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CHANGES IN THE 11 MINUTE PERIOD OF 4U 1820−30

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ABSTRACT

Observations made in 1989 February and April with the *Ginga* satellite show that the times of maximum light for the 685 s X-ray intensity variations of 4U 1820−30 occur 71±21 and 94±21 s earlier than would be expected for the constant-period ephemeris based on previous observations. The times of maximum light observed between 1976 and 1989 are consistent with a constant rate period *decrease* of 0.074±0.013 ms yr^{-1} ($\dot{P}/P = -1.08 \pm 0.19 \; 10^{-7}$ yr^{-1}). We find the decrease is significant at the 99.9% level. If this reflected a true change in the orbital period, this result would be inconsistent with the standard model in which the 685 s period is that of the orbit of a binary star consisting of a neutron star whose companion is a low-mass (~0.07 $M_\odot$) degenerate helium star, and mass transfer is driven by loss of orbital angular momentum through gravitational radiation. The apparent period change may be explained in two ways: either the standard model is incorrect, or 4U 1820−30 is being accelerated toward us by the gravitational field of another body. Acceleration of the binary by a distant third companion in a hierarchical triple, or by the cluster potential, are both possibilities.

Subject heading: X-rays: binaries

1. INTRODUCTION

The bright X-ray source 4U 1820−30, near the center of the globular cluster NGC 6624 (Giacconi et al. 1974; Jernigan & Clark 1979; Hertz & Grindlay 1983), has the shortest orbital period of any known binary star (685.0118 s; Stella, Priedhorsky, & White 1987, hereafter SPW87; Morgan, Remillard, & Garcia 1988, hereafter MRG88). The source shows a rich variety of X-ray phenomena, including X-ray bursts (it was one of the first X-ray burst sources to be discovered; Grindlay et al. 1976; Belian, Conner, & Evans 1976), rapid aperiodic variability (Stella, Kahn, & Grindlay 1984), long-term changes between high-intensity and low-intensity states (Priedhorsky & Terrel 1984), and quasi-periodic oscillations (Stella, White, & Priedhorsky 1986; see, however, Hasinger & Van der Klis 1989). The 11 minute intensity variation is most prominent when the X-ray source is in the high state, which it is ~75% of the time.

The stability of the period of the X-ray modulation ($|\dot{P}/P| < 2.7 \; 10^{-7}$ yr^{-1}; MRG88) implies that this modulation represents the orbital period of a binary system (SPW87). In view of the high X-ray luminosity of a few times 10^{37} ergs s^{-1} (for a distance of 6.4 kpc; see Vacca, Lewin, & Van Paradijs 1986), it is generally accepted that the secondary fills its Roche lobe. The mean density of the secondary is then uniquely determined by the orbital period (see, e.g., Warner 1976), and in the case of 4U 1820−30 is $\sim 3 \times 10^3$ g cm^{-3}. As discussed in detail by Rappaport et al. (1987), this mean density implies that the secondary is a hydrogen-depleted degenerate dwarf with mass $M_2 \sim 0.07 \; M_\odot$. An $\sim 0.3 \; M_\odot$ helium-burning secondary star is also consistent with this mean density; however, such a companion star is highly unlikely, since it would have recently evolved from a binary containing a $\sim 5 \; M_\odot$ progenitor (Savonije, de Kool, & Van den Heuvel 1986) and such massive stars are not present in globular clusters. It is generally assumed that the evolution of very compact binary stars, such as 4U 1820−30, is controlled by loss of orbital angular momentum, primarily because of gravitational radiation.

X-ray bursts from 4U 1820−30 are only observed when the source is in its low state. They occur fairly regularly, and the interval between bursts is anticorrelated with the strength of the persistent emission (Clark et al. 1977). All bursts show radius expansion (Vacca et al. 1986), during which the burst peak luminosity is expected on theoretical grounds to be equal to the Eddington limit to within a few percent (Ebisuzaki, Hanawa, & Sugimoto 1983; Kato 1983; Paczyński 1983). The observed peak luminosity (for an assumed distance of 6.4 kpc) of 2.5×10^{38} ergs s^{-1} is consistent with the Eddington limit for hydrogen-poor matter (Vacca et al. 1986; Haberl et al. 1987), which fits the above idea of mass transfer from a helium star.

The average X-ray luminosity of 5×10^{37} ergs s^{-1} corresponds to a mass accretion rate of $\sim 5 \times 10^{-9} \; M_\odot$ yr^{-1} (for a neutron star with mass $M_1 \sim 1.4 \; M_\odot$, and radius ~10 km). The secondary must be losing at least this much mass, so that $\dot{M}_2 \le -5 \times 10^{-9} \; M_\odot$ yr^{-1}.

Rappaport et al. (1987) calculated models for the evolution of a binary star consisting of a neutron star and a Roche lobe–filling hydrogen-depleted degenerate star, from which they predict the mass transfer rate based on a detailed description of the interior structure of the secondary, and on the assumption that mass transfer is driven by gravitational radiation. They derived (see Fig. 1 of their paper) the X-ray luminosity and the period derivative as a function of three parameters, which they call f, β, and M_1. The parameter f is the ratio of the radius of the secondary to that of a completely degenerate star of the same mass and is thus constrained to be larger than unity. The parameter β, which is the fraction of

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mass transferred by the secondary that is captured by the neutron star, cannot be greater than unity. When all free parameters in this model are chosen so as to minimize the period derivative ($f = 1.0$; $\beta = 1.0$; $M_1 = 1.0\ M_\odot$), a minimum rate of period change of $+0.06$ ms yr^{-1} is found. Rappaport et al. conclude that there is no acceptable model for this source with a period increase of less than 0.06 ms yr^{-1}.

