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**DOI**
10.1093/mnras/282.3.L37
**Publication date**
1996
**Document Version**
Final published version
**Published in**
Monthly Notices of the Royal Astronomical Society

**Citation for published version (APA):**
Homer, L., Charles, P. A., Naylor, T., van Paradijs, J. A., Aurière, M., & Koch-Miramond, L. (1996). Periodic UV modulation of X1850-087: a double degenerate binary in the globular cluster NGC 6712? *Monthly Notices of the Royal Astronomical Society*, *282*, L37-L46. https://doi.org/10.1093/mnras/282.3.L37

1996MNRAS.282L..37H

Mon. Not. R. Astron. Soc. **282**, L37–L46 (1996)

# Periodic UV modulation of X1850 − 087: a double degenerate binary in the globular cluster NGC 6712?

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Accepted 1996 August 6. Received 1996 July 16; in original form 1996 May 22

## ABSTRACT

We report the discovery with the *Hubble Space Telescope* (*HST*) of a short-period (20.6 min) UV modulation in X1850 − 087, the luminous X-ray source in the globular cluster NGC 6712. The low-amplitude modulation ($0.044 \pm 0.007$ mag) is not detected in archival X-ray observations with *EXOSAT*. We compare the properties of X1850 − 087 with the 11-min binary X1820 − 303 and identify the modulation as the orbital period, which requires the mass-losing companion to be degenerate and of low mass ($0.04\ \mathrm{M}_{\odot}$).

**Key words:** binaries: close – stars: individual: X1850 − 087 – globular clusters: individual: NGC 6712 – X-rays: stars.

## 1 INTRODUCTION

The unusual nature of the 12 bright ($>10^{36}$ erg s$^{-1}$) X-ray sources in globular clusters (see e.g. Charles 1989; Verbunt et al. 1995) has been apparent for almost 20 years. Their overabundance, compared with those in the Galaxy as a whole, requires entirely different formation mechanisms (see e.g. Verbunt 1988). That they are all neutron star low-mass X-ray binaries (LMXBs) is indicated by the fact that they have all produced type I X-ray bursts, and by their mean (system) mass of $\sim 1.5\ \mathrm{M}_{\odot}$ (based on their location relative to the cluster centres; Grindlay et al. 1984). However, determining their binary parameters and the nature of the mass-losing components has proven to be extremely difficult. Not surprisingly, this is partially a result of the lack of any optical identifications until about 10 years ago, caused by the extremely crowded fields in which these objects are located. The identification of X2127 + 119 in M15 with the 15th-magnitude variable AC211 (Aurière et al. 1984; Charles et al. 1986) showed that optically it is one of the most luminous of all LMXBs, and this raised the hope for the discovery of similar objects in other clusters. A photometric period for X2127 + 119 of either 8.5 or 17 h (Ilovaisky et al. 1993) suggests an evolved secondary which supports a relatively high mass transfer rate. The only other cluster X-ray binary periods have come directly from X-ray observations, namely the 5.7-h 'dip' period of X1746 − 370 in NGC 6441 (Sansom et al. 1993) and the extraordinary 11.4-min X-ray flux modulation discovered by Stella, Priedhorsky & White (1987) from X1820 − 303 in NGC 6624. This latter object is interpreted as a double degenerate binary (Stella et al. 1987), and was finally identified by *HST* (King et al. 1993) with an ultraviolet-bright, 19th-magnitude star.

Of all the clusters with luminous LMXBs, NGC 6712 is the least concentrated, with a core radius of 56 arcsec, almost ten times larger than the other X-ray-bright clusters (see Trager, Djorgovski & King 1993). With only modest reddening of $E(B-V)=0.46$ (Peterson 1993), NGC 6712 has therefore been the target of many optical searches (Bailyn et al. 1988; Cudworth 1988; Bailyn 1990; Nieto et al. 1990; Bailyn et al. 1991; Aurière & Koch-Miramond 1992) within the X-ray and radio source locations of X1850 − 087 (which have a precision of 2–3 and 0.4 arcsec respectively, see Grindlay et al. 1984 and Lehto et al. 1990).

However, it was clear from the earliest optical searches that X1850 − 087 was not similar to AC211, as the counterpart had to be fainter than 20th magnitude (Bailyn et al.

1988). With an implied X-ray to optical luminosity ratio in excess of 5000 and an accurately known distance, the orbital period must be short ($\lesssim 1$ h, see van Paradijs & McClintock 1994), hence another double degenerate binary was strongly suggested. But such a faint counterpart is still extremely difficult to observe from the ground, even in an unconcentrated globular cluster. This was admirably demonstrated by Anderson, Margon & Deutsch (1993), who were able to use *HST* and the WFPC to locate the UV-excess object convincingly. They measured $V=21$, confirming the faintness of the counterpart, and invited comparison with the other galactic ultra-short-period binaries X1626 − 673 and X1916 − 053 (see Nelson, Rappaport & Joss 1986). This photometric identification has also been confirmed by the ground-based astrometric work of Geffert et al. (1994), who were able to determine a new accurate position for the counterpart, which is only 0.1 arcsec from the radio position. However, a UV-variability study of such a faint star remained impossible until after the installation of WFPC2 on *HST*, with its corrective optics. As part of Cycle 5 we were allocated 10 orbits on *HST* to study the short-term variability of the Anderson et al. UV counterpart, and it is these observations that are reported in this paper.

## 2 OBSERVATIONS

A total of 53 exposures of the X1850 − 087 region were made on 1995 May 25 and 26 with WFPC2, through the F300W (wide *U*) filter (all approximately 300 s), plus a further 5 exposures through the WFPC2 *UBVRI* filters (exposure times: 160, 160, 60, 60 and 120 s, respectively). These images underwent standard reduction through the STScI 'pipeline' processing. Subsequent data reduction was performed using NOAO–IRAF routines.

