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# Searching for the orbital period of the ultraluminous X-ray source NGC 1313 X-2

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## ABSTRACT

We analysed the longest phase-connected photometric data set available for NGC 1313 X-2, looking for the ∼6-day modulation reported by Liu et al.. The folded *B*-band light curve shows a ∼6-day periodicity with a significance slightly larger than $3\sigma$. The low statistical significance of this modulation, along with the lack of detection in the *V* band, makes its identification uncertain.

**Key words:** techniques: photometric – stars: individual: NGC 1313 X-2 – stars: variables: general – galaxies: individual: NGC 1313 – X-rays: binaries – X-rays: individual: NGC 1313 X-2.

## 1 INTRODUCTION

X-ray observations of nearby galaxies show a population of point-like, off-nuclear sources with luminosities (if isotropic) in excess of the classical Eddington limit for a 10–$M_\odot$ compact object; they are referred to as ultraluminous X-ray sources (ULXs; see Fabbiano 2006; Feng & Soria 2011 for a review). Nowadays, hundreds of ULX candidates have been detected and many of them have been studied in detail (see e.g. Roberts & Warwick 2000; Colbert & Ptak 2002; Swartz et al. 2004, 2011; Liu & Bregman 2005; Liu & Mirabel 2005; Walton et al. 2011). Their high X-ray luminosities and short-term variability suggest that the majority of these puzzling sources are likely to be accreting black holes (BHs) in binary systems (see e.g. Zampieri & Roberts 2009 and references therein). Although X-ray data alone have provided evidence that ULXs are different from stellar-mass Galactic BHs – either a different class of BHs or a different accretion state – X-ray spectral and timing results remain consistent with various alternative scenarios characterized by BHs of different mass and origin. These go from the challenging intermediate-mass BHs of $\approx 10^2$–$10^4\,M_\odot$ (Colbert & Mushotzky 1999), to massive stellar BHs of $\simeq$25–80 $M_\odot$ formed from the direct collapse of low-metallicity massive stars (Mapelli, Colpi & Zampieri 2009; Zampieri & Roberts 2009), to stellar-mass BHs ($\lesssim 20\,M_\odot$) accreting above the Eddington limit (King et al. 2001; King 2008).

A necessary pre-condition for determining (or at least constraining) the BH mass is to measure the period of a ULX binary system. This represents a crucial preliminary step, required to perform an efficient spectroscopic follow-up in search of radial velocity variations and hence measure the mass function of the system, and so the BH mass. The best way to quantify the binary period is to study the optical emission of the counterpart and to determine its periodic modulation. The same strategy was successfully adopted for measuring the orbital period and mass of the compact object in Galactic BH X-ray binaries (e.g. van Paradijs & McClintock 1995).

To date, a single dedicated monitoring campaign has been performed on NGC 1313 X-2 with the *Hubble Space Telescope*(*HST*), providing the only tentative optical periodicity available. NGC 1313 X-2 is located in the outskirts of the barred spiral galaxy NGC 1313 at a distance of 3.7–4.27 Mpc (Tully 1988; Méndez et al. 2002; Rizzi et al. 2007). Its observed X-ray luminosity varies between a few $\times 10^{39}$ erg s$^{-1}$ and $\sim 10^{40}$ erg s$^{-1}$ in the 0.3–10 keV band (e.g. Feng & Kaaret 2006; Mucciarelli et al. 2007). The source has been extensively studied in the X-ray and optical bands (e.g. Zampieri et al. 2004; Mucciarelli et al. 2007; Grisé et al. 2008 and references therein). The large amount of data available makes this object a cornerstone for the study of ULXs. It belongs to a handful of ULXs clearly associated with stellar optical counterparts (e.g. Liu et al. 2004; Mucciarelli et al. 2005; Soria et al. 2005). These optical sources appear to be almost ubiquitously hosted in young stellar environments (e.g. Pakull et al. 2006; Ramsey et al. 2006; Liu et al. 2007) and have properties consistent with those of young, massive stars. However, some ULXs appear to be associated with older stellar populations and at least one possible later-type stellar counterpart is now known (Feng & Kaaret 2008; Roberts, Levan & Goad 2008), although its spectral classification may be affected by significant galactic and extragalactic reddening (Grisé et al. 2006).

