The optical ephemeris and X-ray variability of 4U 1735–44 (V926 Sco)

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ABSTRACT
Optical observations of the low mass X-ray binary 4U 1735–44 were obtained during 1997 – 2007 and combined with earlier published observations from 1984 – 1993 to refine the ephemeris for the system. The linear fit for the time of maximum optical light has the ephemeris HJD = 2445904.0494(90) + [ N \times 0.19383222(29) ] with a value of $\chi^2 = 253.5$ for 16 dof and a scatter about phase zero of $\sigma = 0.061$. The new data reconciles the discrepancy between the previous ephemeris and the more recent spectral ephemeris, based on emission from the companion star, which defined the systems true dynamical phase zero. The optical maximum for 4U 1735–44 now occurs at spectral phase $0.47 \pm 0.05$ and thus supports the classic model for an LMXB system. Our data further supports the standard model in several ways. The mean optical flux shows a positive correlation with the RXTE ASM X-ray flux, the relative increases suggesting that the non-X-ray induced optical flux from the companion is $\lesssim 14$ percent of the total optical light from the system. There is no apparent trend in the optical modulation percentage with increasing X-ray flux. The X-ray flux for various ASM energy bands shows no evidence of orbital modulation, eclipses or dips when folded using the new ephemeris.

Key words: accretion, accretion discs – binaries, close – stars: individual: 4U 1735–44 – X-rays, binaries.

1 INTRODUCTION
Millisecond oscillations in the X-ray brightness of low mass X-ray binaries (LMXB) have been observed for a large and growing number of sources since the launch of the Rossi X-ray Timing Explorer (RXTE) in late 1995. A review of those sources which exhibit nearly coherent oscillations during their Type I X-ray bursts, a class that includes 4U 1636–53, can be found in Strohmayer (2001). The larger group that exhibit quasi-periodic oscillations only during their quiescent non-bursting state, a class that includes 4U 1735–44, have been reviewed by Van der Klis (2000). Relatively few of the non-transient X-ray sources exhibiting kHz oscillations have permanent optical counterparts but the similar systems 4U 1735–44 and 4U 1636–53 are ideal for studies at optical wavelengths with small telescopes. The many similarities of these two systems are discussed in Casares et al (2006) and references therein and will not be repeated here.

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A more general summary of the many known X-ray emitting accreting neutron stars can be found in Watts et al. (2008).

In 1997 we commenced a program of occasional monitoring of 4U 1735–44 and 4U 1636–53. The initial thrust of this work was twofold in nature. One program was to obtain an updated ephemeris for 4U 1636–53 and to use this to examine the binary phases of a large sample of X-ray bursts observed with RXTE. The intention was to search for possible Doppler shift modulations in the bursts kHz oscillation frequency induced by the orbital motion of the neutron star. This work has been reported by Giles et al. (2002). The initial start on 4U 1735–44 was part of a coordinated program in 1997 to observe simultaneous X-ray and optical bursts but no X-ray burst were seen (RXTE observation 20084). In this paper we present our data and results for CCD optical photometry of the 4U 1735–44 system obtained since 1997.

The optical counterpart of 4U 1735–44, V926 Scorpii, has been observed on a number of occasions since its identification in 1977 by McClintock et al. (1977). A collection of all these photometric data, covering the interval from 1984 July to 1993 August, was compiled by Augusteijn et al. (1998) (see references therein) to derive an accurate photometric ephemeris. Detailed spectroscopic studies have been

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To look for possible correlated changes. In our new optical data to revise the Augusteijn et al. (1998) ephemeris, effectively defining a dynamical phase zero, by 2 A. B. Giles and K. M. Hill