From earlier time-series studies undertaken with the WFPC (Gilliland et al. 1995), it is known that the *x*, *y* pixel positions of stars do vary from frame to frame, during a single run, even when using the fine-lock mode of *HST*. The guiding is excellent by normal standards, but the variations are $\gtrsim 0.1$ pixels, and are sufficient to cause problems. We examined the shifts using 18 bright reference stars, which have no nearby cosmic ray events. They were found to be similar to those detected by Gilliland et al. and therefore could have detrimental effects on the photometry, particularly for small aperture sizes. As a precaution, the same data reduction procedures were followed exactly for both the original and a new set of 53 registered images. The images were registered using the 'IMALIGN' task in IRAF, which computes the mean shift of a set of reference objects on a frame (we used the same 18 stars) relative to an arbitrary reference frame. A fifth-order interior polynomial in *x* and *y* was used to interpolate and calculate the new shifted pixel values (the shifts not being an integer number of pixels). All 53 exposures were then median stacked using the 'CRREJECT' routine in STSDAS, to produce a single deep *U*-band image free from cosmic ray events, enabling a good measurement of star centres (see Fig. 1). The 'DAOFIND' and 'PHOT' routines in IRAF/DAOPHOT (Stetson 1987) were run on the image, to compute centres for all the stars, and then to measure approximate instrumental magnitudes via aperture photometry. A sample of 38 stars were selected, including the counterpart S, the 24 brightest stars in the field and a number of stars with brightness comparable to that of S for reference purposes. The 'PHOT' routine was used for all subsequent aperture photometry.

### 2.1 *U*-band photometry

A circular aperture was chosen for photometry, and we examined the effect of the aperture and annulus size (as used to determine the background flux) for non-variable stars of comparable brightness. Both the sizes were adjusted independently, but applied to all the frames and stars for each pair of trial values, in order to produce the minimum mean scatter. A radius of 1.6 pixel was chosen for the aperture, which encircles about 65 per cent of the energy in the core of the point spread function (PSF).

Differential photometry was particularly important, due to the pronounced instrumental intensity variations during each *HST* orbit. These are caused by the combined effects of *x*, *y* motions and CCD defects, leading to flat-fielding errors on contributing pixels for some stars (see Gilliland et al. 1995). Performing a direct Fourier transform (DFT) upon the non-differential light curve for S clearly showed this, with much of the power going into the *HST* orbital period (and harmonics) rather than into the candidate binary period. Furthermore, the choice of local standard stars becomes critical if these artefacts are to be fully removed, as the amplitude of the effect may vary strongly for different stars. We chose a set of 6 of the brightest stars, which also showed clear *HST* orbital variation. The DFT of the resulting differential light curve shows how the artefact peaks at 15 and 30 $\mathrm{d}^{-1}$ have been almost completely removed (see Fig. 2). There was no significant difference between the results using the original or registered set of images, and the former data set was therefore subsequently used.

### 2.2 Colour photometry

Aperture photometry was also used to obtain calibrated magnitudes for S and a nearby bright star, C28 (Sandage & Smith 1966), in the STMAG system (Korne 1988), in *U*, *B* and *V* bands (filters F336W, F439W and F555W, respectively). We followed the procedure outlined in Holtzmann et al. (1995). Since a 0.5-arcsec aperture is standard for WFPC2 observations, a radius of 10.87 pixel was used for C28, giving $V(555)=16.20\pm0.01$, $B(439)-V(555)=0.36\pm0.01$ and $U(336)-B(439)=1.39\pm0.03$. However, this large aperture is not optimal for fainter stars such as S, where 2–4 pixel was better in order to minimize the sky. Measurements were thus made with these apertures and an offset applied to adjust them to the larger aperture. The difficulty in determining an accurate offset is the largest contribution to our quoted uncertainties. We find the magnitudes and colours for S to be $V(555)=20.34\pm0.07$, $B(439)-V(555)=-0.44\pm0.15$ and $U(336)-B(439)=-0.50\pm0.16$.

## 3 TEMPORAL ANALYSIS

We first pre-whitened the differential photometry data for S with a cubic polynomial (for the light curve see Fig. 3), to remove any long-term trends, such as that due to the sys-

