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DOI
10.1093/mnras/260.3.686

Publication date
1993

Published in
Monthly Notices of the Royal Astronomical Society

Link to publication

Citation for published version (APA):
van der Klis, M., Hasinger, G., Dotani, T., Mitsuda, K., Verbunt, F., Murphy, B. W., van Paradijs, J. A., Belloni, T., & Makishina, K. (1993). Simultaneous ROSAT/Ginga observations of 4U 1820-30. *Monthly Notices of the Royal Astronomical Society*, *260*(3), 686-692. https://doi.org/10.1093/mnras/260.3.686

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1993MNRAS.260..686V

Mon. Not. R. Astron. Soc. **260**, 686–692 (1993)

Simultaneous *ROSAT/Ginga* observations of 4U 1820 − 30

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Accepted 1991 August 6. Received 1992 August 3; in original form 1992 March 20

ABSTRACT

We have made simultaneous *Ginga* LAC and *ROSAT* PSPC observations of 4U 1820 − 30. The 685-s orbital light curves obtained with the two instruments are very similar, indicating that the energy dependence of the orbital modulation is small. Our measurements extend the baseline over which the period variations can be measured to 15 yr. The previous possibility, that the changes in the period are themselves periodic, with a period of about 8 yr, is no longer preferred over a constant $\dot{P}$. Over the interval 1976–91 the period has decreased, rather than increasing as predicted by the standard model for the orbital evolution of the binary. The average period derivative $\dot{P}/P$ was $(-0.88 \pm 0.16) \times 10^{-7}$ yr^{-1}, different by 11σ from the predicted value. Under the assumption that there are no intrinsic changes in the light curve that mimic a period change, we discuss three possible explanations. The possibility that the observed $\dot{P}$ is due to spin–orbit coupling (with a companion that is out of corotation due to stellar radius changes) is rejected, as there is no known mechanism that could cause these radius changes. The possibility of acceleration of the system by the gravitational potential of the cluster is reinvestigated in the light of a new detailed model of the mass distribution of NGC 6624. We conclude that it is unlikely that acceleration by the cluster can fully explain the observed $\dot{P}$. Acceleration by a distant triple companion or in a chance encounter with another star in the cluster remains a possibility. Finally, we investigate the possibility that the companion is a helium-burning star. This could explain the observed $\dot{P}$, but the likelihood of this scenario depends strongly on unknown aspects of the stellar population of NGC 6624.

Key words: binaries: close – stars: individual: 4U 1820 − 30 – X-rays: stars.

1 INTRODUCTION

The low-mass X-ray binary 4U 1820 − 30, located in the globular cluster NGC 6624 (Giacconi et al. 1974; Jernigan & Clark 1979; Hertz & Grindlay 1983), has the shortest-known orbital period of all binary stars: ~685 s (Stella, Priedhorsky & White 1987; Smale, Mason & Mukai 1987; Morgan, Remillard & Garcia 1988). The source alternates between X-ray high and low states with a period of ~176 d (Priedhorsky & Terrell 1984). It is a well-known X-ray burst source, whose bursts always show radius expansion at the Eddington limit appropriate to hydrogen-depleted matter (Haberl et al. 1987). On the basis of its X-ray spectral and fast-variability characteristics, Hasinger & van der Klis (1989) classified 4U 1820 − 30 as an atoll source. Atoll sources display characteristic correlated variations in

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their X-ray spectra and rapid X-ray variability, but there is no evidence for three distinct spectral states or quasi-periodic oscillations such as seen in the other sub-class of bright low-mass X-ray binaries, the Z sources. It has been suggested that this is evidence for a lower magnetic field strength in the neutron stars in atoll sources than in those in Z sources.

Observations of the X-ray modulation made with the *Ginga* satellite indicate that the period is decreasing on a time-scale of $\sim 10^7$ yr (Tan et al. 1991, hereafter Paper 1; see also Samson et al. 1989). This result is in conflict with the scenario for the evolution of the source (Rappaport et al. 1987; Verbunt 1987), which involves conservative mass transfer through Roche-lobe overflow from a low-mass ($\sim 0.07\ M_\odot$) white dwarf donor star. This scenario predicts that the orbital period increases at a rate of $> +0.88 \times 10^{-7}$ yr^{-1}.

In Paper 1, it was concluded that the observed period decrease is consistent with gravitational acceleration of the binary system, either in the gravitational potential of NGC 6624 or by a distant third star. It was noted that the observations were also consistent with a long-term (roughly 8-yr) periodic variation of the light-curve arrival times. The origin of this possible 8-yr period remained unexplained, as it is much longer than the predicted apsidal motion period.