The optical counterpart of NGC 1313 X-2 was first identified on a European Southern Observatory (ESO) 3.6-m *R*-band image, thanks to *Chandra*'s accurate astrometry, after the X-ray image was registered on the position of SN 1978K (Zampieri et al. 2004). ESO Very Large Telescope (VLT) images of the field showed that the counterpart was actually composed of two distinct objects (C1 and C2), separated by ∼0.7 arcsec (Mucciarelli et al. 2005). Further refinement in the astrometry and accurate modelling of the optical

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emission indicated that object C1 was the more likely counterpart (Liu et al. 2007; Mucciarelli et al. 2007; Patruno & Zampieri 2008). However, this was established beyond any doubt by the detection of the He II λ4686 emission line in its optical spectrum, a characteristic imprint of X-ray irradiation (Pakull et al. 2006; Grisé et al. 2008). This star has an extinction-corrected absolute magnitude $M_B \sim -4.5$ mag and colours $(B - V)_0 \sim -0.15$ mag and $(V - I)_0 \sim -0.16$ mag (Mucciarelli et al. 2007; Grisé et al. 2008), consistent with a B spectral type.

The stellar environment of NGC 1313 X-2 has also provided interesting constraints. There are two groups of young stars spread out over ∼200 pc. Isochrone fitting of the colour–magnitude diagram of these groups has been attempted and provides cluster ages of $20 \pm 5$ Myr (Pakull et al. 2006; Ramsey et al. 2006; Liu et al. 2007; Grisé et al. 2008). As several other ULXs, NGC 1313 X-2 is also associated with a very extended (∼400 pc) optical emission nebula that gives important information on the energetics and lifetime of the system (Pakull & Mirioni 2002). Assuming that it is formed in one or more explosive events or that its mechanical energy comes from the ULX wind/jet activity, the characteristic age and energetics of the nebula turn out to be ∼1 Myr and $\approx 10^{52\div 53}$ erg or $\sim 4 \times 10^{39}$ erg s$^{-1}$, respectively (Pakull et al. 2006). The most up-to-date binary model calculation, including X-ray irradiation effects, finds consistency between all the available optical measurements if C1 is a terminal-age main sequence or early giant donor of 12–15 $M_\odot$ undergoing Roche lobe overflow. The same calculations provide estimates of the masses also for the BH, which is in between 20 and $\sim 100\, M_\odot$ (Patruno & Zampieri 2010; see also Copperwheat et al. 2007 for a similar result including star+disc irradiation but without considering binary evolution effects).

Quite recently, Liu et al. (2009) found a possible periodicity of $6.12 \pm 0.16$ days in a monitoring campaign of the optical counterpart of NGC 1313 X-2 performed with the *HST*. This modulation was interpreted as the orbital period of the binary system. Three cycles were detected in the *B* band, while no modulation was found in *V*. Previous studies carried out on the available *HST* and VLT observations led to negative results (Grisé et al. 2008). More recently, a lack of significant photometric variability on a new sequence of VLT observations has been reported by Grisé et al. (2009). In principle, the detection of the orbital period would definitely confirm the identification of the optical counterpart and the binary nature of this system. Most importantly, it would open the way to perform a dynamical measurement of the BH mass.

Here we present a re-analysis of the joint VLT+FORS1 and *HST*+Wide Field Planetary Camera 2 (WFPC2) photometric observations of NGC 1313 X-2 obtained during the years 2007 and 2008, with the aim of clarifying the statistical significance of the orbital periodicity identified by Liu et al. (2009). We did not consider previous VLT observations taken in 2003 and 2004 because they cannot be phase connected to the more recent observations. In Section 2 we present the data reduction procedure that we have adopted, while in Section 3 we show the results of the statistical analysis. Section 4 summarizes our results.

## 2 VLT AND *HST* OBSERVATIONS

NGC 1313 X-2 was observed with VLT+FORS1 between 2007 October and 2008 March (11 epochs; Grisé et al. 2009) and with *HST*+WFPC2 between 2008 May and June (20 epochs; Liu et al. 2009). During the VLT observations the sky was clear and the average seeing was in the range of 0.8–1.2 arcsec$^2$. The quality of the WFPC2 images is fair, despite the degradation of the central PC chip. A log of the observations is reported in Table 1. We reanalysed the whole data set in a homogeneous way, looking for the ∼6-day periodicity reported by Liu et al. (2009).