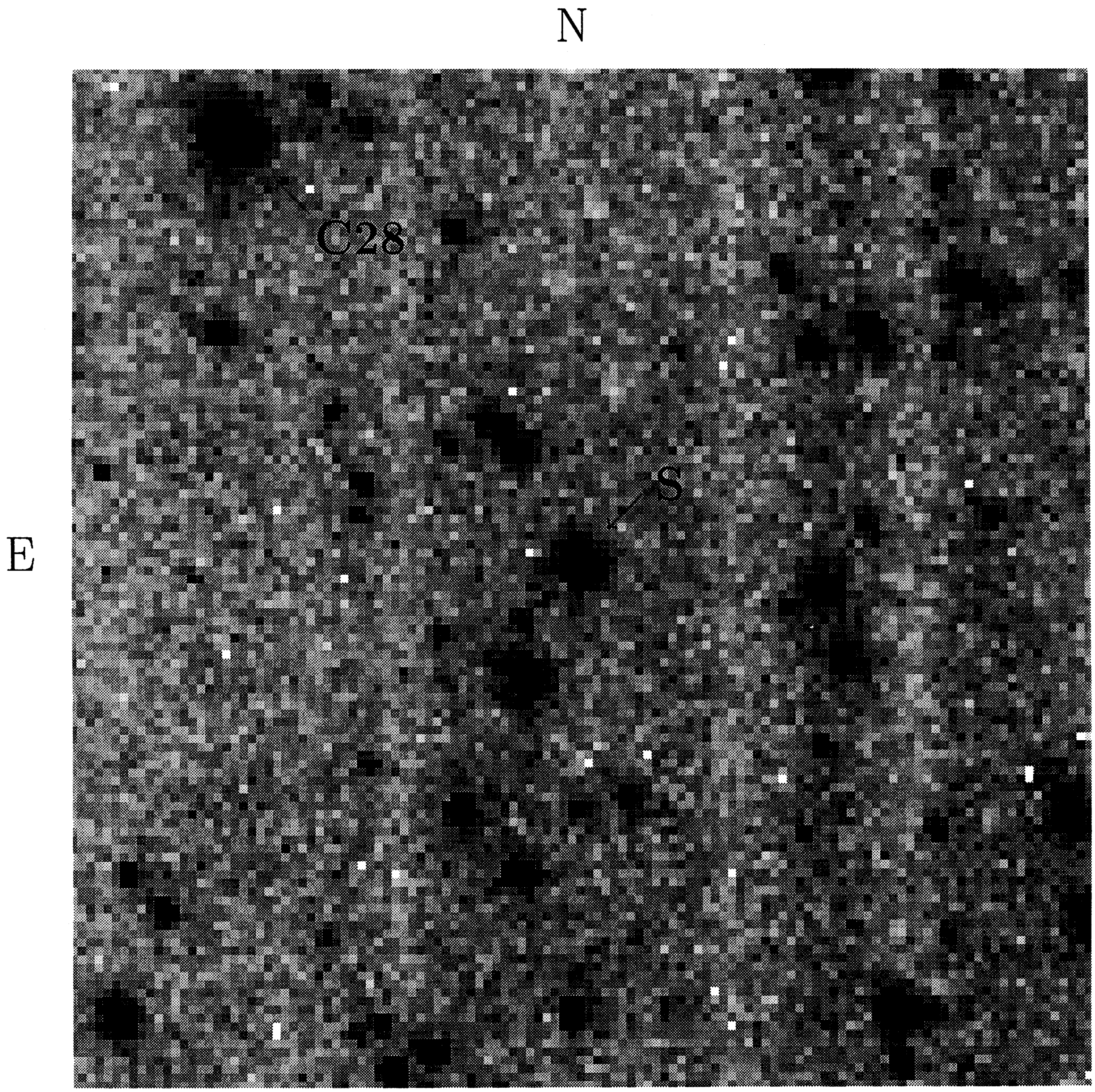

**Figure 1.** A 5.5 × 5.5-arcsec$^2$ section of the deep (15 680 s) *U*-band image (F300W filter) centred on the NGC 6712 counterpart S.

tematic image motion over the 0.56-d duration of the observation. To search for periodic modulations, three different methods were employed: (i) we ran three Lomb–Scargle (LS) periodogram routines on this data set, as implemented in different software packages, to search for sinusoidal modulations [this periodogram is a modified DFT, with normalizations which are explicitly constructed for the case of uneven time sampling (Scargle 1982)]; (ii) we performed a one-dimensional Bayesian analysis (Bretthorst 1988) [this method assumes the a priori knowledge that there is only one sinusoid present, and can distinguish more clearly between the true frequency and aliases]; and (iii) we constructed a phase-dispersion minimization (PDM) periodogram (Stellingwerf 1978), which works well even for highly non-sinusoidal light curves. The first two methods are only able to search for modulations up to the effective Nyquist frequency of about 90 cycles per day ($P \simeq 16$ min) because of the sampling rate.

The LS periodograms all have a significant peak consistent with a frequency of $70.06 \pm 0.15$ d$^{-1}$ (see Fig. 2). Additionally there are smaller peaks at 55 and 85 d$^{-1}$, which are aliases due to the sampling. The *HST* orbital frequency is about 15 d$^{-1}$. From a least-squares fit of a sinusoid to the data, the semi-amplitude of this modulation was found to be $0.044 \pm 0.007$ mag, or approximately 4 per cent of the flux, although the true modulation could be larger as the sampling would reduce it. The alias structure could be clearly identified simply by taking the periodogram of a pure sinusoid with the peak frequency and phase as given by the least-squares fit, sampled at the same time points (see Fig. 2c).