In this paper, we present new X-ray observations of 4U 1820 – 30 that were made simultaneously with the *Ginga* and *ROSAT* satellites. These observations extend the baseline over which the period changes can be measured to more than 15 yr and confirm the period decrease. We discuss various possible explanations for this result.

2 OBSERVATIONS

The *Ginga* (Makino et al. 1987) observations were performed with the large-area counter array (LAC; Turner et al. 1989) between 1991 March 11 14:36 and March 13 07:33 UT. Total source coverage was about 4×10^4 s, distributed over 22 satellite orbits. All *Ginga* data were rebinned to a time resolution of 16 s and into 8 energy channels covering the 1–30 keV band. The data were corrected for background, deadtime and aspect. Fig. 1(a) shows the 1.9–19 keV light curve obtained with *Ginga*. The observations occurred at phase 0.8 ± 0.3 of the 176-d high/low-state cycle of the source (Priedhorsky & Terrell 1984). The observed count rates, in the 1800–2600 count s^{-1} range (1 count s^{-1} corresponds to $\sim 3.9 \times 10^{-12}$ erg cm^{-2} s^{-1}), show that the source was in the high state.

The *ROSAT* (Trümper 1983) observations were performed with the Position Sensitive Proportional Counter (PSPC: Pfeffermann et al. 1986) between March 12 05:07 and March 13 15:49 UT and extracted in the 0.5–1.2 keV band with a time resolution of 50 s. The data are distributed over nine approximately 1400-s satellite-orbit blocks and have negligible background and deadtime. The source was observed at an offset of ~40 arcmin in order to avoid spurious time variability due to time-variable obscuration of the PSPC entrance window support structure. The raw source count rate varied between 60 and 70 count s^{-1}; we corrected these count rates for an ~60 per cent telescope vignetting factor, which varied slightly as a function of time due to satellite wobble. The *ROSAT* light curve is shown in Fig. 1(b).

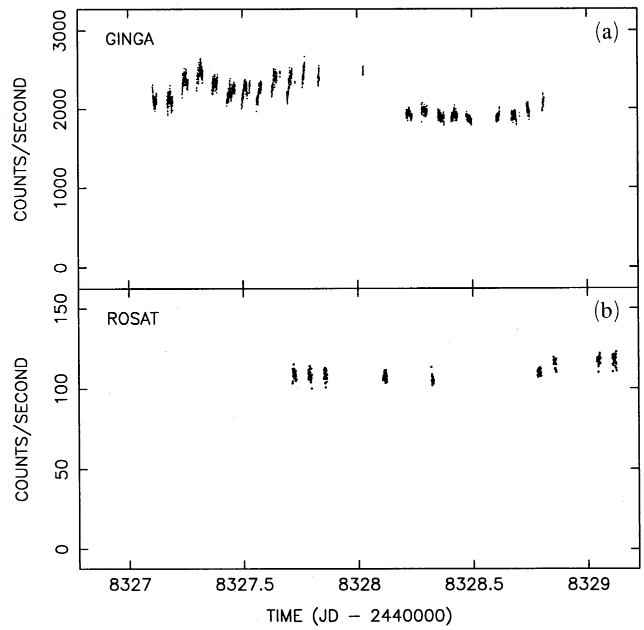

Figure 1. Light curves of the *Ginga* (a) and *ROSAT* (b) observations. Each point corresponds to the average background-subtracted, deadtime- and vignetting-corrected count rate of 16 s (*Ginga*) or 50 s (*ROSAT*) of data. Effective energy ranges are 1.9–19 keV (*Ginga*) and 0.5–1.2 keV (*ROSAT*).

3 ANALYSIS

Considerable intrinsic X-ray intensity variations from one satellite orbit to the next are present in the light curves (Fig. 1). We therefore normalized the data by separately subtracting a mean count rate in each satellite orbit. We then constructed phase-dispersion periodograms (see Stellingwerf 1978) for the two data sets independently. The 685-s period is clearly detected in the *Ginga* (Fig. 2a) and, independently, also in the *ROSAT* (Fig. 2b) data. The period deduced from each periodogram is consistent with the ephemeris value of 685.011 s (Paper 1; this paper).

Light curves folded at the orbital period are shown in Fig. 3. In view of the relatively coarse time bin sizes of the data (16 s and 50 s for *Ginga* and *ROSAT*, respectively) compared to the phase bin size (34.25 s), we proportionally rebinned the time bins into the phase bin grid in these foldings. The light curves from the two instruments are very similar in shape with, in both cases, a broad maximum covering ~70 per cent of the orbital cycle and a relatively narrow minimum. There is an indication of a difference in the detailed shape of the maximum, the *Ginga* light curve peaking ~0.3 earlier in phase than the *ROSAT* light curve. The two light curves have about the same relative full amplitude (2–3 per cent).

