Evidence for a 2 hr Optical Modulation in GS1826-24

L. Homer¹, P. A. Charles¹, D. O’Donoghue²,³

¹Department of Astrophysics, Nuclear Physics Lab., Keble Road, Oxford OX1 3RH
²Department of Astronomy, University of Cape Town, Rondebosch 7700, Cape Town, South Africa
³South African Astronomical Observatory, PO Box 9, Observatory 7935, Cape Town, South Africa.

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ABSTRACT
We report the discovery of a 2.1 hr optical modulation in the transient source GS1826-24, based on two independent high time-resolution photometric observing runs. There is additional irregular variability on shorter timescales. The source also exhibited an optical burst during each observation, with peak fluxes consistent with those of the three X-ray bursts so far detected by BeppoSAX. We compare the low-amplitude variation (≈ 0.06 mCrab) to that seen on the orbital periods of the short period X-ray bursters, X1636-536 and X1735-444, as well as the similarity in their non-periodic fluctuations. Other transient neutron star LMXBs possess short periods in the range 3.8-7.1 hrs. However, if confirmed as the orbital, a 2.1 hr modulation would make GS1826-24 unique and therefore of great interest within the context of their formation and evolution.

Key words: binaries: close - stars: individual: GS1826-24 X-rays: stars

1 INTRODUCTION
GS 1826-24 was discovered serendipitously in 1988 by the Ginga LAC during a satellite manoeuvre (Makino et al. 1988). The source had an average flux level of 26 mCrab (1-40 keV), and a power law spectrum with α = 1.7. Observations both a month before and after by the Ginga ASM, by TTM in 1989 (In’t Zand 1992) and by ROSAT in 1990 and 1992 (Barret, Motch & Pietsch 1995) found comparable flux levels. Temporal analyses of both the Ginga detection and ROSAT data yielded a featureless f^−1 power spectrum extending from 10^{-4} – 500 Hz (Tanaka & Lewin 1995; Barret, Motch & Pietsch 1995), with neither QPO nor pulses being detected.

Despite its detection by Ginga, the source had not been previously catalogued. Neither were X-ray bursts detected by Ginga. Together with its similarities to Cyg X-1 (hard X-ray spectrum, strong flickering), this led to an early suggestion by Tanaka (1989) that it was a soft X-ray transient with a possible black-hole primary. Later, Strickman et al. (1996) called this suggestion into doubt, following examination of data from CGRO/OSSE observations. They found that fitting both the Ginga and OSSE spectra produced a model with an exponentially cutoff power law plus reflection term. The observed cut-off energy of ≈58 keV is typical of the cooler neutron star hard X-ray spectra. The recent report of three X-ray bursts detected by BeppoSAX (Ubertini et al. 1997) and our detection of optical bursts here confirms the presence of a neutron star accretor.

Following the first ROSAT/PSPC all-sky survey observations in September 1990, and the determination of a preliminary X-ray position, a search for the counterpart yielded a time variable, UV-excess, emission line star (Motch et al. 1994; Barret, Motch & Pietsch 1995). This source had B = 19.7 ± 0.1, and an uncertain V magnitude of V ≈ 19.3, due to contamination by a nearby star. There was also evidence for ≈ 0.3” variations on a one hour timescale, but the time sampling was fairly poor. For this reason, we included this object in our target list for a high-speed photometry run at the South African Astronomical Observatory (SAAO). Further time-series photometry was also obtained on the William Herschel Telescope, La Palma (WHT) to confirm the variability that was seen.

2 OBSERVATIONS AND DATA REDUCTION
2.1 SAAO 1996 June

Observations of a small (50x33 arcsecs) region surrounding the optical counterpart to GS1826-24 were made using the UCT-CCD fast photometer (O’Donoghue 1995), at the Cassegrain focus of the 1.9m telescope at SAAO, Sutherland on 1996 June 20. The UCT-CCD fast photometer is a Wright Camera 576x420 coated GEC CCD which was used here half-masked so as to operate in frame transfer mode, allowing exposures of as short as 1s with no dead-time. We observed from UT 00:03:27 to UT 04:15:15, obtaining 1507 consecutive 10s exposures. The conditions were generally good, being almost photometric, and the mean seeing was ≈1.5 arcsec. However, problems with telescope focus drift...
Owing to the variable seeing conditions and problems with telescope focus drift during the run, a small portion of the SAAO data is of poor quality. Hence, before subsequent analysis those data points corresponding to frames with estimated seeing $>$2.5 arcsecs were deleted. The resulting 4.19 hour and 3.26 hour duration lightcurves for the optical counterpart to GS1826-24 and a suitable star of comparable brightness are shown in Fig. 2, with a quadratic de-trend applied. Two features are immediately apparent: two very clear optical bursts, and evidence for short-term variations in brightness.