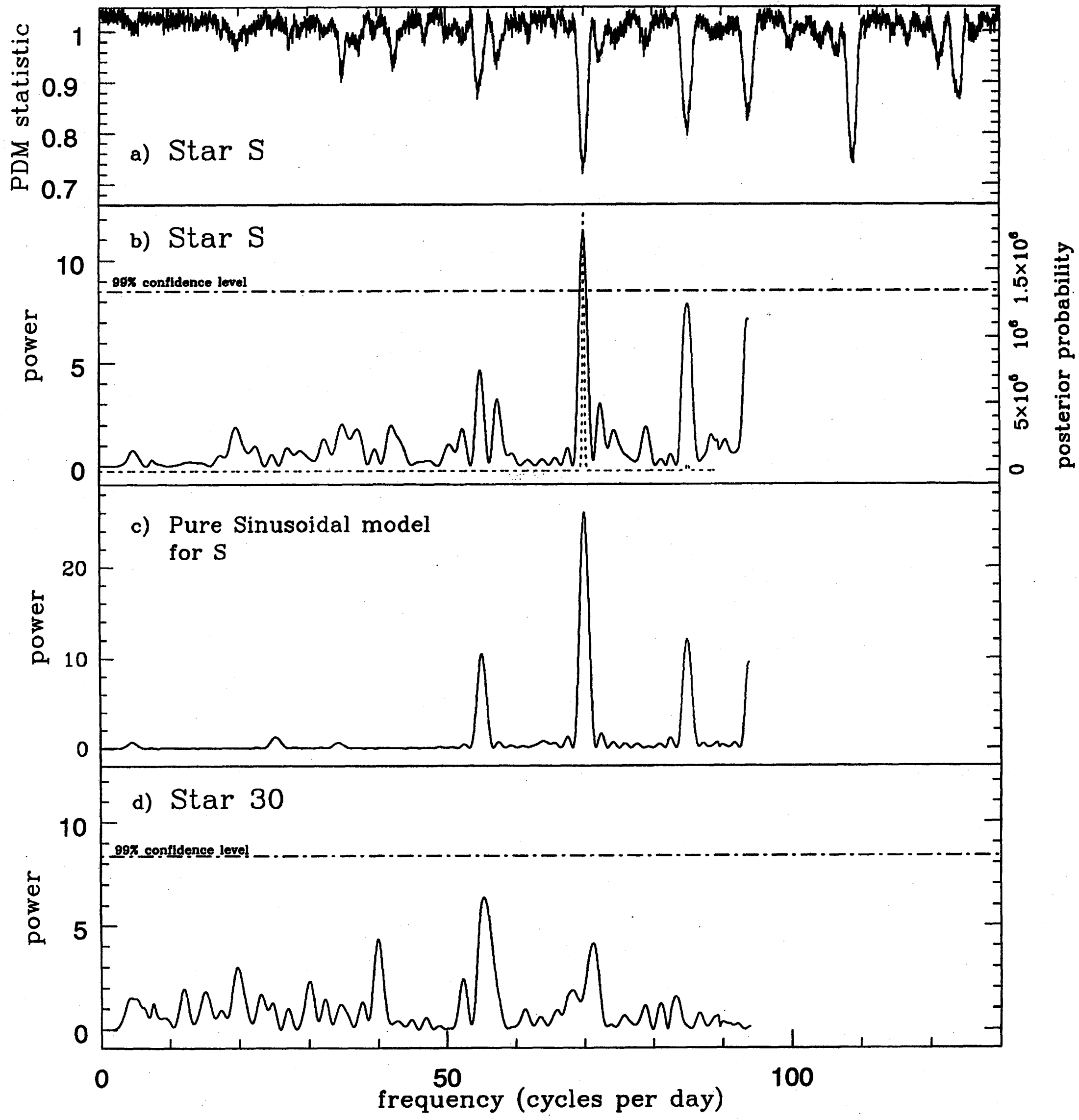

**Figure 2.** Periodograms for the light curves of the NGC 6712 counterpart S and a comparison star (number 30). (a) Phase dispersion minimization analysis of star S [note the peak at 70.1 $\mathrm{d}^{-1}$ (20.6 min) *and* the equivalent peak above the Nyquist frequency of ~ 90 at 109.2 $\mathrm{d}^{-1}$ (13.2 min)]. (b) Lomb–Scargle periodogram (solid line) and Bayesian posterior probability (dotted line) of star S. (c) Lomb–Scargle periodogram of a simulated data set consisting of a pure sinusoid ($P = 20.6$ min) sampled temporally in exactly the same way as star S, therefore showing that the peaks at 55 and 85 $\mathrm{d}^{-1}$ are a result of the *HST* orbital observing window. (d) Lomb–Scargle periodogram of star number 30 which is of comparable brightness to star S, and which displays no significant peaks.

With Scargle normalization, the peak power has a value of 11.37 compared with that of the largest noise peak of 2.02 (excluding the alias structure). The corresponding confidence is 99.98 per cent (the 99 per cent confidence level being at a power of 8.5). These were read from the cumulative distribution function (CDF) plot for this data set. The CDF is the cumulative probability distribution of the random variable $P_X(\omega)$, the power at a given frequency, where $X$ is pure noise (Scargle 1982). In practice the CDF was constructed using a Monte Carlo simulation method. Noise sets with the same sampling times were generated, and the LS periodogram was run upon each one. The peak power occurring in the periodogram due purely to noise was then recorded. This was repeated for a large number of noise sets, to produce good statistics. From these values the probability of obtaining a given peak power from noise can then be calculated and the CDF derived. In order to test the significance of peaks from a given data set, the noise sets generated should have the same variance. We used two methods of generating such noise sets: (i) a random number generator, which takes values from a Gaussian distribution with the same variance as the data set, and (ii) the actual magnitude values from the light curve, which were then randomized with respect to the sampling points. A total of approximately 6000 noise sets were generated by each

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[1] The Bayesian posterior probabilities as given here have not been normalized, since only the relative probabilities are important.

method. The resulting CDFs were virtually identical, and agreed exactly on the confidence levels.

The 1D Bayesian search also yields a peak frequency of $70.08 \pm 0.22$ $\mathrm{d}^{-1}$, with $\log_{10}(\mathrm{prob}) = 6.29$,[1] compared with the next highest (non-alias) peak of 0.875, and a semi-amplitude of 0.045 mag (see Fig. 2b). It also clearly shows that the peaks at 55 and 85 $\mathrm{d}^{-1}$ are aliases, having only $\log_{10}(\mathrm{prob}) = 2.13$ and 4.69, respectively.

The PDM confirms the results of LS periodograms, again with $>99.0$ per cent confidence (as given by an analogous significance test). It also shows the frequency of the above-Nyquist alias of $109.16 \pm 0.2$ $\mathrm{d}^{-1}$ (see Fig. 2a).

The light curves for a further 10 stars with brightness comparable to that of S, and expected to be non-variable, were examined. The data for these stars had been reduced in exactly the same manner. We ran LS periodograms on each of the data sets, in order to find the peak powers present. In two cases the periodograms were dominated by artefacts arising from the *HST* orbital variations and were therefore discounted. Star number 30 proved to have the largest peak power of 6.37 at a frequency of 55.39 $\mathrm{d}^{-1}$ (Fig. 2d). A CDF was computed, and showed that there was a 10 per cent probability that such a peak could be due to random noise. The light curve for star 30 was also folded on this period. Comparison with that for S showed none of the underlying sinusoidal-type modulation, just a number of fainter points which occur in one particular phase region (Fig. 4).