We determined two arrival times, one from the *Ginga* and one from the *ROSAT* data. The fiducial point in the light curve of 4U 1820–30 used in previous work (Paper 1 and references therein) is the maximum of the best-fit sine wave. Although the light curve is not a sinusoid, this is a valid phase marker as long as the light-curve shape does not change. As noted in Paper 1, intrinsic shape variations in the light curve do exist, so that one should be careful in interpreting the results of the phase measurements. In particular, shifts in

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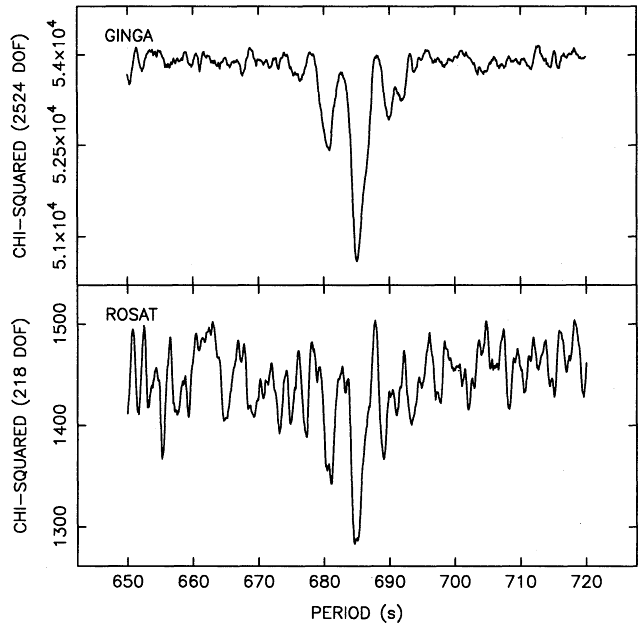

Figure 2. Phase-dispersion periodograms of the *Ginga* and *ROSAT* data folded into 20 phase bins with trial periods around 685 s. Data were normalized by subtracting the mean of each satellite orbit and time bins were proportionally binned into the phase bin grid (see text). Plotted is the χ^2 of the data around the average light curve. One thousand trial periods were used in each diagram; the scanned range contains 22 (*Ginga*) or 18 (*ROSAT*) fully statistically independent trial periods. The minimum near 685 s in each diagram corresponds to the orbital modulation of the source.

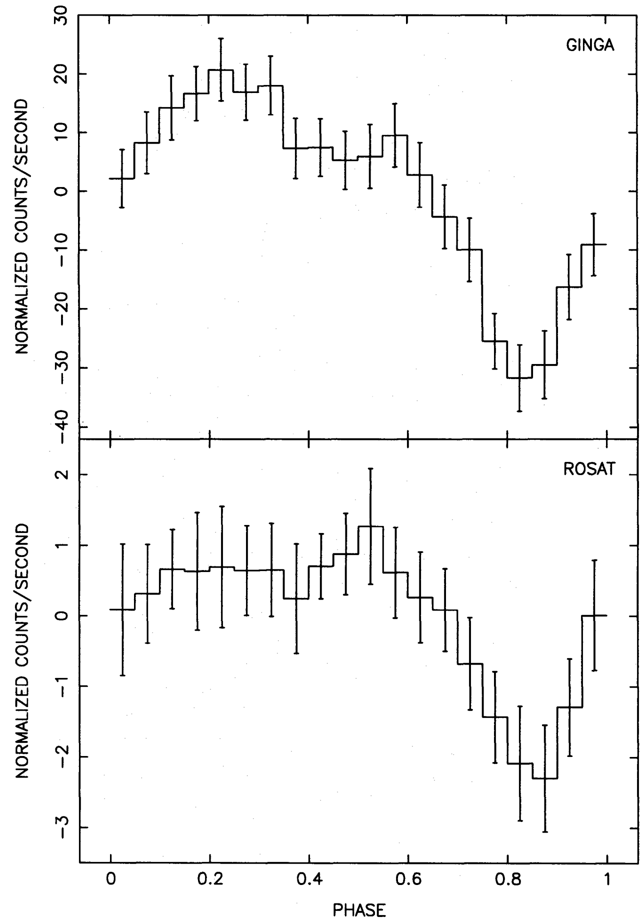

Figure 3. Folded light curves of the *Ginga* and *ROSAT* data. Folding ephemeris was T_0 = HJD 244 8326.5 and P = 685 s. Data were normalized by subtracting the mean of each satellite orbit. Error bars were calculated from the observed variance of the data points in each bin and therefore include the intrinsic light-curve variations. The phase of the maximum of the best-fitting sinusoid is 0.307 in the *Ginga* and 0.357 in the *ROSAT* light curve.

azimuth of the structure on the accretion disc (e.g., at the point of impact of the accretion stream) that may be causing the X-ray intensity modulation might result in phase shifts in the fiducial point without any true changes in the period. The average light-curve shape seen in the present observations is similar to that seen in previous work.