3 OPTICAL BURSTS

A simple burst profile consisting of a linear rise, plus exponential decay was fitted to a 1200s section of each lightcurve including the bursts (as shown in Fig. 2). When fitting the burst a number of different models were used for the variable persistent flux; a double sinusoid constrained to fit the entire lightcurve and a linear or a quadratic baseline over the 1200s section, however the burst parameters were found to be insensitive to the model chosen. The time sampling (10 and 25s at SAAO and WHT respectively) was adequate to constrain the decay of the burst, but not the fast rise and hence peak flux. We can therefore only place limits. The fit to the SAAO June 1996 burst (reduced $\chi^2 = 1.6$ for 113 d.o.f.) yielded the following parameters: rise time $< 20$ s, e-folding decay time $= 53.3 \pm 2.7$ s, $\Delta F_{\text{opt}} = 1100\text{cts s}^{-1}$ (i.e. 2.0 x average flux). Similarly for the WHT August 1997 burst (reduced $\chi^2 = 0.8$ for 29 d.o.f.), we obtained a rise time $< 65$ s, e-folding decay time $= 69.5 \pm 4.3$ s, $\Delta F_{\text{opt}} = 390\text{cts s}^{-1}$ (note: constraining the rise time to $< 20$ s gives $\Delta F_{\text{opt}} = 500\text{cts s}^{-1}$, i.e. 2.4 x average flux). The results are summarised in Table 3.

Many optical bursts have been detected from the X-ray burster X1636-536 (see e.g. Pedersen et al. 1982). In general, they exhibit a wide range of peak fluxes and profiles, with $F_{\text{max}}/F_{\text{opt}} = 1.4 - 4.8$ (in white light) and typical decay times $\sim$few tens of seconds. Clearly, the bursts from GS1826-24 are not dissimilar.

Lastly, we may compare the corresponding X-ray peak fluxes of these optical bursts to those of the bursts detected by BeppoSAX (Ubertini et al. 1997), using the results of Lawrence et al. 1983. They derived a simple power law relation between the changes in the U, B and V band fluxes and corresponding X-ray flux variations during a well-studied burst of X1636-536, with

$$\left(\frac{F_{\text{X, max}}}{F_{\text{X, pers}}}ight) = \left(\frac{F_{\text{opt, max}}}{F_{\text{opt, pers}}}ight)^\alpha,$$

where $\alpha$ varies with the passband.

The results of these calculations are presented in Table 4, where we use the $\alpha$ value for V as an approximation for the white light observations. The peak fluxes measured by BeppoSAX range from 350 to 520 mCrab, hence our lower limits of 190 and 270 mCrab imply consistency.

4 SHORT PERIOD MODULATIONS

Firstly, we detrended the extracted light curves for each of the stars using quadratic fits. In the case of GS1826-24 the data points corresponding to the burst were also excluded. The maximum of the subtracted polynomial was constrained...
Evidence for a 2 hr Modulation in GS1826-24

Figure 1. Images showing the field of GS1826-24 (North up, East to the left): 10s white light exposure from SAAO June 1996 - 49x33 arcsecs field of view (left), 25s B band exposure from WHT 1997 - 33x33 arcsecs field of view (right). The optical counterpart and the bright stars used for PSF fitting are labelled in each case.

Figure 2. Lightcurves of GS1826-24 and star of comparable brightness. a) High speed photometry in white light from SAAO with 10s resolution, b) conventional B band photometry from WHT with 35s time resolution.