## 4 ARCHIVAL X-RAY OBSERVATIONS

An almost continuous 12.5-h *EXOSAT* observation of X1850 − 087 was made in 1985 September. Data were obtained with all three main instruments, but the count rates were too low for temporal analysis for all but the medium-energy instrument (ME). Previously, Parmar et al. (1989) performed a period search on the ME data, quoting an upper limit of 4–6 per cent semi-amplitude modulation for the 1–10 keV band in the frequency range 0.48 mHz–1 Hz. With our a posteriori knowledge of a candidate binary period, we re-examined the ME light curves for count rates in the 0.8–3.6 keV and 3.6–8.9 keV bands, and the complete 0.8–8.9 keV interval, using both a DFT and epoch-folding period search. A time resolution of 87.82 s was used, enabling both the 70-$\mathrm{d}^{-1}$ (0.8-mHz) frequency and above-Nyquist alias of 109 $\mathrm{d}^{-1}$ (1.3 mHz) to be investigated). No distinct peaks were present in the DFTs at the known frequencies for any of the energy bands. We can therefore set upper limits for the semi-amplitudes of the modulations at these two frequencies (see Table 1).

## 5 DISCUSSION

With such a short *HST* data set, and no prospect of a corroborating detection from existing data, we clearly cannot make a firm statement about the long-term stability of the modulation that has been detected. This prevents us from unambiguously identifying the modulation as orbital based on constraining $\dot{P}$. However, given the extreme faintness of the counterpart, and an accurate knowledge of the distance (and reddening) to NGC 6712 of 6.8 kpc [and $E(B-V) = 0.46$] (Peterson 1993), then the absolute magnitude of X1850 − 087 must be ~5. With the light known to be dominated by the featureless UV spectrum (Downes, Anderson & Margon 1996), which presumably originates from an X-ray illuminated disc, this is very similar to the properties of the Galactic ultra-short-period binaries X1627 − 673 and X1916 − 053 (Peterson et al. 1980; Callanan et al. 1995). Furthermore, we can apply to X1850 − 087 the relation between $L_V$ and $L_X$ found by van Paradijs & McClintock (1994) for other LMXBs with periods between 11 min and several days, i.e.

$$M_V = 1.57(\pm 0.24) - 2.27(\pm 0.32) \log \Sigma,$$

where $\Sigma = (L_X/L_{\mathrm{Edd}})^{1/2}(P/1\ \mathrm{h})^{2/3}$. Taking the relevant values as given in Table 2, and $L_{\mathrm{Edd}} = 2.5 \times 10^{38}$ erg $\mathrm{s}^{-1}$, gives $M_V = 5.1$, $A_V = 1.4$, and finally $V = 20.7$ in agreement, given

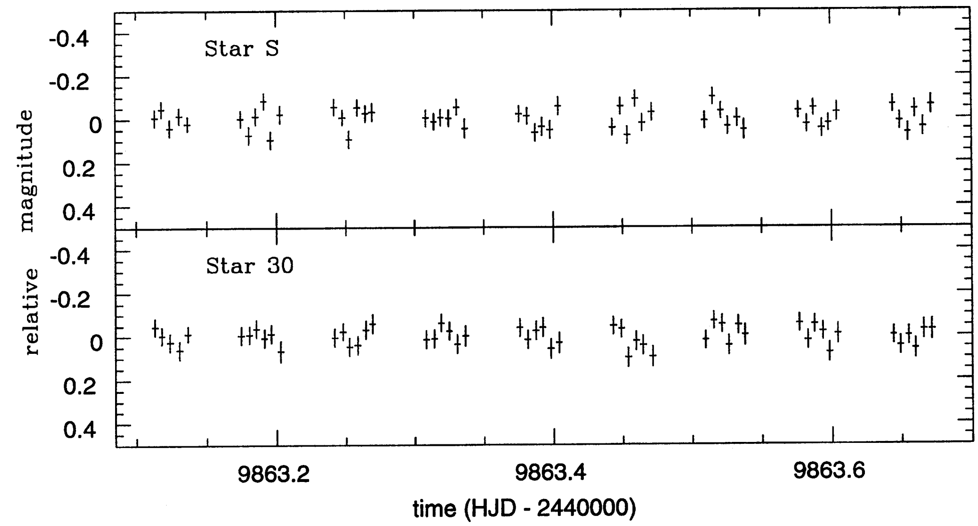

**Figure 3.** Mean subtracted and detrended light curves for the counterpart S of X1850 − 087 and a comparison star. These were generated using aperture photometry in IRAF/DAOPHOT, as described in the text.