We fitted sine waves to the data folded with a period of 685 s into 10-bin average light curves. Phase smearing within our observation was less than 0.004 in phase and therefore negligible. The heliocentric arrival times of the maxima of the best-fit sinusoids are given in Table 1 (last two entries). The uncertainties in these values were estimated from the $\Delta\chi^2 = 1$ contours in parameter space (1σ single parameter errors). We took account of the random source variability by increasing the error bars of the 10-bin folded light curve to make the reduced χ^2 of the best fit equal to 1. The uncertainties obtained in this way agree with the range of arrival times obtained from subsets of the data. The arrival times correspond to phases of 0.307 ± 0.026 and 0.357 ± 0.039 in the folded light curves of Figs 3(a) and (b), respectively. The difference between these two values is within the errors, and is probably related to the difference in the shape of the maximum of the light curves mentioned above.

Adding our two new measurements to the previous ones (Table 1), the baseline over which the period variations can be measured is extended to 15 yr. To determine the ephemeris of 4U 1820 − 30 from these measurements, it is necessary to assign to each arrival time a cycle number that indicates the number of binary cycles elapsed since the first measurement. As the binary period is very short, it has historically only been possible to keep track of the cycle count between observations by a 'ladder' approach, increasing the precision of the measured period by bridging progressively larger gaps in the observational record. We checked that this method has not led to spurious results by performing a systematic scan of all combinations of cycle numbers possible in a parabolic ephemeris among the present 19 arrival-time measurements. Our scan shows that, if the average period is between 683 and 687 s and if all data points are within 6σ of their quoted values, then the best alternative-cycle-count parabolic ephemeris has an unacceptably large χ^2 of 75 for 16 d.o.f. (compared with 14 for 16 d.o.f. for the canonical solution, see below). We conclude that it is very unlikely that spurious cycle counts are behind the negative period derivative. The cycle counts that we used in our ephemeris determination are given in Table 1.

We performed polynomial and sinusoidal fits to the arrival times versus cycle number. A constant period is excluded by its χ^2/d.o.f. of 73.9/17, and a constant period-derivative (parabolic) ephemeris provides an acceptable (23.0/16) fit. With two more free parameters, a sine wave fits significantly

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Table 1.

Cycle number[a]	Arr. time (HJD - 2440000.)	Error (d)	Satellite	Reference
0	2803.63551	0.00026	SAS-3	Morgan *et al.* (1988)
7975	2866.86419	0.00030	"	"
9229	2876.80661	0.00030	"	"
10791	2889.19090	0.00067	Ariel V	Smale *et al.* (1987)
27118	3018.63738	0.00036	SAS-3	Morgan *et al.* (1988)
31193	3050.94530	0.00016	"	"
49606	3196.93086	0.00040	"	"
75989	3406.10547	0.00027	"	"
147012	3969.20245	0.00048	Einstein	"
346915	5554.10890	0.00050	Tenma	Sansom *et al.* (1989)
399356	5969.88059	0.00022[b]	EXOSAT	Stella *et al.* (1986)
424877	6172.22088	0.00022[b]	"	"
440667	6297.41073	0.00052[b]	"	"
444976	6331.57349	0.00023[b]	"	"
518753	6916.50477	0.00024	GINGA	Sansom *et al.* (1989)
601157	7569.83429	0.00024	"	Tan *et al.* (1991)
610179	7641.36378	0.00024	"	"
696779	8327.96122	0.00021	"	This paper
696837	8328.42146	0.00031	ROSAT	"

[a]Supersedes values given in Tan et al. (1991), some of which were incorrectly tabulated.
[b]Error was quadratically increased by 0.0002 d; see text.

better (12.3/14) than a parabola (98 per cent confidence from an F-test for two additional terms).

However, this is entirely due to the small error bars reported for three of the four data points corresponding to the 1984–85 *EXOSAT* discovery measurements of the 685-s cycle. These measurements, being the first, have error bars that do not take into account the intrinsic variability of the light curve that is now known to exist (the errors of the retrospective *SAS-3, Ariel V* and *Einstein* measurements are dominated by counting statistics so that this problem does not occur for them). If we quadratically add 0.0002 d (the rms dispersion of all data points around the parabolic fit) to the *EXOSAT* error bars to take account of this systematic effect, we obtain the results listed in Table 2 and shown in Fig. 4. A linear ephemeris is excluded at the 99.94 per cent confidence level, and a parabolic ephemeris now provides an excellent fit (14.0/16). From an F-test for one additional term, the improvement in chi-squared between linear and parabolic fits is significant at the 99.997 per cent confidence level. A sinusoid, with two more free parameters, does not fit significantly better ($\chi^2=11.5$ for 14 d.o.f.; best-fit period was 7.4 yr). We conclude that the period of 4U 1820 − 30 shows a decrease that is consistent with being constant at a rate of $\dot{P}/P=(-0.88\pm0.16)\times10^{-7}\ \mathrm{yr}^{-1}$ over the itnerval 1976–91.