Limits can be placed on the period derivative using measurements of the phases of the observed modulation phase over a long time interval. Using *SAS 3*, *Einstein*, and *EXOSAT* data, which provide an 8 yr baseline, MRG88 found $-0.09 < \dot{P} < 0.18$ ms yr^{-1} (3 σ confidence level). Sansom et al. (1989, hereafter S89) added *Tenma* and *Ginga* data, which increased the baseline to 11 yr. They found $\dot{P} = -0.04 \pm 0.10$ ms yr^{-1} (4 σ confidence level).

We here report on two observations made with the Japanese X-ray satellite *Ginga* (Makino et al. 1987) made in 1989 February and April, which extends the baseline to more than 13 yr. We find that the 685 s period decreases at a 99.9% level of confidence. We describe the observations in § 2. In § 3 we describe the analysis of the data. In § 4 we compare our results with earlier work and derive new results on the orbital period and the period derivative. We discuss our results in § 5 and formulate our conclusions in § 6.

2. OBSERVATIONS

The observations of 4U 1820−30 were made in 1989 with the Large Area Counter (LAC; see, e.g., Turner et al. 1989) between February 10.5 and 14.1, and between April 24.1 and 25.7 UT. The optimal use of the on-board data storage capacity, in relation to the time intervals between subsequent ground contacts, led to the use of different combinations of temporal and spectral resolutions. The total exposure times of the observations, which were regularly interrupted by Earth occultations and periods of high particle background in the South Atlantic Anomaly, were 17.0 and 8.8 hr, in February and April, respectively.

As 4U 1820−30 is a bright source with considerable intrinsic stochastic variability in addition to the orbital modulation, background variations on the time scales that we are interested in (~11 minutes) are small compared to intrinsic source variability. Therefore, the data were not background subtracted. No aspect corrections were performed for similar reasons. We detrended the data to remove all long-term variability, including intrinsic source variability, background variations, and aspect changes, by mean subtracting each individual orbit of data separately.

3. RESULTS

In Figure 1 we show the light curves as observed during the two observations. During both the 1989 February and April observations 4U 1820−30 was in a high state; no X-ray bursts were observed. The average X-ray flux in the 1–18 keV band was 7×10^{-9} and 5×10^{-9} ergs cm^{-2} s^{-1} for the February and April observations, respectively; there was significant variability on a time scale of hours (~25% in February and ~20% in April).

To search for the period, we used the phase dispersion minimization technique of Stellingwerf (1978). For this analysis we used only 1–3.5 keV data (MPC-3 mode, high-gain) collected at various time resolutions, which we rebinned to a time resolution of 16 s. The February data included the lowest energy channel (<1.2 keV), while the April data excluded this channel. In Figure 2 we present the Θ statistic as a function of trial period; Θ is the ratio of the sum of the variances of the individual phase bins to the overall variance. In this analysis we used 10 phase bins. The 685 s period is clearly evident in both observations. The February observation shows a minimum Θ at 685.1 s (2 σ confidence limits $684.9 < P < 685.4$). The April observation show a minimum Θ at 685.5 s (2 σ confidence limits $684.6 < P < 686.5$). This determination of the period is not accurate enough to show changes in the orbital period; such changes may be seen only by matching the phases of the different observations.

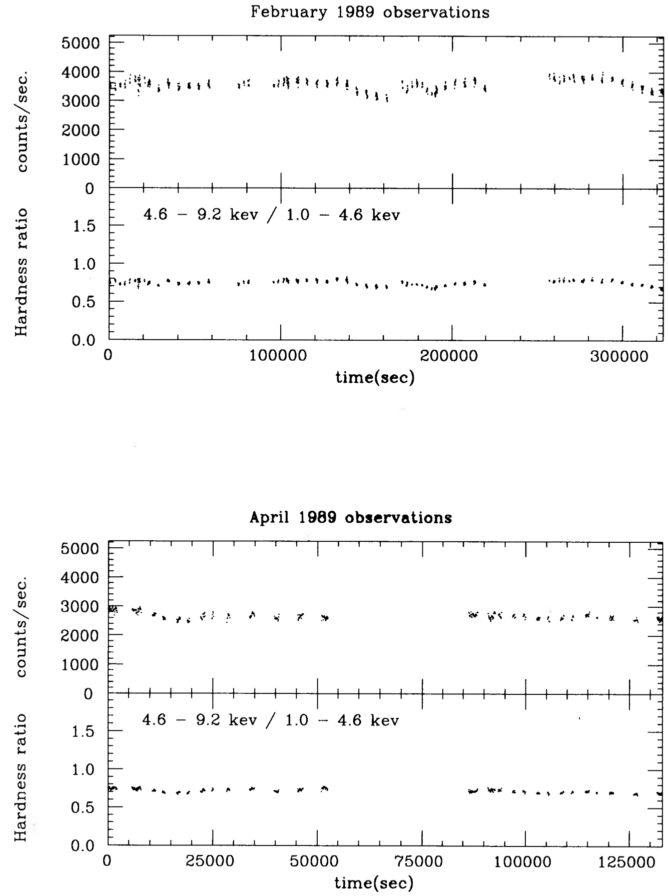

FIG. 1.—Light curves and hardness ratios of 4U 1820−30 obtained from the LAC on the *Ginga* satellite in 1989. The first observation was from February 10.5–14.1 and the second from April 24.1–25.7. The light curves represent the sum of all energy channels in the high-gain MPC-3 mode (1–18 keV) averaged over 80 s. The data have not been aspect corrected or background subtracted.