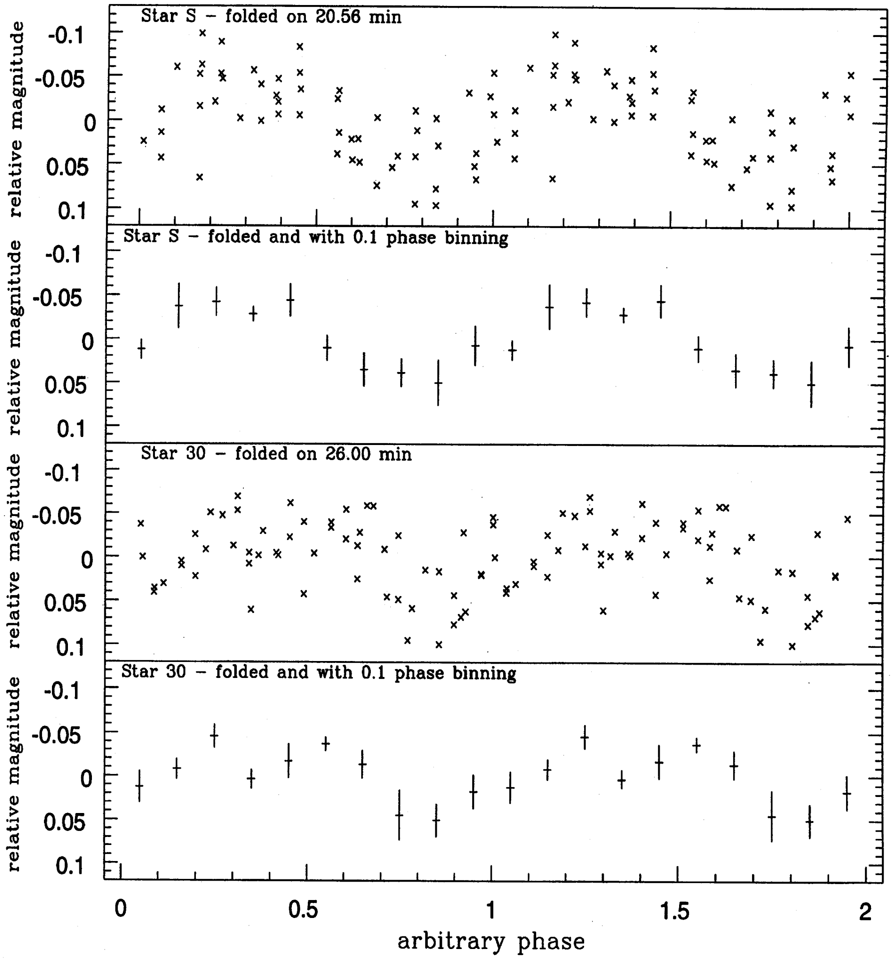

**Figure 4.** Folded light curves of S and the comparison star (on their respective peak periods of 20.56 and 26.00 min). Error bars for the binned light curves are the standard errors for the data points in each bin.

the uncertainties, with the measured value of $V = 20.34 \pm 0.07$.

For this reason we therefore choose to interpret the modulation as being orbital rather than as being the rotation period of the neutron star. However, confirmation of this will require long-term observations to determine accurately the period and its stability.

As to the cause of such an orbital modulation, Arons & King (1993) have proposed that for X1820 – 303 the modulation of the reprocessed UV and optical light is due to a variable contribution from the heated face of the companion, which changes as a function of binary phase. However, in their model the bulk of the reprocessing of X-rays is performed by the outer regions of an optically thick, geometrically thin accretion disc. In contrast, X1916 – 053 is an X-ray dipper (of higher orbital inclination) and the partial eclipsing of a raised bulge or ring on the disc by the companion has been suggested by Grindlay et al. (1988).

Furthermore, we must address the question of the ambiguity arising from the proximity of this 20.6-min period to the Nyquist frequency ($P_{\mathrm{Ny}} \simeq 16$ min). We find that our periodogram can also be perfectly adequately fitted with a sinusoidal modulation at a period of 13.2 min. However, such a short-period is very close to that observed in X1820 – 303, a much more luminous X-ray source. As will be shown later, we believe this greater luminosity to be largely a result of the much higher mass transfer rate, which is driven in very short-period systems by gravitational radiation (Rappaport et al. 1987). If the period of X1850 – 087 is 13 min, then it is under-luminous compared with expectation by almost two orders of magnitude. Whilst this evidence is circumstantial

**Table 1.** Upper limits on the X-ray modulation (*EXOSAT* observations).

| Frequency range sampled (days$^{-1}$) | Energy range (keV) | Upper limit (%)[a] | |
|---|---|---|---|
| | | 70 days$^{-1}$ | 109 days$^{-1}$ |
| 0.1 – 492.2 | 0.8 – 3.6 | 3.5 | 3.8 |
| | 3.6 – 8.9 | 9.4 | 9.0 |
| | 0.8 – 8.9 | 3.3 | 3.2 |

[a] The semi-amplitudes of the modulation that would have been detected at > 99.7 per cent confidence (from another CDF, constructed by the randomization method).

**Table 2.** Properties of the ultra-short-period X-ray binaries.[a]

| Source | $P$ (min) | $\dot{P}$ (s yr$^{-1}$) | $V$ | $E(B-V)$ | Distance (kpc) | $L_X$ ($10^{36}$erg s$^{-1}$)[b] low | high | avg. |
|---|---|---|---|---|---|---|---|---|
| 1627-673 | 41.4 | -0.45[c] | 18.5 | 0.1 | 6[d] | 1.7 | 2.4[e] | 2.1 |
| 1820-303 | 11.4 | $(-3.6\pm0.8)\times10^{-5}$[f] | 18.9[g] | 0.28[h] | 8.1[h] | 19 | 57[i] | 38 |
| 1850-087 | 20.6[j] | - | 20.4[j] | 0.46[h] | 6.8[h] | 0.4 | 1.1[k] | 0.74 |
| 1916-053 | 49.8[l] | - | 21.0 | 0.7 | 10.8[m] | - | - | 6.7 |

[a] van Paradijs 1995 and references therein, unless cited elsewhere.
[b] Approximate low- and high-state values taken from the cited papers, and scaled according to the long-term average, 2–10 keV fluxes as given in van Paradijs 1995.
[c] Levine et al. 1988.
[d] This distance is assumed as it is not well determined (see e.g. Joss, Avni & Rappaport 1978; Levine et al. 1988).
[e] McHardy et al. 1981.
[f] van der Klis et al. 1993b.
[g] van Paradijs & McClintock 1994.
[h] Peterson 1993.
[i] Forman et al. 1978.
[j] This paper.
[k] Cominsky et al. 1977.
[l] X-ray period, cf. optical period of 50.5 min (Callanan, Grindlay & Cool 1995).
[m] Smale et al. 1988.

and by no means definitive, we prefer the 20-min interpretation and shall assume this value in the following sections.