4 DISCUSSION

Our observations show that the approximate energy independence of the modulation, first noted by Stella et al. (1987), extends into the *ROSAT* PSPC band. This strengthens conclusions by previous authors (e.g., Morgan et al. 1988; Sansom et al. 1989) that the modulation is caused either by optically thin material that due to the small dimensions of the system is completely photoionized by the X-rays, or by optically thick material that periodically partially obscures an extended emission region. In both cases, the obscuring material is probably associated with the accretion disc.

The observed period derivative differs from the period derivative expected in the simplest model for the X-ray binary, in which the donor star is a Roche-lobe filling white dwarf and the receiving star a neutron star.

If the mass–radius relation of the donor star is given by

$$\frac{R_*}{\mathrm{R}_\odot}=k\left(\frac{M_*}{\mathrm{M}_\odot}\right)^n,$$

where R_* and M_* are the radius and mass of the donor star, respectively, and if the Roche-lobe radius is given by

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Table 2.

Linear ephemeris: $T_n = T_0 + Pn$

T_0 = HJD 2442803.635738 ± 0.000098

P = (0.0079283761 ± 0.0000000002) d

$\mathrm{Cov}(T_0, P) = -1.78516\ 10^{-14}\ \mathrm{d}^2$

χ^2 = 42.2 for 17 dof

Parabolic ephemeris: $T_n = T_0 + P_0 n + cn^2$, where $c = \frac{1}{2}P_0\dot{P}$

T_0 = HJD 2442803.63547 ± 0.00011

P_0 = (0.0079283810 ± 0.0000000009) d

$c = (-7.6 \pm 1.4)\ 10^{-15}$ d

$\dot{P}/P_0 = (-0.88 \pm 0.16)\ 10^{-7}\ \mathrm{yr}^{-1}$

$\mathrm{Cov}(T_0, P_0) = -6.27353\ 10^{-14}\ \mathrm{d}^2$

$\mathrm{Cov}(T_0, c) = 6.99872\ 10^{-20}\ \mathrm{d}^2$

$\mathrm{Cov}(P_0, c) = -1.30725\ 10^{-24}\ \mathrm{d}^2$

χ^2 = 14.0 for 16 dof

F-statistic for additional term: 32.4 for 1 and 16 dof

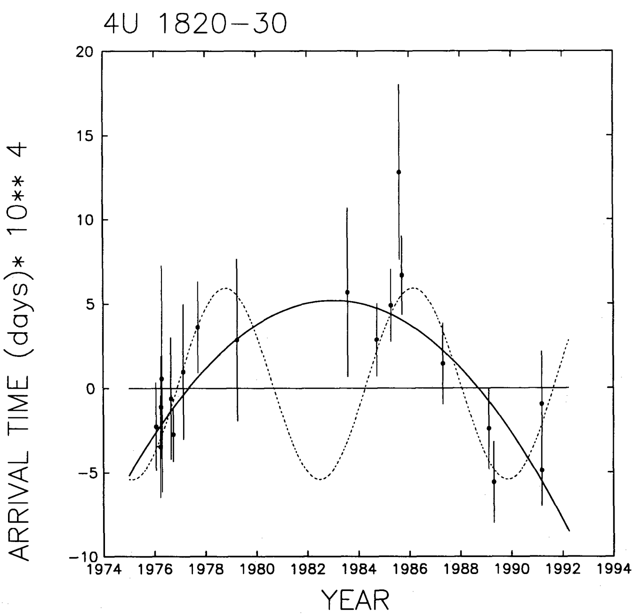

Figure 4. Arrival-time residuals (data points; see Table 1) with respect to the best-fitting linear ephemeris (thin horizontal line; Table 2). Best-fitting parabolic (solid curve; Table 2) and sinusoidal (dashed curve) ephemerides are shown.

$$\frac{R_{\mathrm{RL}}}{a} = 0.46\left(\frac{M_*}{M_{\mathrm{x}} + M_*}\right)^{1/3},$$

where a is the binary separation and M_{x} the mass of the accreting star, then the condition that the star fills the lobe ($R_* = R_{\mathrm{RL}}$), in combination with Kepler's law and the assumption of conservative mass transfer, gives $P \propto M_*^{(3/2)n-1/2}$, so that

$$\frac{\dot{P}}{P} = \left(\frac{3}{2}n - \frac{1}{2}\right)\frac{\dot{M}_*}{M_*}.$$

For a white dwarf, n is negative, so that a negative value of $\dot{P}/P$ is predicted where a positive value is observed.