Table 1. Fitted parameters of a simple burst profile, with linear rise-time and exponential decay

| Date          | Time (UT) | Rise time (s) | $\Delta F_{opt}$ (cts s$^{-1}$) | $\Delta F_{opt}$ (cts s$^{-1}$) | Reduced $\chi^2$ |
|---------------|-----------|---------------|---------------------------------|---------------------------------|------------------|
| 20 June 1996  | 02:18     | < 20          | 1100                            | 53.3 ± 2.7                      | 1.55 (113 d.o.f) |
| 1 August 1997 | 01:02     | < 65          | 390                             | 69.5 ± 4.3                      | 0.8 (29 d.o.f.)  |
|               |           | < 20          | 500                             | 69.1 ± 2.8                      | 0.9 (29 d.o.f.)  |
Figure 3. Optical burst lightcurves (symbols) plus model fit (dashed line). a) High speed photometry in white light from SAAO with 10s resolution, b) conventional B band photometry from WHT with 35s time resolution. The limiting model parameters are adopted with a rise time of 20s in each case.

Table 2. Calculation of the peak X-ray burst flux corresponding to the two optical bursts of GS1826-24

| Date        | Passband | $\alpha$ | $\Delta F_{opt}$ (cts s$^{-1}$) | $\left(\frac{F_{opt,max}}{F_{opt,pers}}\right)$ | $F_{X,pers}$ (mCrab) | $F_{X,max}$ (mCrab) |
|-------------|----------|----------|-------------------------------|--------------------------------|-----------------------|---------------------|
| 20 June 1996| White light | 2.8      | > 1100                        | 2.0                          | 27                    | > 190               |
| 1 August 1997| B        | 2.55     | > 500                         | 2.35                         | 31                    | > 270               |

* Estimates of persistent flux taken from the XTE/ASM 2-10keV one-day average on the observation date

to the time of least airmass for the field, ensuring reasonable compensation for the slow variations due to airmass changes. To search for periodic modulations two different methods were employed: (i) we calculated a Lomb-Scargle (LS) periodogram routine on each data set, to search for sinusoidal modulations (this periodogram is a modified discrete Fourier transform (DFT), with normalisations which are explicitly constructed for the general case of time sampling, including uneven sampling, see Scargle 1982); (ii) we constructed a phase dispersion minimisation periodogram (PDM), which works well even for highly non-sinusoidal light curves (see Stellingwerf 1978).

The resultant LS periodograms for both GS1826-24 datasets show distinct peaks at close to 11.5d$^{-1}$ ($P = 2.1$ hr) (see Fig. [Fig. 4]). The exact measured frequencies are $11.0 \pm 0.2$ d$^{-1}$ and $12.0 \pm 0.4$ d$^{-1}$ for the SAAO and WHT lightcurves respectively, with semi-amplitudes of 0.05m and 0.07m for a fitted sinusoid. Although the frequencies are only
Evidence for a 2 hr Modulation in GS1826-24

Figure 4. Lomb-Scargle Periodograms (left) Phase-Dispersion Minimisation Periodograms (right) for GS1826-24 lightcurves from a) SAAO and b) WHT with bursts excluded. The PDM plots have been truncated at the lowest frequencies corresponding to the reciprocal of the data duration.

marginally consistent (at \(\approx 2\sigma\) level) within the formal random errors quoted, it must be noted that the datasets span only 2.0 and 1.6 cycles, with airmass changes of 1.0-2.4 and 1.6-2.0 respectively, and hence the precision of the period determination is limited to \(\pm 0.8\text{d}^{-1}\) according to the exact form of detrending used. The formal confidence of these peak frequencies are greater than 99.98 per cent, as determined from a cumulative probability distribution (CDF) appropriate for the dataset (see Homer et al. 1996 section 3 for details of the method employed). There are also significant peaks at the higher frequencies of 25.9 \(\pm 2.3\text{d}^{-1}\), 33.4 \(\pm 0.25\text{d}^{-1}\) (\(P = 55.7\pm 0.5\text{ min}\), \(P = 43.1\pm 0.3\text{ min}\) [SAAO] and 21.4 \(\pm 0.45\text{d}^{-1}\) (\(P = 67.3\pm 1.6\text{ min}\) [WHT] corresponding to the shorter timescale variations. The results of PDMs confirm those of the Fourier analysis, with peaks occurring at 11.5d\(^{-1}\) and 11.0d\(^{-1}\), corresponding to the longer periods and also at 25.8d\(^{-1}\), 32.8d\(^{-1}\) and 21.2d\(^{-1}\) (see Fig. 4).