In Figure 3 we present light curves, selected to show the modulation, with 16 s time bins in the 1–3.5 keV energy band for the February observation, along with the average modulation determined from the folded light curve. Each individual sample has had the mean subtracted. While the 11 minute period is evident in these light curves, there is random aperiodic variability as well.

In Figure 4 we present the light curves for the two observations folded at the orbital period. The February light curve is similar to those seen by previous observers (SPW87, MRG88, S89). The full amplitude of the modulation is 1.6% ± 0.4%; both the amplitude and shape of the modulation appear to be independent of X-ray energy. There is some evidence for a

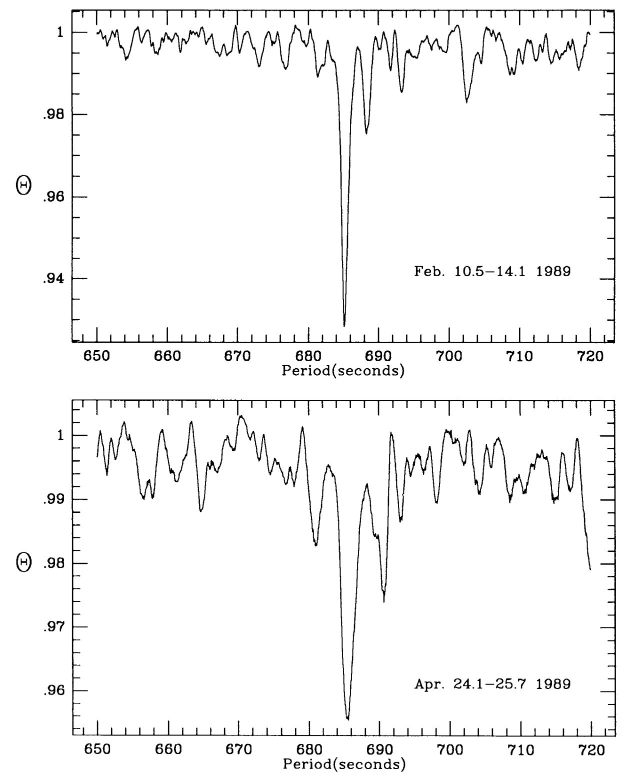

FIG. 2.—Stellingwerf (1978) Θ statistic analysis clearly shows a narrow dip at 685.1 s in the February observation, and a somewhat broader dip in the April observation centered at 685.5 s.

double peak in the modulation, similar to that seen by S89. The amplitude of the April light curve (1.3% ± 1.1%) is the lowest seen during any observation, with the possible exception of the first *SAS 3* observation (MRG88) when the source was in its low (bursting) state.

The epoch of maximum flux was determined by fitting a sine to the detrended data and minimizing χ^2 with respect to the orbital phase and amplitude. The heliocentric epochs of maximum flux (with 1 σ errors) are HJD 2,447,569.83429(24) for the February observation, and HJD 2,447,641.36378(24) for the April observation. The uncertainties in these epochs were determined as 1 σ single-parameter errors ($\Delta\chi^2 = 1$; Lampton, Margon, & Bowyer 1976), where we took account of the random source variability by increasing the error bars of the data such that the reduced χ^2 corresponding to the best fit equaled 1.0. These uncertainties agree with the range of epochs obtained from subsets of the data.

4. COMPARISON WITH PREVIOUS PHASE MEASUREMENTS

Measurements of the arrival times of the 685 s modulations have been obtained from observations made with *SAS 3* and *Einstein* (MRG88), *Ariel 5* (Smale, Mason, & Mukai 1987), *EXOSAT* (SPW87), *Tenma*, and *Ginga* (S89). We combined those *SAS 3* points that were within 1 week of each other by taking a weighted average. Table 1 lists the heliocentrically corrected epochs of maximum flux that we used. The arrival time residuals for these measurements and our results, relative to the values expected for an assumed constant period of 685.0118 s (the best value from MRG88), are plotted in Figure 5. The strong deviation from the expected phase seen in our