Putting in the numbers appropriate for a white dwarf ($k = 0.0115$, $n = -1/3$) and using $M_{\mathrm{x}} = 1.4\ \mathrm{M}_\odot$ and $P =$ 685 s, one finds a white dwarf mass M_* of about 0.058 $\mathrm{M}_\odot$ (Verbunt 1987) and $\dot{P}/P = -\dot{M}_*/M_*$. We may determine $\dot{M}_*$ theoretically by assuming that mass transfer is driven by gravitational radiation:

$$-\frac{\dot{J}}{J} = \frac{32G^3}{5c^5}\frac{M_{\mathrm{x}}M_*(M_{\mathrm{x}} + M_*)}{a^4}$$

(Paczyński 1967), where J is the orbital angular momentum. Assuming that the star fills the lobe and using the expression for the orbital angular momentum of a binary, we also have

$$-\frac{\dot{J}}{J} = -\left(\frac{5}{6} + \frac{n}{2} - \frac{M_*}{M_{\mathrm{x}}}\right)\frac{\dot{M}_{\mathrm{x}}}{M_*}.$$

Combination of the last two expressions gives $-\dot{M}_*/M_* = \dot{P}/P \sim +1.2 \times 10^{-7}\ \mathrm{yr}^{-1}$. This is not very accurate, because of the strong dependence of $\dot{J}$ on a, which in turn depends strongly on the exact mass–radius relation for the white dwarf. From the article of Rappaport et al. (1987), who investigated this and several other uncertainties, the minimum acceptable lower limit to $\dot{P}/P$ is $+0.88 \times 10^{-7}\ \mathrm{yr}^{-1}$. Our measured period derivative of $\dot{P}/P = (-0.88 \pm 0.16)\ 10^{-7}\ \mathrm{yr}^{-1}$ differs from this predicted value by 11σ.

With our proposed correction to the *EXOSAT* error bars there is no longer a compelling case for the observed $\dot{P}$ being the result of a periodic variation in the arrival times. In spite of this, there is, of course, no direct evidence from the 15-yr stretch of observational information that the observed $\dot{P}$ really is the evolutionary orbital-period change. In the above scenario for the binary evolution, the rate of change of the orbital angular momentum of the system due to its period decrease is $\sim -1.4 \times 10^{43}\ \mathrm{g\ cm^2\ s^{-1}\ yr^{-1}}$, whereas the angular momentum in the rotation of the white dwarf (assumed corotating) is $\sim 6 \times 10^{47}\ \mathrm{g\ cm^2\ s^{-1}}$. For sufficiently efficient spin–orbit coupling, the white dwarf could therefore act as an orbital angular-momentum sink for intervals of several 10^4 yr (at the present rate) before its rotational angular momentum would change appreciably. As this is much shorter than the evolutionary time-scale of the system, an additional mechanism would be required to (occasionally) bring the white dwarf out of corotation. A possible mechanism is irradiation-induced changes in the radius of the donor star due to absorption of X-rays from the neutron star. This has been suggested for the low-mass X-ray binary EXO 0748−676 (Parmar et al. 1991). However, the structure of a white dwarf does not depend on its temperature, and therefore is not affected by irradiation. Unless the white dwarf in the binary is so hot that degeneracy is lifted, irradiation with X-rays does not provide a viable explanation in the case of 4U 1820−30. Similarly, stellar magnetic activity, proposed as a mechanism for radius and orbital-period changes (Van Buren & Young 1985), is not known to occur in white dwarfs.

We now investigate two other possible explanations for the observed period decrease: (i) there is acceleration of the binary by the gravitation of the cluster, and (ii) the donor star is a helium-burning star. The first of these possibilities was explored in Paper 1; we now re-evaluate it in the light of a new detailed model of the mass distribution within the

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globular cluster. The second possibility was previously discussed by Stella et al. (1987).

4.1 Acceleration in the cluster potential

The binary will be accelerated by the mean gravitational potential of the globular cluster, causing a time derivative in the observed orbital period of $\dot{P}/P = a\cos\phi/c$, where a is the acceleration towards the cluster centre and ϕ the angle between the line of sight and the line connecting the binary with the centre of the cluster. For every projected distance to the cluster centre, there is a maximum value $a_{\rm max}$ for $a\cos\phi$, which can be calculated provided the structure of the cluster is known.