### Table 1. Optical observations of 4U 1735–44.

| Obs. No. | Date      | HJD Start (-2450000) | HJD End (-2450000) | Filter | Integration Time (s) | Number of Exposures |
|---------|-----------|----------------------|--------------------|--------|-----------------------|---------------------|
| 1       | 1997 Aug 1 | 661.92966            | 662.13406          | V, I   | 120                   | 64                  |
| 2       | 1997 Aug 29| 689.89771            | 690.08805          | V, I   | 60                    | 115                 |
| 3       | 1999 Sep 16| 1437.89914           | 1438.11925         | V      | 150                   | 93                  |
| 4       | 1999 Sep 20| 1441.89958           | 1442.11134         | V      | 300                   | 52                  |
| 5       | 2000 May 25| 1689.90368           | 1690.30974         | V      | 300                   | 92                  |
| 6       | 2001 Jul 3 | 2093.89874           | 2094.32339         | V      | 300                   | 110                 |
| 7       | 2001 Jul 4 | 2094.90880           | 2095.31425         | V      | 300                   | 111                 |
| 8       | 2004 May 7 | 3133.09892           | 3133.34262         | V      | 300                   | 63                  |
| 9       | 2004 May 14| 3139.92629           | 3140.35182         | V      | 300                   | 115                 |
| 10      | 2004 May 15| 3141.01611           | 3141.18857         | V      | 300                   | 46                  |
| 11      | 2005 May 12| 3502.95212           | 3503.33362         | V      | 300                   | 80                  |
| 12      | 2005 May 13| 3503.92808           | 3504.31953         | V      | 300                   | 106                 |
| 13      | 2007 Apr 20| 4211.00317           | 4211.19962         | V      | 300                   | 51                  |
| 14      | 2007 May 12| 4231.92835           | 4232.34208         | V      | 300                   | 58                  |

\[\text{Table 2. Sine curve fits, times of maximum optical light and RXTE ASM X-ray data for 4U 1735–44.}\]

| Obs. No. | Cycle Number (N) | HJD Start (-2450000) | Error (d) | Amplitude \(V\) mag. | Mean \(\Delta V\) mag. | ASM Daily X-ray Flux Units \(\text{cm}^{-2}\) | No. ASM Dwell |
|----------|------------------|----------------------|-----------|-----------------------|-----------------------|-----------------------------------------------|---------------|
| 1        | 24547            | 662.0435            | 0.0046    | 0.188 ± 0.028         | 1.190 ± 0.010         | 8.97 ± 0.50                                    | 0             |
| 2        | 24561            | 689.9535            | 0.0018    | 0.254 ± 0.017         | 1.335 ± 0.006         | 12.89 ± 0.28                                   | 8             |
| 3        | 28550            | 1437.9459           | 0.0021    | 0.236 ± 0.018         | 1.345 ± 0.006         | 10.81 ± 0.43                                   | 7             |
| 4        | 28571            | 1442.0236           | 0.0032    | 0.180 ± 0.016         | 1.375 ± 0.007         | 13.25 ± 0.23                                   | 10            |
| 5        | 29851            | 1690.1214           | 0.0046    | 0.116 ± 0.016         | 1.421 ± 0.006         | 12.97 ± 0.42                                   | 9             |
| 6        | 31935            | 2094.0484           | 0.0030    | 0.183 ± 0.018         | 1.499 ± 0.006         | 10.98 ± 2.48                                   | 1             |
| 7        | 31940            | 2095.0451           | 0.0030    | 0.145 ± 0.014         | 1.216 ± 0.005         | 12.35 ± 0.50                                   | 6             |
| 8        | 37296            | 3133.2238           | 0.0022    | 0.193 ± 0.012         | 1.152 ± 0.005         | 17.85 ± 0.47                                   | 0             |
| 9\text{a} | 37337            | 3141.1581           | 0.0019    | 0.282 ± 0.015         | 1.202 ± 0.006         | 18.89 ± 0.37                                   | 2             |
| 10       | 39204            | 3503.0260           | 0.0058    | 0.114 ± 0.022         | 1.183 ± 0.008         | 17.25 ± 0.43                                   | 0             |
| 11       | 39209            | 3504.0359           | 0.0022    | 0.217 ± 0.016         | 0.964 ± 0.005         | 16.76 ± 0.41                                   | 8             |
| 12       | 42857            | 4211.1238           | 0.0033    | 0.253 ± 0.027         | 1.299 ± 0.010         | 14.64 ± 0.51                                   | 3             |
| 13       | 42965            | 4232.0368           | 0.0045    | 0.179 ± 0.027         | 1.314 ± 0.011         | 12.94 ± 0.39                                   | 13            |

\[\text{a Observation not suitable for a sine curve fit.}\]

reported by Smale & Corbet (1991), Augusteijn et al. (1998) and Casares et al. (2006). This latter observation of 4U 1735–44 (and 4U 1636–53) is particularly relevant for the latter discussion as it established an important spectroscopic ephemeris, effectively defining a dynamical phase zero, by observing emission from the optical donor star.