We also examined the LSP results for stars of comparable brightness. None of the four in the SAAO dataset exhibit any peak on 2-3 hr timescales with amplitude greater than 0.015\(m\), nor do these variations bear any phase relationship with the 2hr modulation seen in GS1826-24. Since the brightest stars in the field also show such small scale variations, they are consistent with the small amplitude atmospheric transparency variations found at SAAO, enhanced by the effect of poorer photometry during the interval of inferior seeing.

Similarly, the largest peak in the 2-3 hr range shown by the 3 check stars in the WHT dataset corresponds to a very low (0.007\(m\)) amplitude modulation. Again this is most probably atmospheric in origin.

In any case, the presence of the 2hr modulation of GS1826-24 in both datasets provides convincing evidence of its reality. Nevertheless, the short data span and the complication of additional variability makes it impossible to constrain the stability of the modulation and hence identify it categorically as orbital in origin. Longer time base observations of this object are clearly necessary.

5 DISCUSSION

The period distribution of low-mass X-ray binaries (LMXB) has shown a scarcity of systems below 3 hr presumably in part due to their faintness, but there is a notable absence of any systems with periods between \(\sim 1\) and 3 hr (White 1985;
White & Mason 1985). Recently, King & Kolb (1997) have investigated the formation of neutron star LMXBs. They found that in order to produce the relatively large fraction of soft X-ray transients in the $\lesssim 1$-2 day range, the secondaries must have $1.3 M_\odot \lesssim M_2 \lesssim 1.5 M_\odot$ at the onset of mass transfer and be significantly nuclear evolved (provided that the SN kick-velocity is small compared to the pre-SN orbital velocity). This mass range ensures that the mass transfer rates driven by angular momentum loss are below the critical velocity. This mass range also ensures that the mass transfer and be significantly nuclear evolved (provided that the SN kick-velocity is small compared to the pre-SN orbital velocity).

However, in many respects GS1826-24 does show similarities to other neutron star binaries with comparable periods. The X-ray bursters X1636-536 and X1735-444 exhibit optical modulations of a similar amplitude on their orbital periods (3.80 and 4.65 hr respectively), plus irregular variability on somewhat shorter timescales. The optical emission of LMXBs is dominated by the reprocessed X-rays from the accretion disc and companion. The origin of the underlying sinusoidal modulation is interpreted as the varying contribution from the X-ray heated face of the companion star (van Paradijs & McClintock 1995). As for the irregular variability, this is probably caused by changes in the spatial distribution of the reprocessing material in the accretion disc and/or fluctuations in the central X-ray luminosity, as suggested in the case of X1636-536 (van Paradijs et al. 1990). Moreover, GS1826-24 has a high $L_X/L_{opt}(\sim 500)$, very similar to that of the compact 41 min binary X1627-673, but lower than the $L_X/L_{opt} \sim 700$ of the 50 min binary X1916-053, which is a higher inclination dipping source (once again these are persistent sources). Since this ratio is related in part to the physical size of the system and the disc reprocessing area available, the similarity supports the hypothesis that GS1826-24 is also a relatively compact system.

Furthermore, the non-detection of GS1826-24 prior to 1988 is characteristic of the observed variability of the transient bursting systems X0748-678, X1658-298 and X2129+470 (White, Nagase & Parmar 1995), which have either been detected over many years and then gone into quiescence for a similar period of time or vice-versa. These transients all have known periods in the range 3.82-7.1 hrs (see Table 3).

Clearly, further high-speed optical photometric monitoring is required in order to confirm the stability of the 2hr modulation and hence its orbital origin. With only a short ROSAT lightcurve published to date (Barret, Motch & Pietsch 1995), confirmation might be possible from a longer X-ray observation. However, the low-amplitude of the observed modulation (0.06") implies a low-inclination system (< 70°), and hence X-ray dipping behaviour is unlikely to be seen.

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