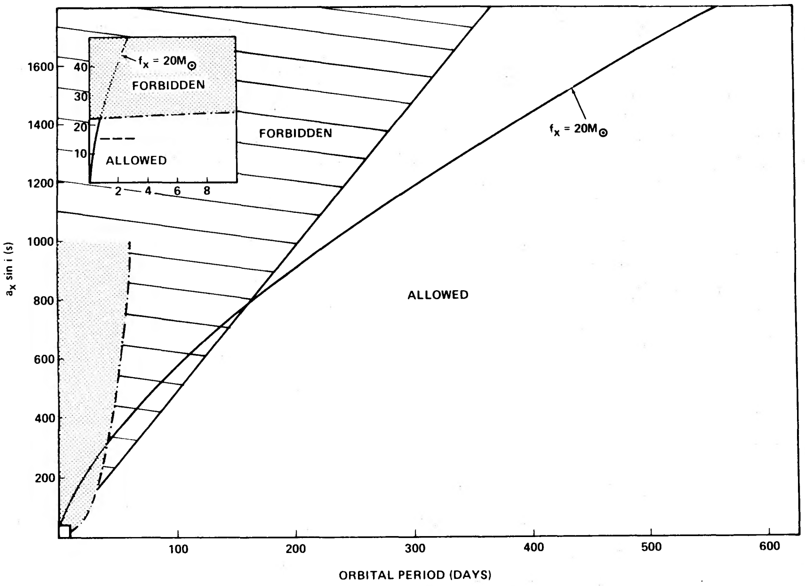

FIG. 5.—Upper limits to $a_x \sin i$ based on the present study as well as previous work. Solid line is the line given by inequality (1) for a value of $\Delta P/P = 2.5 \times 10^{-4}$. Dash-dot line represents the limit quoted in White *et al.* (1982). We also show the line corresponding to $a_x \sin i$ vs. orbital period for an X-ray mass function $f_x = 20\ M_\odot$. The inset shows the upper limits to $a_x \sin i$ at short orbital periods. Here the dashed line shows the upper limit to $a_x \sin i$ quoted in Rappaport and van den Heuvel (1982) for orbital periods between $0^{\rm d}.7$ and $2^{\rm d}.0$.

scales which would be expected from accretion onto a degenerate dwarf. In any case, the existence of a long-term spin-up trend is not yet established for 4U 0352+30, nor is it ruled out by the X-ray period history. This X-ray source cannot yet be used to test accretion torque models.

The pulse period history of 4U 0352+30 is *not* formally consistent with a 580 day orbital period, although it is not possible to set useful constraints on the orbital parameters at the orbital period because of the observed pulse period variability. Optical data supporting a 580 day orbital period (Hutchings, Crampton, and Redman 1975; Hutchings 1977; Kemp and Barbour 1983) lead to the conclusion that the mass of the X-ray source must exceed 16 $M_\odot$ and therefore that the X-ray source is probably a black hole. As noted by previous authors, the X-ray and optical data present a problem with our understanding of the 4U 0352+30/X Per system. The optical data do not support a model with a neutron star or degenerate dwarf in a 580 day orbit about the Be star. However, it is also difficult to understand how accretion onto a black hole can produce X-ray pulses, particularly with a period as long as 13.9 minutes. Possible resolutions include the presence of a third massive body in the system, alternative interpretations of the 580 spectroscopic results (e.g., apsidal motion), gaps in our understanding of accretion onto black holes, or the possibility of misidentification.

Based on the above, we are left with the unsatisfactory situation that the nature of the compact object in the 4U 0352+30/X Per system is still unknown. Very detailed and sensitive X-ray observations of 4U 0352+30 will be required in the future to understand this system. Pulse timing observations will be complicated by the presence of pulse shape variations and probably period noise as well.

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