The paper is organised as follows. In Section 2 we report new photometric light curves of 4U 1735–44 obtained over the period 1997 August to 2007 May. In Section 3 we use our new optical data to revise the Augusteijn et al. (1998) ephemeris and in Section 4 we explore aspects of the historical X-ray data to look for possible correlated changes. In Section 5 we briefly discuss the 4U 1735–44 system based on our new observations.

## 2 Optical Observations

All the optical observations were made between 1997 and 2007 using the 1-m telescope at the Mt. Canopus Observatory, University of Tasmania. The observations used standard Johnson V and I filters and the CCD reduction procedure was identical to that described in Giles, Hill & Greenhill (1999). All times presented in this paper have been corrected to Heliocentric Julian Dates (HJD) and a complete journal of the observations is given in Table 1. Throughout this paper, except when discussing spectroscopic observations, phase zero is defined as superior conjunction of the companion star (neutron star closest to the Earth) when the system optical flux is at a maximum.

All the images were reduced with between 3–7 nearby stars being used as local standards. However, the light curves in Fig. 1 plot the differential magnitude between 4U 1735–44 and only one of these stars which can be located on the finder chart in Jernigan et al. (1977). This brighter secondary standard is star number 6 on their 2S1735–444 chart which we find to have a \(V\) magnitude of 16.10 ± 0.02. 4U 1735–44 is star number 5 on this same chart and is \(\sim 1.4\) mag fainter. For the 1997 observations the telescope was equipped with an SBIG CCD camera having 375 x 242 pixels with an image scale of 0.42 × 0.49 arcsec pixel\(^{-1}\). On the nights of 1997 August 1 and 29 continuous pairs of \(V\) and I integrations were obtained but the I-band data are not discussed further.
in this paper. For the 1999 and later observations the telescope was equipped with a SITe CCD camera having 512 x 512 pixels with an image scale of 0.42 arcsec pixel\(^{-1}\).

The entire data set represented in Tables 1 and 2 are plotted in Fig. 1. Observation 9 has no clear modulation and has therefore not been fitted with a sine curve. The data are included since the mean level is used in section 4 of this paper and it also illustrates this unmodulated state at the time of highest X-ray flux. Observation 12 is also interesting as it appears to show two cycles containing a definite dip, midway in phase between maximum brightness.

### 3 OPTICAL MAXIMUM EPHEMERIS

The ephemeris for times of maximum optical light given by Augusteijn et al. (1998) was $HJD = 2447288.0143(25) + [N \times 0.19383351(32)]$ where the errors are indicated in the round brackets ($\pm \sigma$) and $N$ is the cycle number starting from zero. This ephemeris was based on observations made between 1984 July 22 and 1993 July 28 and covered a total of 16,986 binary periods. We have fitted a sine curve to each new night’s observations listed in Table 1 taking the amplitude, phase and mean as free parameters but fixing the binary period at the value given by Augusteijn et al. (1998). The appropriate sine curve fits are shown as solid traces through the respective data points in Fig. 1. From these fits we derive the times of optical maxima, peak-to-peak ampli-
tudes and mean intensities listed in Table 2. This table is intended to be complimentary to the similar table 3 of Augusteijn et al. (1998) and continues the same cycle number sequence.

The predictions from the previous Augusteijn et al. (1998) ephemeris are also shown on Fig. 1 as the dotted traces in the lower part of each light curve panel. There is a significant phase shift evident between the two sets of sine curves. The new observed maxima also fall increasingly earlier than expected, indicating a different period, over the additional ~25,979 binary periods to 2007 May. However, a quick examination shows that the earlier period was close enough to avoid any cycle count ambiguity through the new data sets and, as stated earlier, the previous cycle sequence is maintained in Table 2.

We then used our new data, together with the data in table 3 of Augusteijn et al. (1998,) to perform the usual $O - C$ analysis on the entire data set and the results are plotted in Fig. 2. Our new linear fit for the time of maximum optical light has the ephemeris HJD = 2452813.495(3) + [ N × 0.19383222(29) ] with a value of $\chi^2$ = 253.5 for 16 dof and a mean phase scatter about phase zero of 0.061. The relatively poor $\chi^2$ value reflects the intrinsic scatter of the data points rather than their error bars. Deriving a highly accurate and reliable ephemeris for systems like 4U 1735–44 (and 4U 1636–53) is not simple due to the lack of any sharp eclipse type feature in the optical light curve and the fact that the profile is quite variable from cycle to cycle. For these reasons and the ‘noise’ in the scatter of the $O - C$ values in Fig. 2, there is still no significant period derivative term. An upper limit for the $P$ term gives $| P/\dot{P} | \lesssim 6.5 \times 10^6$ yr.