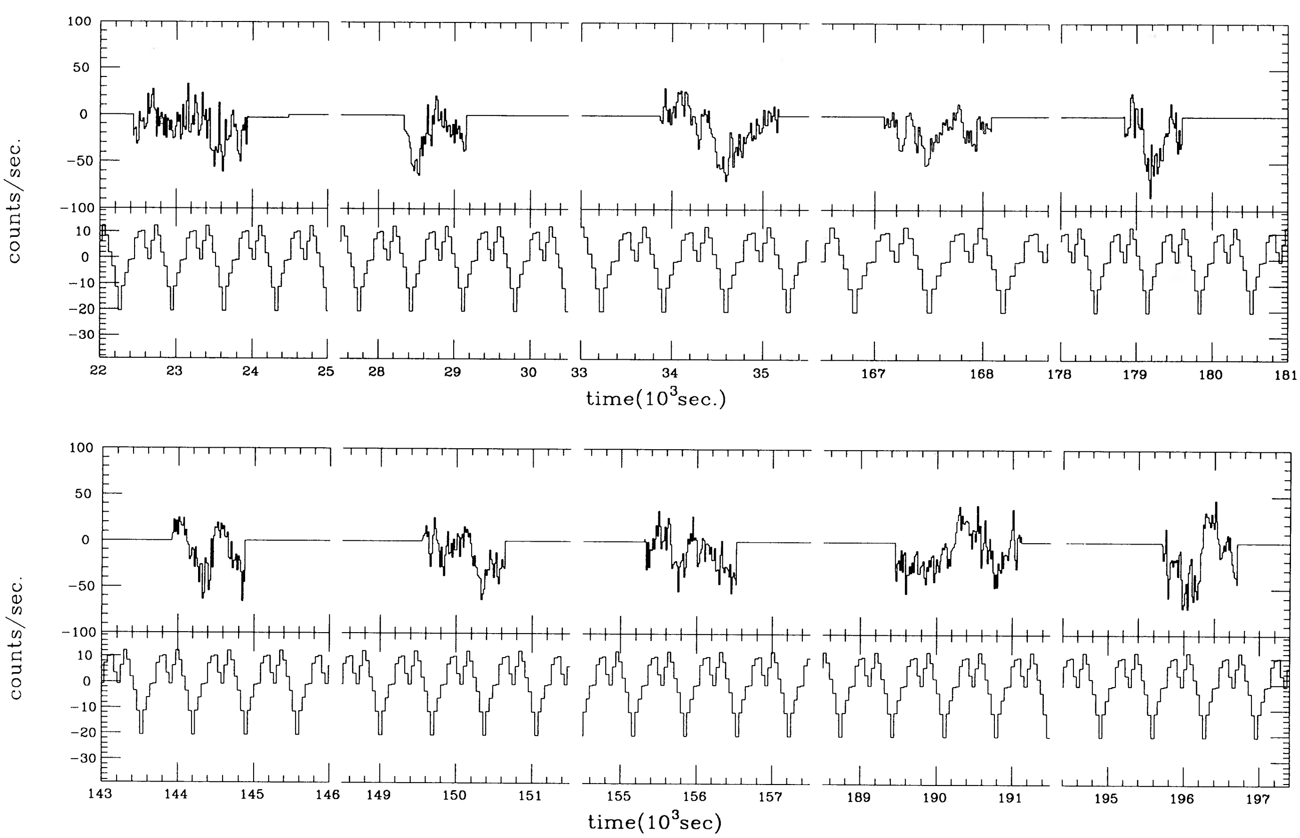

FIG. 3.—Selected pieces of the February observation are shown at a 16 s time resolution. The individual sections have been mean subtracted. The lower frames show the average modulation of the entire observation.