To determine the magnitude of this maximum acceleration along the line of sight, we have generated a library of dynamically evolving models using the direct Fokker–Planck method (cf. Murphy & Cohn 1988; Murphy, Cohn & Hut 1990; Murphy 1991). This method uses a statistical description of the distribution of stars along their orbits rather than following the progress of the individual stars such as in an N-body simulation (cf. Cohn 1985 for a review). The evolution of the stellar distribution due to the effects of star–star gravitational scatterings is computed, yielding the time evolution of the structure of the globular cluster. Using this method, we are able to follow the evolution of a variety of initial models up to and past the time of core collapse. The evolving models include a stellar mass spectrum, the formation and subsequent hardening of binaries through three-body encounters, and mass loss from the stars due to stellar evolution.

The basic input parameters to our models are the initial values for the half-mass radius $r_{\rm h}$ of the cluster, the slope x of the initial mass function, and the cluster mass $M_{\rm CLUSTER}$. The model starts with 14 mass groups with masses ranging from 0.12 to 12.0 $M_\odot$. Stars with initial masses between 4.7 and 8 $M_\odot$ destroy themselves in type I1/2 supernovae. The remaining 13 mass groups have the following characteristics at a Hubble time: one group for neutron stars, with mass 1.38 $M_\odot$; five for white dwarfs, with masses between 1.26 $M_\odot$ and 0.62 $M_\odot$, and seven for main-sequence stars, with masses between 0.75 $M_\odot$ and 0.14 $M_\odot$. We used initial values for x, $r_{\rm h}$ and $M_{\rm CLUSTER}$ varying from -0.85 to -1.85, 1.85 to 3.69 pc, and 2.5×10^5 to 10^6 $M_\odot$, respectively. These parameters were adjusted to make the evolved cluster (after one Hubble time) fit the surface-brightness profile of NGC 6624 using data from Lugger et al. (1987) and the central velocity dispersion found by Pryor et al. (1989). The best-fitting model had $x=-1.85$, $M^{\rm Hubble}_{\rm CLUSTER}=2.25\times10^5$ $M_\odot$, and $r_{\rm h}^{\rm Hubble}=7.6$ pc. The resulting mass-to-light ratio for our model was 1.24.

In Fig. 5 we show $a_{\rm max}/c$ as a function of the projected distance $r_{\rm p}$ of the source to the cluster centre as found from this model. We also show the value of $a\cos\phi/c$ required if the orbital $\dot{P}$ of 4U 1820−30 is zero and the observed $\dot{P}$ is entirely caused by the accretion. Note that if the binary has a positive orbital $\dot{P}$ according to the evolutionary scenario described above, this required value will be a factor of about 2 larger. The distance to the cluster centre was taken from Hertz & Grindlay (1983), who give a value of 4 ± 1 arcsec. The position of the cluster centre is itself uncertain by 1 arcsec; the error bar given in Fig. 5 corresponds to a range of 2–6 arcsec. We used a distance to the cluster of 6.4 kpc.

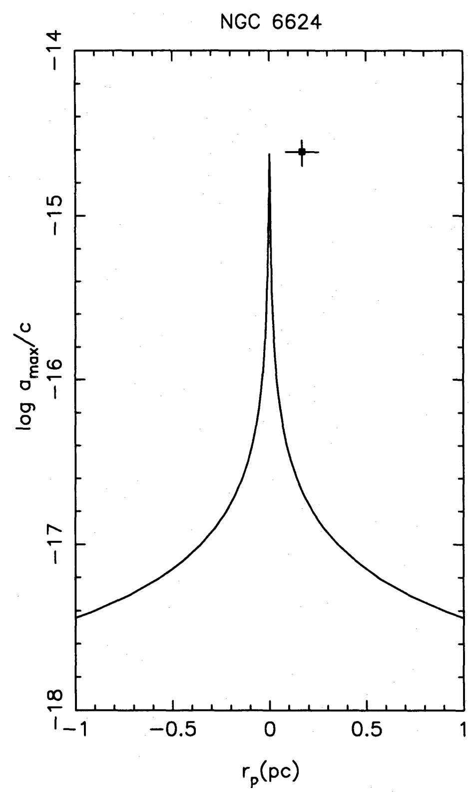

Figure 5. The maximum acceleration along the line of sight $a_{\rm max}$ as a function of projected distance r to the cluster centre, according to our best model for NGC 6624 (curve), and the position of the X-ray source in this diagram (point with error bars), under the assumption that the observed period derivative is due solely to acceleration in the cluster potential. The error bars reflect the uncertainty in the period derivative of the source and the combined uncertainties in the position of the source and the cluster centre.