Until relatively recently it had proved impossible to reliably identify features in the optical spectrum of 4U 1735–44 that originated from the irradiated donor companion star which could be used to define a dynamical phase zero. This has been achieved for a number of LMXB systems by following the Bowen transition feature and Casares et al. (2006) have obtained a spectroscopic based ephemeris for 4U 1735–44 using observations made in 2003 June. Phase zero, in this spectral definition, corresponds to inferior conjunction of the companion (donor) star and occurs at HJD = 2452813.495(3) + [ N × 0.19383222(32) ] where the period was taken as the Augusteijn et al. (1998) value. Note that this definition has a 0.5 phase shift with respect to that used for optical intensity. Our new photometric ephemeris places the optical maximum at a phase of 0.47 ± 0.05 on this spectral ephemeris.

Since the spectral ephemeris date falls well within the sequence of new optical observations (see Fig. 3) the phase zero error in our new optical ephemeris is primarily due to the uncertainty in defining when the optical maximum occurs rather than to period uncertainty accumulations or the spectral phase zero error.

4 OPTICAL - X-RAY CORRELATIONS

Since our data set spans an ~10 year interval and overlaps with much of the duration of the RXTE mission we have also examined the All Sky Monitor (ASM) (Levine et al. (1996)) database to look at the X-ray light curve history for 4U 1735–44. Fig. 3 shows this data together with the dates on which our optical observations were made.

We have attempted to extract the ASM fluxes corresponding to the exact times of the observations listed in Table 1 in order to compare them to the corresponding optical intensities and amplitude modulations listed in Table 2. ASM X-ray fluxes can be obtained as individual dwell cycle values, effectively 90 s integrations, or as daily averages which are summations of all the dwell cycles falling within 24 h intervals. Unfortunately, due to a combination of orbital and aspect constraints, the dwell cycle values for 4U 1735–44 occur in irregularly spread groups with gaps containing no observations. Although daily values are virtually always available they may be calculated from data within 24 h intervals that fall outside the precise span of any particular...
For the analysis we have chosen to use daily values as many optical nights have few or no dwell cycles. A visual inspection of the appropriate ASM data sections suggests that, in general, the daily values represent reasonable local estimates even where they do not overlap with the optical data. Any effort to be more selective rapidly becomes problematic and rather arbitrary in nature. Fig. 4 shows that there is a roughly linear trend between the X-ray flux and the optical intensity with the optical source brightening, as expected, when the X-ray flux increases. The linear fit, to the all the observations, has a value of $\chi^2 = 93.9$ for 12 dof and a modest correlation coefficient of 0.64. The slope of the line gives a $\Delta$ optical increase of 59 percent (0.5 mag.) for a $\Delta$ X-ray increase of 69 percent. This suggests that the non-X-ray induced optical flux from the companion is $\lesssim$ 14 percent of the total light from the system as expected from a late type dwarf star.

In contrast, there is no apparent correlation between the X-ray flux and the amplitude modulation for 4U 1735–44 in Fig. 5 though the modulation error bars are relatively large in this case. Perhaps only observation 1 seems to stand outside the general linear trend in Fig. 4 and this happens to be both the oldest optical data and also has no contained ASM dwell cycles. However, the daily X-ray flux value appears to be consistent with that for adjacent days and dwell cycles and the relative values of the various calibration stars on this night are also consistent with the many later CCD sequences.

The entire ASM data set has been folded, modulo the period, using the new ephemeris and there is no evidence for any orbital modulation, dips or eclipses. This applies for combined energy bands (A+B+C) as well as just the low (A, 1.5–3 keV) and high (C, 5–12 keV) bands. This is also true whether the data is selected for when the source is bright (above the mean for the whole record) or weak (below the mean).