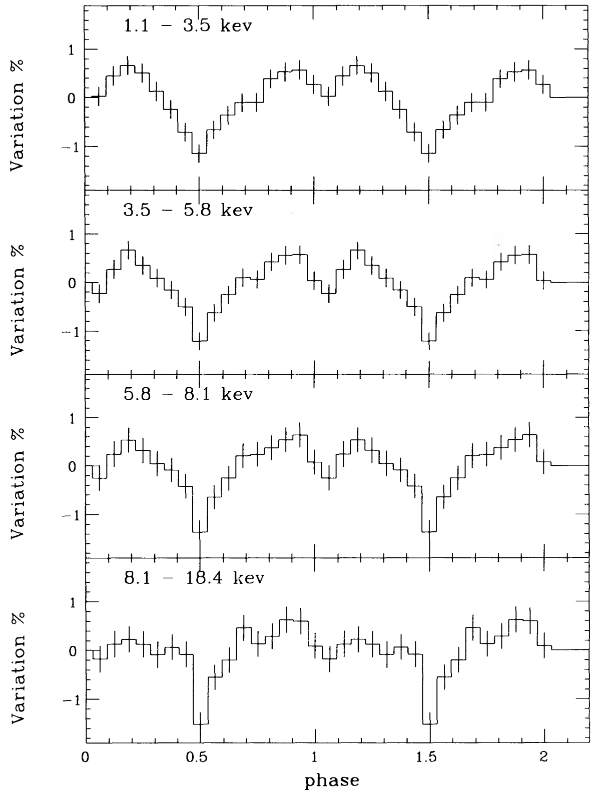

FIG. 4*a*

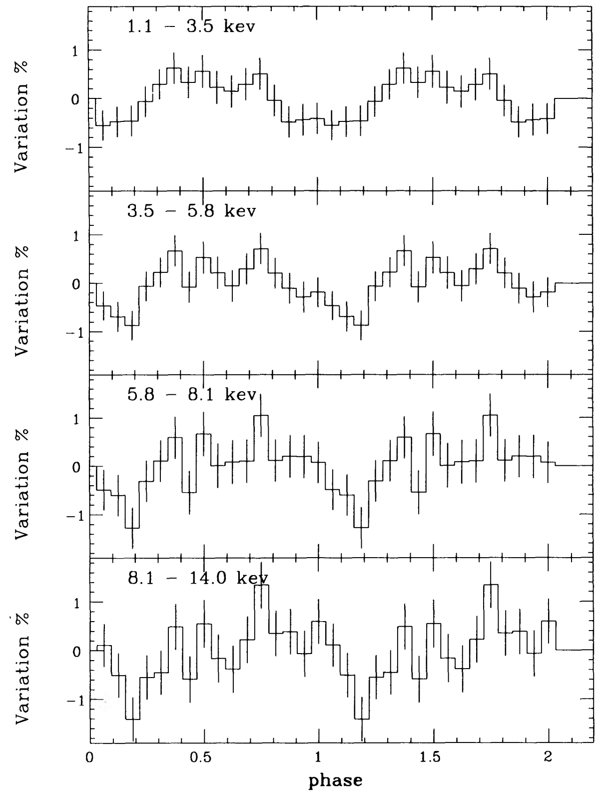

FIG. 4*b*

FIG. 4.—(*a*) Folded light curves for the 1989 February observations. Data were folded about a period of 685.0 s with an epoch of HJD 2,447,567.970824. Folds have been normalized by dividing each bin by the average counting rate. Each individual section of data had its mean subtracted before folding. Error bars reflect only counting statistics and not the intrinsic source variability. There is no evidence for any energy dependence of the modulation, which has an amplitude of ~2%. (*b*) Folded light curves for the 1989 April observations. Data were folded about a period of 685.0 s with an epoch of HJD 2,447,640.62861.

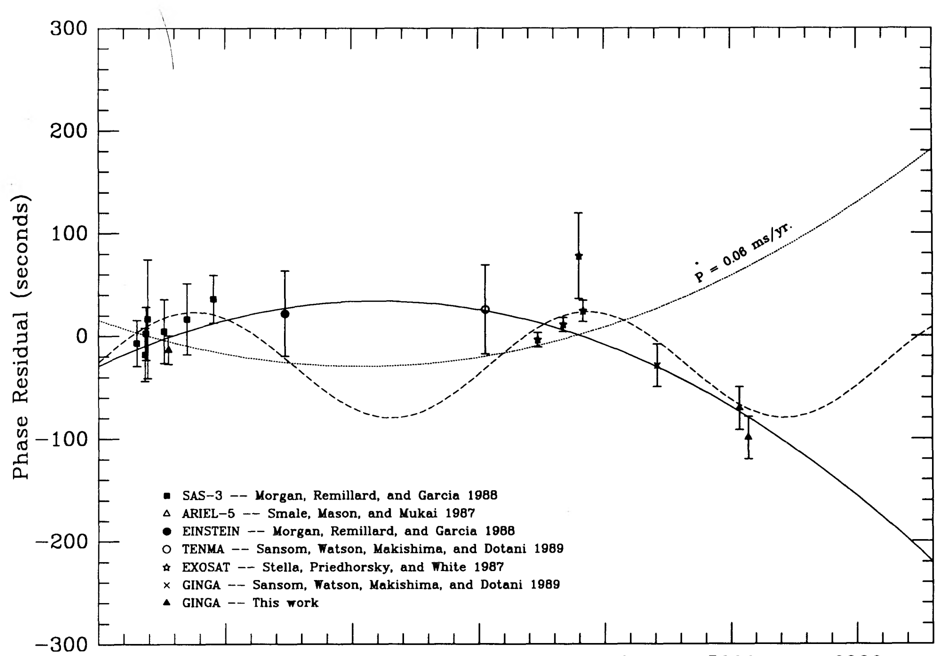

FIG. 5.—Phase residuals for all known phase measurements of 4U 1820–30, assuming a constant period of 685.0118 s. The solid curve represents the best-fit second-order polynomial to all data points which corresponds to a period decreasing at a rate of 0.07 ms yr^{-1}. Long dashed curve represents a sinusoid with amplitude of 50 s and period 8.5 yr. Dotted line represents the best fit to all points excluding the two from this work, with the period derivative fixed at the minimum acceptable value from Rappaport et al. (1988).

TABLE 1

SUMMARY OF OBSERVED EPOCHS

X-Ray Satellite	Epoch (HJD)	Cycle Number	Reference
SAS 3	2,442,803.63551(26)	0	1
SAS 3	2,442,866.86419(30)	7975	1
SAS 3	2,442,876.80661(30)	9230	1
SAS 3	2,442,889.19090(67)	10,792	1
SAS 3	2,443,018.63738(36)	27,119	1
Ariel 5	2,443,050.94530(16)	31,193	2
SAS 3	2,443,196.93086(40)	49,607	1
SAS 3	2,443,406.10547(27)	75,990	1
Einstein	2,443,969.20245(48)	147,013	1
Tenma	2,445,554.1089(5)	346,916	3
EXOSAT	2,445,969.88059(8)	399,357	4
EXOSAT	2,446,172.22088(8)	424,878	4
EXOSAT	2,446,297.41073(48)	440,668	4
EXOSAT	2,446,331.57349(12)	444,977	4
Ginga	2,446,916.50477(24)	518,753	3
Ginga	2,447,569.83429(24)	601,157	5
Ginga	2,447,641.36378(24)	610,179	5

REFERENCES.—(1) Morgan, Remillard, & Garcia 1988; (2) Smale, Mason, & Mukai 1987; (3) Sansom et al. 1989; (4) Stella, Priedhorsky, & White 1986; (5) This work.

observation is a continuation of the trend seen in the 1987 *Ginga* point (S89).