### 5.1 A double degenerate binary?

With a likely total mass of $\simeq 1.5\ \mathrm{M_\odot}$, Kepler's 3rd law implies an orbital separation of 0.28 $\mathrm{R_\odot}$. As X1850 – 087 is a (steady) bright X-ray source, the mass-losing star must be filling its Roche lobe. This allows us to combine Eggleton's (1983) general expression for the ratio $R_2/a$ (equivalent size of the secondary star divided by the binary separation) with Kepler's law to give

$$\frac{R_2}{\mathrm{R_\odot}}=\frac{2.1M_X^{1/3}(1+q)^{1/3}P^{2/3}}{0.6q^{1/3}+q\ln[1+q^{-(1/3)}]},\tag{1}$$

where $q=M_X/M_2$, and the mean density of the secondary is

$$\bar{\rho}=\frac{0.161}{P^2(1+q)}\{0.6+q^{2/3}\ln[1+q^{-(1/3)}]\}^3\ \mathrm{g\ cm^{-3}}.\tag{2}$$

Both of these are plotted in Fig. 5 as a function of the mass ratio $q$. This can be further constrained by following Rappaport et al. (1987) in assuming that the secondary is an $n=3/2$ polytrope whose mass–radius relation is given by

$$\frac{R_2}{\mathrm{R_\odot}}=0.0128(1+X)^{5/3}f\left(\frac{M_2}{\mathrm{M_\odot}}\right)^{-(1/3)},\tag{3}$$

and where we assume that the fractional hydrogen abundance $X=0$ (i.e. it is a pure helium white dwarf) and that $f=1$ (the star is fully degenerate). From these equations we derive a secondary mass of 0.04 $\mathrm{M_\odot}$ and a radius of 0.04 $\mathrm{R_\odot}$ (i.e. a mean density of 910 g cm$^{-3}$), which gives a mass ratio of $q\sim30$ for a canonical 1.4-$\mathrm{M_\odot}$ neutron star.

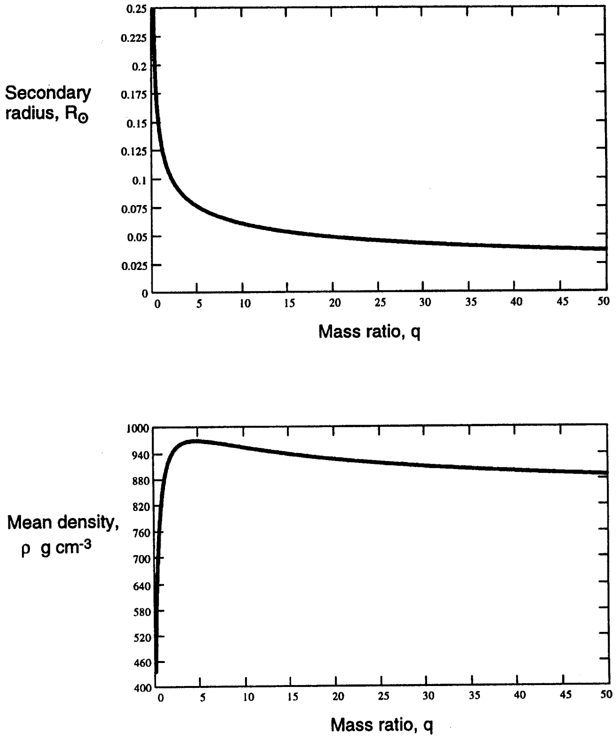

**Figure 5.** Radius (above) and mean density (below) as a function of mass ratio for the secondary star in the X1850 – 087 system, using our measured 20.6-min period. See text for method of calculation.

### 5.2 Comparison with X1820 – 303

The ultra-short period of X1820 – 303 (the shortest period binary system known) requires a double degenerate consisting of a 0.05-$\mathrm{M_\odot}$ helium white dwarf which fills its 0.03-$\mathrm{R_\odot}$

Roche lobe and transfers mass on to its neutron star companion (see Stella et al. 1987). The alternative interpretation is that the modulation is the rotation period of the neutron star, but the high X-ray luminosity (average $\simeq 2.4 \times 10^{37}$ erg s$^{-1}$) requires a mass transfer rate which would then lead to a rapid spin-up of the neutron star, an effect that is not observed. Instead the period change is very slow and requires observations over a very long time-base in order to be detected (Tan et al. 1991). Previously, the principal uncertainty in the double degenerate model has been the fact that it predicts a slow but positive $\dot{P} > 6.0 \times 10^{-5}$ yr$^{-1}$ (Verbunt 1987; Rappaport et al. 1987), whereas a negative value has been measured. However, the most recent analysis by van der Klis et al. (1993b), following observations by *ROSAT*, shows that the period derivative is only slowly negative or possibly even zero, with the uncertainty due to the time-varying shape of the modulation. The location of the source at only 0.026 pc (projected) from the core (King et al. 1993) means that acceleration in the cluster potential can now almost account for the discrepancy (see also van der Klis et al. 1993a). At most, all these uncertainties imply that the model is not well constrained.

As already mentioned, the X-ray emission from X1820 – 303 has been interpreted by Rappaport et al. (1987) as arising from gravitational radiation-driven evolution of the 11.4-min binary. They give the mass transfer rate from the secondary as

$$\dot{M}_2 = 4.14 \times 10^{-4} \left(\frac{M_1}{\mathrm{M}_\odot}\right) \left(\frac{M_1 + M_2}{\mathrm{M}_\odot}\right)^{-(1/3)} \left(\frac{P}{\mathrm{min}}\right)^{-(14/3)} \times (1 + X)^5 f^3 \ \mathrm{M}_\odot \ \mathrm{yr}^{-1}, \qquad (4)$$

in which we take $X = 0$ and $f = 1$ as above. Since the secondary mass in both systems is extremely small, then such a value of $\dot{M}$ gives an X-ray luminosity of