5 DISCUSSION

In the traditional model of an LMXB system there are three regions which contribute to its optical variability due to X-ray heating. These are the accretion disc itself, a bright hot spot or bulge on the outer edge of the accretion disc due to the impact of inflowing material and the hemisphere of the companion facing the neutron star which is not shadowed by the accretion disc. For most LMXB systems the reprocessed X-ray optical flux is assumed to come from the facing hemisphere of the companion star and to dominate the optical light from the rest of the system (van Paradijs 1983, van Paradijs & McClintock 1995). The optical maximum was therefore assumed to occur when the companion was on the far side of the neutron star but variations about the mean modulation profile were expected due to gas flows causing various X-ray shielding effects (Pedersen et al. 1982). Since the magnetosphere of the neutron star in the 4U 1735–44 system is so small the Roche lobe overflow through the inner Lagrange point (L1) must form a standard Keplerian accretion disc (Frank, King & Raine, 1992).

Smale & Mukai (1988) investigated the optical flux and modulation created by the persistent X-ray heating of the companion’s facing hemisphere, and although they assumed this scenario in their modelling they commented that a thick disc would also likely contribute to the variable optical flux.

We have not attempted any detailed modelling of our observations but a number of comments can be made. The earlier optical ephemeris due to Augusteijn et al. (1998) placed maximum optical light for 4U 1735–44 at phase 0.68 ± 0.06 on the spectral ephemeris of Casares et al. (2006) which was between the expected maximum visibility of the irradiated donor and the disc bulge. This was in contrast to the result for 4U 1636–53 where their spectral ephemeris and the optical ephemeris of Giles et al. (2002) placed op-

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tical maximum at a more reasonable phase of 0.47 ± 0.06. Our new photometric ephemeris for 4U 1735–44 resolves this issue by placing the optical maximum much closer to phase 0.5 (at 0.47 ± 0.05). Indeed, Casares et al. (2006) comment on the uncertainty of the Augusteijn et al. (1998) ephemeris and Fig. 2 clearly shows how an ephemeris based on only the 5 earliest data points leads to a significant phase error of ∼0.2 after the passage of 10-yr.

The correlation between optical flux and X-ray flux, evident in Fig. 4, is not unexpected, but Fig. 5 shows no apparent correlation between optical modulation amplitude and X-ray flux. If the X-ray induced optical flux were sitting on a substantial and constant base component from the companion star then Fig. 5 would be expected to show a small increase in modulation percentage (essentially just ∆ mag. for small values < 0.30) for increasing X-ray flux. There is no evidence for this. Therefore, the companion contribution must be minor and may be obscured, on Fig. 5, by the variability in the relationships between the different components generating, or obscuring, the optical flux. The X axis in Fig. 5 is still in magnitudes, rather than on a linear intensity scale, as in Fig. 4.

The X-ray flux and optical intensity were also shown to be positively correlated in observations of 4U 1636–53 by Shih, Charles & Cornelisse (2011) who performed a 100 day, monitoring program of this source in which daily spot optical measurements were made. Only the lower energy X-ray intensity (1.5–12 keV RXTE ASM) showed a positive correlation, the high energy X-ray flux (15–50 keV Swift BAT) being anti-correlated. In the present paper, the optical and X-ray data have been measured across binary cycles and many hours respectively and thus hopefully represent more reasonable ‘steady-state’ average values. There is insufficient data to be certain, but there is a suggestion in the light curves that at the very highest X-ray flux the optical modulation has almost gone away and the faster optical variability decreased. Perhaps this is an indication of an optical state change. The continuing lack of any orbital modulation signature in the folded X-ray data suggests i ≤ 60°, based on the modelling of Frank, King & Lasota (1987).

Several key aspects of the standard model for an LMXB system are supported by the following results:
- Optical maximum at spectral phase 0.47 ± 0.05
- Positive correlation, optical flux – X-ray flux
- No correlation, optical amplitude – X-ray flux
- Non-X-ray induced optical flux is < 14 percent

The dynamical ephemeris for 4U 1735–44 is now obtained by combining the new period derived in this paper with the phase zero epoch from Casares et al. (2006). Phase zero, in this spectral definition, again corresponds to inferior conjunction of the companion star. The ephemeris is therefore HJD = 2452813.495(3) + [ N × 0.19383222(29) ].

Clearly, on-going occasional optical photometry and spectroscopy are desirable for both 4U 1735–44 and 4U 1636–53 to monitor any possible changes, in order to better understand LMXB systems in general. These two X-ray binaries continue to be quite similar and are apparently viewed from much the same perspective. Future simultaneous X-ray and optical studies may be problematic with the recent decommissioning of the long running RXTE mission in 2012 January. A number of alternative, somewhat equivalent, ASM type systems are presently operating. Perhaps the LOFT mission, if selected for flight by ESA, will provide a more continuous X-ray coverage.

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