The solid curve in Figure 5 represents the best fit of all data to a second-order polynomial, for which the period of 4U 1820−30 between 1976 and 1989 is given by $P = [685.012184(77) - 2.03(36) \times 10^{-7}]$ $(T - 2{,}442{,}500)$ s, where T is the HJD. The best-fit epoch of maximum flux for this fit is HJD 2,442,803.63544(11). The reduced χ^2 for this fit is 1.4 for 14 degrees of freedom (dof). The corresponding value of $\dot{P}$ is $(-2.3 \pm 0.4) \times 10^{-12}$. A linear fit yields a reduced χ^2 of 3.4 for 15 dof. Performing an F-test, we find that the parabolic term in the ephemeris is significant at the 99.9% level. For comparison, the solid line in Figure 5 represents the best fit to the previous phase points for a period derivative equal to $+0.06$ ms yr^{-1}, the minimum period derivative acceptable in the model by Rappaport et al. (1987).

The phase measurements may be equally well fitted by a sinusoid with a period of 8.5 ± 0.2 yr and amplitude 50 s. The reduced χ^2 for this fit is 1.18 for 14 dof. The fact that this 8.5 yr sinusoid fits is likely an artifact of the 8 yr interval between the *SAS 3* and the *EXOSAT* observations, and the long gap in the observations between 1981 and 1984.

It is possible that systematic effects could have influenced the results. A different method to determine the epoch than used by us was used by MRG87, who performed a fit using a fit function composed of the fundamental plus the second and third harmonics of the modulation. We found that the difference in method does not lead to differences in the determined epochs of more than 5 s, which would have a negligible effect on the observed period change. Another possible concern is that the light curve is not stable (see Fig. 3), so that it is possible that the epoch of maximum X-ray flux does not always correspond to the same phase in the orbital cycle. The largest change seen in the light curve is the secondary minimum seen in Figure 4*a*, but missing in the *EXOSAT* light curves of SPW87. This change would only affect the higher order harmonics and would have little effect on the location of the phase of maximum flux in the fundamental frequency. In order for such random changes in the light curve to explain our observed phase measurements, the phase of maximum flux would have to change by $\sim 50°$, which seems unlikely.

5. DISCUSSION

The new *Ginga* observations show that the 685 s period of 4U 1820−30 is *decreasing*. This is in strong disagreement with the "standard model" for this system, in which the 685 s variation of the X-ray intensity reflects the orbital period, which in the course of the evolution of this compact binary should increase (Rappaport et al. 1987). This is illustrated in Figure 5, in which the dotted curve represents the best fit to the data (excluding the 1989 data), with the minimum acceptable value of $\dot{P}$ ($+0.06$ ms yr^{-1}) for this standard model. The discrepancy may be explained in a number of ways. In the first place the changes in period we observed may not be real changes in the orbital period; they could be caused by gravitational acceleration of the binary system, or by effects related to a possible eccentricity of its orbit. Alternatively, the standard model may be incorrect. We discuss these possibilities in turn.

5.1. *Gravitational Acceleration*

It is possible that the binary is being accelerated in the gravitational potential of the globular cluster; this has been observed for the isolated radio pulsar in M15 (Wolszczan et al. 1989). If we assume that the period is constant and the period change results from the acceleration, a, of the binary toward us, then the acceleration along the line of sight due to the mass of the cluster will be given by

$$a = GM(R_x)R_x^{-2} \cos\theta = GR_x \rho(R_x) \cos\theta . \quad (1)$$

Here R_x is the distance between the X-ray source and the center of the globular cluster, θ is the angle between the line of sight to 4U 1820−30 and the line between the source and the center of the globular cluster, $M(r)$ is the globular-cluster mass inside a radius r, and $\rho(r)$ is the corresponding average mass density.

The observed $\dot{P}$ implies an acceleration $a > c\dot{P}/P = 9.6 \pm 2.5 \times 10^{-5}$ cm s^{-2} and requires a mass and average density inside R_x of

$$M(R_x) > 6.9 \pm 1.8(R_x/1 \text{ pc})^2(\cos\theta)^{-1} \times 10^6 \, M_\odot , \quad (2a)$$

$$\rho(R_x) > 1.6 \pm 0.4(R_x/1 \text{ pc})^{-1}(\cos\theta)^{-1} \times 10^6 \, M_\odot \text{ pc}^{-3} . \quad (2b)$$

The observed position of the X-ray source is $4'' \pm 1''$ from the center of the globular cluster (Hertz & Grindlay 1983). For an assumed distance $d = 6.5$ kpc (Vacca et al. 1986), this corresponds to $R_x = (0.13 \pm 0.03)(\sin\theta)^{-1}$ pc, and

$$M(R_x) > (1.10 \pm 0.46)(\sin^2\theta \cos\theta)^{-1} \times 10^5 \, M_\odot , \quad (3a)$$

$$\rho(R_x) > (1.27 \pm 0.45) \tan\theta \times 10^7 \, M_\odot \text{ pc}^{-3} . \quad (3b)$$

Since NGC 6624 is a globular cluster with a collapsed core, there is little basis for defining a central core radius or density. However, based on observed structural parameters compiled by Webbink (1984) and Chernoff & Djorgovski (1989). Aguilar, Hut, & Ostriker (1988) calculate a central density of 4.5×10^6 $M_\odot$ pc^{-3} by assuming a King model with concentration parameter $c = 2.7$, which corresponds to a core radius of 3″.75. Since 4U 1820−30 is located approximately one such core radius from the center of the cluster, the average density inside R_x should be close to this calculated value. This leads to an expected value for θ of $\sim 20°$. In view of the uncertainty of both values we consider acceleration of 4U 1820−30 in the cluster potential a viable mechanism for the apparent period decrease of 4U 1820−30.