$$L_X = 1.06 \times 10^{38} \left(\frac{M_1}{1.4 \ \mathrm{M}_\odot}\right)^{5/3} \left(\frac{R_1}{10 \ \mathrm{km}}\right)^{-1} \times \left(\frac{P}{11.4 \ \mathrm{min}}\right)^{-(14/3)} \mathrm{erg \ s}^{-1}, \qquad (5)$$

in which we have assumed a 100 per cent efficiency for converting gravitational potential energy into X-radiation and that all the mass lost from the secondary is accreted by the primary (i.e. fully conservative mass transfer). Assuming that the neutron stars in both X1820 – 303 and X1850 – 087 have similar properties, then the key difference in luminosity is driven solely by the $P^{-(14/3)}$ factor. Equation (5) is plotted in Fig. 6, but with the normalizing factor adjusted to account for the peak X-ray luminosity of X1820 – 303; the luminosities of these ultra-short-period binaries are from Table 2. (Note that, unlike most galactic LMXBs, the distances to globular clusters are known to an accuracy of about 30 per cent, thus enabling an accurate comparison of their properties.) Remarkably, equation (5) accounts reasonably well for the relative X-ray output of X1820 – 303 and X1850 – 087 (unless, as is also clear in Fig. 6, the period of X1850 – 087 really is 13 min), but fails significantly for the other ultra-short-period binaries, and implies that they are somewhat different. Whilst this could also be the result of an inaccurate distance determination, it is worth pointing out that X1916 – 053 has exhibited radius expansion bursts which have hitherto been shown to be Eddington limited and hence are assumed to produce an accurate luminosity measurement (Lewin et al. 1995). In fact Nelson et al. (1986) applied detailed evolutionary calculations to X1627 – 673 and X1916 – 053 in an attempt to explain their ultra-short periods, assuming once more that gravitational

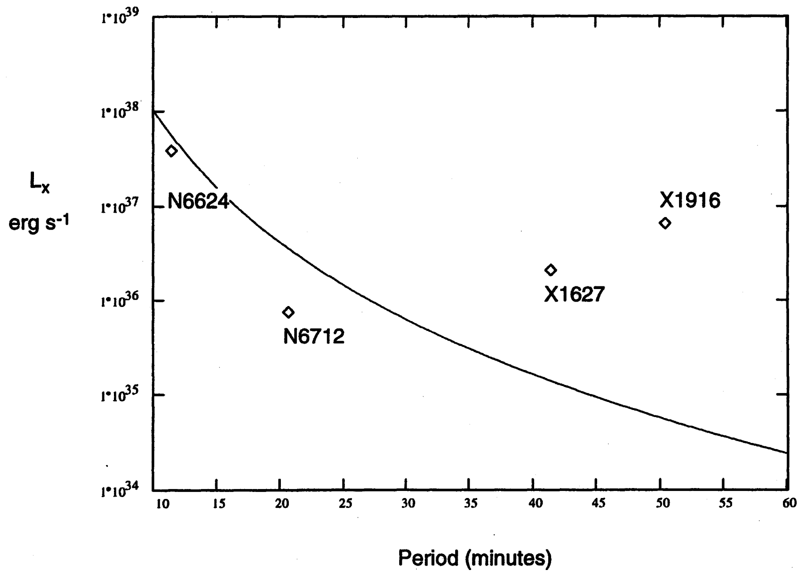

**Figure 6.** Observed X-ray luminosities of the four ultra-short-period systems in NGC 6624 and 6712, X1627 – 673 and X1916 – 053, using data from the catalogue of van Paradijs (1995). The smooth curve (equation 5) shows the expected luminosity as a function of period for a double degenerate system when the mass transfer rate is driven by gravitational radiation. It is scaled according to the peak luminosity of NGC 6624.

radiation (GR) was the only source of angular momentum loss. They found that, although hydrogen-rich systems can only attain periods $\gtrsim 70$ min (Rappaport et al. 1982), the 41- and 50-min periods of these systems and appropriate mass transfer rates (inferred from their X-ray luminosity) could be explained if the companion were evolved and hydrogen depleted with $X \lesssim 0.02$. The star need not be fully degenerate nor burning helium to achieve this. Furthermore, Nelson et al. calculated that the minimum orbital period attainable for a chemically homogeneous but severely hydrogen-depleted secondary ($X \sim 5 \times 10^{-4}$) was $\sim 35$ min, which underlines the fact that X1820 − 303 with $P = 11$ min (and now X1850 − 087 with $P < 20.6$ min) cannot have a non-degenerate hydrogen secondary.

Recent investigations into the effects of the X-ray irradiation of the secondary (Podsiadlowski 1991; Harpaz & Rappaport 1991; Harpaz & Rappaport 1994) have indicated another method of attaining a higher mass transfer rate (at least over a sufficiently long time-scale) without invoking an evolved companion. They show that irradiation may drive cyclical variations in the transfer rate. Hence the difference shown in Fig. 6 between the galactic ultra-short-period binaries and those in globular clusters could be the result of the fact that (i) in the globular cluster systems, GR is the dominant angular momentum loss mechanism, and (ii) the *average* accretion rate of the two galactic systems is driven by GR losses, but they also undergo cycles of high and low mass transfer rates. If, as seems most popular, cycles associated with the secondary star are responsible for driving the variations, these results would suggest that as the envelope of the star becomes increasingly degenerate, these cycles may disappear.

## ACKNOWLEDGMENTS

We are grateful to Bruce Margon for some useful comments on an early version of this paper and for sending us preprints in advance of publication, and to the referee, Frank Verbunt, for comments that significantly improved the paper. We would also like to thank Darragh O'Donoghue for providing his time-series analysis programs, which were particularly useful in performing the differential photometry. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA-Goddard Space Flight Center; the work is based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy Inc., under NASA contract NAS 5-26555. LH acknowledges the support of a PPARC studentship. TN acknowledges the support of a PPARC Advanced Fellowship.

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