The maximum acceleration for projected positions close to the centre of the cluster is large enough to explain the observed $\dot{P}$, assuming that the orbital period derivative is zero. However, if 4U 1820−30 is at the position given by Hertz & Grindlay (1983), it is too far away from the cluster core for the observed change in the period to be due to the acceleration by the cluster potential. Moreover, if the orbital $\dot{P}/P$ has its theoretically minimum acceptable value of $+0.88\times10^{-7}$ yr^{-1}, then the gravitational acceleration is not sufficient even if the source is very close to the line of sight to the cluster core. We therefore conclude that it is unlikely that the observed $\dot{P}$ of 4U 1820−30 is caused by acceleration by the gravitational potential of NGC 6624. The possibility that acceleration in a chance encounter with another cluster star, or by a triple companion, causes the observed $\dot{P}$ cannot be excluded (Paper 1); this is not further discussed here. We note that confirmation of the position of 4U 1820−30 well away from the cluster centre is important.

4.2 Helium-burning companion

Finally, we discuss the possibility that the donor star is a helium-burning star. This was originally proposed by Stella et al. (1987), but subsequently dropped, because, as noted by Stella et al., massive progenitors of He-burning stars are not

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expected to exist in an old population of stars (Verbunt 1987). The investigation of radio pulsars in globular clusters has lead to a realization, however, that encounters between stars may be rather more common than previously thought (e.g. Phinney & Sigurdsson 1991), so that stars more massive than the turn-off mass may be formed by stellar mergers. Also, even low-mass stars burn helium, on the horizontal branch. Let us therefore allow for the possibility that the donor is a helium-burning star after all. We may now repeat the above discussion, but using a mass–radius relation appropriate for a helium-burning star (e.g. Savonije, de Kool & van den Heuvel 1986), i.e. $k=0.20$ and $n=1$, which leads to a relation between orbital period and donor mass

$$P=2870\,\frac{M_*}{\mathrm{M}_\odot}\ \ \mathrm{s}.$$

Thus the mass of the helium star is $\sim 0.24\ \mathrm{M}_\odot$, and the period derivative is $\dot{P}/P \sim -2.6\times10^{-7}\ \mathrm{yr}^{-1}$. These numbers must be considered as rough approximations, because of uncertainty in the exact mass–radius relation for the helium star, and because of the possibility of mass loss from the binary. In this evolutionary scenario, once the mass of the donor star becomes too small, the star becomes degenerate and, on further mass loss, expands. The binary evolution therefore passes through a minimum period, which for a helium-burning star is around 10 min (Savonije et al. 1986). Close to the minimum period, the period derivative will obviously be smaller than that found for the quoted mass–radius relation; the observed value is therefore compatible with the value for a non-degenerate helium star. The mass-transfer rate found by Savonije et al. (1986) is higher by a factor of a few than the lower limit implied by the observed luminosity of 4U 1820 − 30. Mass loss from the system would decrease the predicted luminosity and also slow down the predicted period decrease.

The progenitor of the non-degenerate helium-burning star is more massive ($\gtrsim 2.4\ \mathrm{M}_\odot$) than the $\lesssim 0.8\ \mathrm{M}_\odot$ stars currently present in NGC 6624. As the total evolution time of helium-burning stars is much less than the age of the cluster, this massive progenitor must have formed well after the primordial star formation of the cluster. In dense clusters like NGC 6624, close encounters may cause stars to merge. Successive mergers may produce a relatively massive star. An efficient formation process for mergers is the formation of a temporary triple star when a single star encounters a binary (Phinney & Sigurdsson 1991). If one of the stars involved is a neutron star, and if the two other stars, at least one of which has already undergone one or more previous mergers, coalesce, then the outcome is a binary with a relatively (by globular-cluster standards) massive star and a neutron star. The newly massive star evolves and expands, at which point the neutron star may plunge into the expanding envelope of its companion and spiral in. From the spiral-in, a close binary emerges, consisting of the helium-burning core and the neutron star. This system may evolve into a system like 4U 1820 − 30, according to the evolutionary scenario outlined by Savonije et al. (1986).

The probability of the formation of a binary with a merged, newly massive star and a neutron star depends critically on the number of suitable binaries present in the cluster core, and is not known. The presence of blue stragglers in several clusters may point to the frequent occurrence of mergers (Phinney & Sigurdsson 1991) and strengthen the case for a scenario involving a helium-burning donor in 4U 1820 − 30. Alternatively, a scenario may be found in which the core of a horizontal-branch star can become the donor to a neutron star.

ACKNOWLEDGMENTS

This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277. BWM is supported by the National Science Foundation under grants NSF-AST-8657467 and NSF-AST-9015451 and by the United States National Aeronautics and Space Administration under grant NAGW-2224. JvP acknowledges support from NATO (grant RG0331/88). WHGL is supported by the United States National Aeronautics and Space Administration under grants NAG8-216, NAG5-1826, NAG5-1821 and NSG-7463.

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