The neutron-star/white-dwarf binary may also be accelerated if it is part of a hierarchical triple system, with a widely separated third star. Hierarchical triples are common in the Galaxy (Batten 1973); however, such systems are likely to have formed and evolved as triples. This cannot be the case in 4U 1820−30 if it was formed by collision of a neutron with a red giant (Verbunt 1987). The formation of stable hierarchical triple systems in a globular cluster by the collision of a binary system with a third star are extremely unlikely (Hut 1983; Rappaport, Putney, & Verbunt 1989).

From the observed phase measurements we infer that the period of the third star around the binary must either be 8.5 yr or larger than 20 yr. If we assume a circular orbit with a period of 8.5 yr (note, however, that this period may be an artifact due to the data gaps; see § 4), then using the relation $M_3 = (P/2\pi)^4\ q^{-2}(1+q)^2 a_b^3 G^{-1}$ we find that the mass of the third body must be greater than $\sim 0.004\ M_\odot$. Here P is the orbital period of the third star around the binary, $q = M_3/M_b$, with M_b the mass of the close binary system and a_b the full acceleration of the binary. The observed acceleration along the line of sight will be smaller than by a factor of $\sin i \cos \phi$, where i is the inclination angle and ϕ is the orbital phase of the third star. If we assume that the third star is a normal cluster member, that is, its mass M_3 is less than $0.8\ M_\odot$, then the observed value of the acceleration implies an upper limit on the triple period of ~ 400 yr.

For the triple system to be stable and not be disrupted by interactions with other cluster members, the distance R_3 between the binary and the third star should not be too large. Using as a criterion for the triple to be "hard" that its orbital velocity be at least the velocity dispersion of the cluster stars (Hut 1983), we find that R_3 should be less than $\sim 5 \times 10^{14}$ cm, with corresponding upper and lower limits on the orbital period and the acceleration of $\sim 10^2$ yr and $\sim 10^{-4}$ cm s^{-2}, respectively, consistent with the observed values.

The probability that the observed acceleration is caused by a chance encounter with an unrelated cluster star is less than $\sim 10^{-3}$ for cluster stars between 0.1 and $0.8\ M_\odot$. As the space density for lower mass objects in the cluster is unknown we cannot estimate the encounter probability with such objects.

5.2. *Effects of an Eccentric Orbit*

In view of the very compact nature of the system and the fact that it is mass transferring, it is natural to assume that the orbit is circular as a result of tidal interaction. Although we consider this likely, it is worthwhile to explore the possibility that this is also the case for 4U 1820−30. Eccentricity of the orbit can give rise to a variation of the observed orbital period as a result of apsidal motion, and of the circularization of the orbit.

The axis of an eccentric orbital ellipse will be rotate slowly, because of the emission of gravitational radiation and of the tidal interaction between the two components (see, e.g., Shapiro & Teukolsky 1983; Schwarzschild 1958). To discuss the possible relevance of this effect to 4U 1820−30 we will take the 8.5 yr period of the sinusoidal fit to the arrival time residuals (see § 4) as a lower limit to the apsidal motion period; likewise we treat the 50 s amplitude as an upper limit to the amplitude, A, of the apsidal motion effect. Note that in this case the X-ray intensity modulation does not reflect the orbital period (i.e., the time interval from periastron to periastron), but the interval between subsequent conjunctions of the binary star.

In the case where the 685 s period is the time interval between subsequent conjunctions, the amplitude of the sinusoidal variation of $(O-C)$ is, to first order in e, given by the relation $A = e(P_{\rm orb}/\pi)$ (Batten 1973), from which we find an upper limit to the eccentricity, $e < 0.25$. The upper limit to the rate of change ($\dot\omega$) of the periastron angle ω is 2.26×10^{-8} (rad s^{-1}).

In case the apsidal motion is driven by tidal deformation of the secondary, the apsidal motion period $P_{\rm aps}$ is given by

$$P_{\rm orb}/P_{\rm aps} = 15\ {\rm k}\ (R_2/D)^5 (M_1/M_2)(1 + 3e^2/2 + e^4/8)(1 - e^2)^5 \quad (4)$$

(Schwarzschild 1958); here R_2 and D are the secondary radius and the binary separation, respectively, e is the orbital eccentricity, and k is the apsidal motion constant. For a degenerate star $k = 0.14660$ (Motz 1952). We will ignore the dependence on e and put the last two factors in the above expression equal to unity. For a Roche lobe–filling secondary, the ratio R_2/D can be approximated by $R_2/D = 0.462[M_2/(M_1 + M_2)]^{1/3}$ (Paczyński 1971). For apsidal motion periods of 8.5 yr and greater than 20 yr we then find that the value of the quantity $M_2^{2/3}(1.4 + M_2)^{-5/3}$ equals 5.4×10^{-5} and less than 2.4×10^{-5}, respectively; that is, the secondary is less massive than a few times $10^{-7}\ M_\odot$. This is inconsistent with the properties of the secondary inferred from the 685 s orbital period.

Irrespective of these considerations concerning the internal structure of the secondary, such an eccentric orbit would have a large component of the apsidal motion due to gravitational radiation. For this component,

$$\dot\omega = 6\pi GM/[R(1 - e^2)P_{\rm orb}\, c^2] \quad (5)$$

(Shapiro & Teukolsky 1983). Here R is the semi-major axis of the relative orbit, and M the sum of masses of the binary system. This gives $M/R < 1.0 \times 10^{22}$ g cm^{-1}. Combining this with Kepler's third law, we find (with $P_{\rm orb} = 685$ s) that $M < 0.014\ M_\odot$, which is irreconcilable with the fact that one of the components is a neutron star.

Thus, we conclude that apsidal motion cannot explain the observed change of the 685 s period of 4U 1820−30.

Another mechanism which may cause a change of the period of an eccentric orbit is the circularization of this orbit: tidal interaction can cause a flow of angular momentum from the (eccentric) orbit to the secondary star, as a result of which the latter spins up and the orbit decays (see, e.g., Lecar, Wheeler, & McKee 1976). It is difficult to calculate the efficiency of this tidal process, since the orbital period is rather short compared to the expected convective-turnover time scale (we are indebted to Ralph Wijers for pointing this out to us). If we make the assumption that the observed decrease of the orbital period is caused by this angular-momentum flow, then the time interval, $t_{\rm syn}$, over which this process can operate (i.e., until the secondary is synchronous near periastron) is approximately given by $t_{\rm syn} \sim 3(P/\dot P)_{\rm obs} I_2/I_{\rm orb} \sim 3 \times 10^5$ yr (here I_2 and $I_{\rm orb}$ indicate the moments of inertia of the secondary and the binary system, respectively). Therefore, if this mechanism causes the orbital period variation of 4U 1820−30, we are observing the system during a stage in its evolution which is very short compared to its total lifetime.

5.3. *A Problem with the Standard Model?*

The above discussion suggests that the observed period change of 4U 1820−30 may be explained by gravitational acceleration of the system in the cluster potential, or by the presence of a third star (hierarchical triple). It is in our opinion, however, of interest to discuss the possibility that the standard binary evolution model may be incomplete. We will briefly address two basic assumptions underlying this model: (1) the 685 s period is orbital; (2) the mass transfer is driven by gravitational radiation, and the secondary always just fills its Roche lobe (this implies that the evolution is a quasi-stationary process).

5.3.1. *The Period Is Orbital*

Our observation supports the conclusion of SPW87 that the 11 minute period cannot be the spin rate of the neutron star. The measured $\dot{P}/P$ is five orders of magnitude smaller than would be expected for spin-up of a neutron star accreting matter from a low-mass companion overflowing its Roche lobe (SPW87), and three orders of magnitude smaller than predicted or typical observed values for high-mass companions with strong stellar winds (Joss & Rappaport 1984).

Sansom et al. (1989) suggested that the 685 s period is due to free precession of a slightly nonspherical neutron star with a rotation period $P_{\rm spin} \sim 1$ ms. If this model would apply here, our observation of a decrease of the 685 s modulation would imply a spin-down of the neutron star rotation on a time scale of $P_{\rm spin}/\dot{P}_{\rm spin} \sim 10^7$ yr. This model may be correct, however, it is unclear what causes the modulation of the X-ray intensity.

5.3.2. *Gravitational Radiation Drives the Evolution; the Secondary Always Fills Its Roche Lobe*

All evolutionary calculations made so far presume that the secondary always exactly fills its Roche lobe. It is this assumption, together with the anticorrelation between the mass and radius of a degenerate secondary star, which ensures that mass transfer from the secondary leads to an expected increase of the orbital period. For unknown reasons this assumption may be incorrect. If the orbit were to shrink, the inner Lagrangean point L_1 would move into the white dwarf and encounter regions of exponentially increasing density. Since the mass transfer rate $\dot{M}$ is proportional to the density in the "nozzle" near L_1, this would lead to an exponential increase of $\dot{M}$.

Near L_1 the local scale height, H, is given by $H \sim 0.5(kT\, R_2^3/\mu m_p\, GM_2)^{1/2}$, where T is the gas temperature near L_1 (see Papaloizou & Bath 1975). For values of T between 10^4 and 10^5 K this leads to $H = (2\text{–}4) \times 10^7$ cm. Using for the radial position of L_1 relative to the secondary the approximation $R(L_1)/a = 0.56813\, q^{1/3}$ (Kopal 1959), we find that the L_1 point moves into the secondary atmosphere at a speed of 1.9×10^{-5} cm s^{-1}. The corresponding e-folding time for $\dot{M}_2$ is $\sim 5 \times 10^4$ yr.

This possibility of a runaway mass transfer is worth considering, since it may entail a limitation of the lifetime of 4U 1820−30 (and perhaps of other low-mass X-ray binaries as well); if such runaways can occur they may contribute to bridging the gap between the estimated birth rates of low-mass X-ray binaries and their descendants, the millisecond binary radio pulsars (Kulkarni & Narayan 1988; see also Cote & Pylyser 1989).

6. CONCLUSION

From our *Ginga* observations of 4U 1820−30 we have found that the 685 s period of this system decreases on a time scale of $\sim 10^7$ yr, contrary to the increase expected on the basis of evolutionary models of ultracompact binary systems. Gravitational acceleration of 4U 1820−30 in the gravitational potential of the cluster, or caused by a distant companion in a hierarchical triple system, are both viable explanations for this apparent discrepancy.

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