Two exposures were taken a few minutes apart each night. For the *HST* data set, we used the calibrated data from the WFPC2 static archive. After performing standard image reduction in the IRAF environment, the exposures were combined together and cleaned for cosmic rays. To accurately perform photometry of the objects, we used the Astronomical Image Decomposition and Analysis (AIDA; Uslenghi & Falomo 2008), an IDL-based package originally designed to perform two-dimensional point-spread-function model fitting of quasar images. For the analysis of the WFPC2 exposures, we loaded into AIDA the appropriate point spread function simulated with Tiny Tim v. 6.3.[1] As the background did not vary significantly among the different *HST* exposures, we decided to keep it fixed at the average value computed from all the observations.

Analysing VLT and *HST* measurements together requires attention to be paid to the systematic differences between the two photometric systems. We then first converted the *HST* instrumental magnitudes to the standard *UBVRI* photometric system using the updated transformation equations and coefficients published in Dolphin (2009) for the appropriate instrumental gain (which is equal to 7 in our case).[2] The colour correction term was computed adopting the $(B - V)$ colour reported in Mucciarelli et al. (2005). In spite of this, residual systematic differences between the two photometric systems might still be present and affect our measurements. In particular, the colour correction term is sensitive to the overall bandpass (telescope plus atmospheric response) of the instruments. We then decided to perform differential photometry of the target with respect to a nearby field star (star D in Zampieri et al. 2004), located on the same chip in both instruments. The coordinates and average *BVR* magnitudes of the optical counterpart of NGC 1313 X-2 (object C1) and the reference star (object D) are reported in Mucciarelli et al. (2005). The reference star is brighter than the target and has a low rms variability (∼0.05 mag in the VLT and $\lesssim 0.02$ mag in the *HST* exposures). For similar reasons, during all the observations performed with *HST*+WFPC2, the field was always oriented in the same direction and the target and reference star were always located on the same position on the central PC chip.

Figs 1 and 2 show the *B*- and *V*-band light curves of NGC 1313 X-2 obtained in this way. The measured values of the differential magnitudes ($\Delta B = B_{\rm D} - B_{\rm C1}$, $\Delta V = V_{\rm D} - V_{\rm C1}$) and the corresponding errors ($\sigma_B$, $\sigma_V$) are reported in Table 1. The mean values and standard deviation of different samples of data are reported in Table 2. A comparison of our *B*- and *V*-band light curves with those of Liu et al. (2009) (shifted by a constant value) shows that they are consistent within the errors, apart from the *V*-band measurements of two observations (24 and 31) that differ by 0.1 mag. The same result is obtained by comparing the light curve of Liu et al. (2009) with ours, before performing the *UBVRI* magnitude system conversion.

Our data show clear short-term (∼1 day) variability. As can be seen from Fig. 1, the *B*-band *HST* data have a larger rms variability than the *B*-band VLT data. Similarly, comparing Figs 1 and 2, it appears that the *B*-band light curve has larger variations than the *V*-band data.

Superimposed on these short-term stochastic changes, the *HST* *V*-band light curve does not show significant regular variability (Fig. 2), whereas the *HST* *B*-band data set shows an approximately

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[1] Available from http://www.stsci.edu/software/tinytim/tinytim.html

[2] Available from http://purcell.as.arizona.edu/wfpc2_calib/

**Table 1.** Log of the VLT+FORS1 and *HST*+WFPC2 photometric observations of the field around NGC 1313 X-2, along with the $B$- and $V$-band differential photometry of object C1 with respect to a reference field star (see text for details).

| Obs. | Date | MJD | Exposure (s) | Telescope+instrument | $\Delta B$ | $\sigma_B$ | $\Delta V$ | $\sigma_V$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 2007-10-21 | 54394.362587 | 242 × 2 | VLT+FORS1 | 3.140 | 0.069 | | |
| 2 | 2007-11-15 | 54419.220472 | 242 × 2 | VLT+FORS1 | 3.220 | 0.045 | | |
| 3 | 2007-11-15 | 54419.277624 | 242 × 2 | VLT+FORS1 | 3.261 | 0.076 | | |
| 4 | 2007-11-16 | 54420.255469 | 242 × 2 | VLT+FORS1 | 3.220 | 0.049 | | |
| 5 | 2007-12-06 | 54440.075805 | 242 × 2 | VLT+FORS1 | 3.172 | 0.042 | | |
| 6 | 2007-12-10 | 54444.173203 | 242 × 2 | VLT+FORS1 | 3.169 | 0.052 | | |
| 7 | 2007-12-14 | 54448.121299 | 242 × 2 | VLT+FORS1 | 3.236 | 0.071 | | |
| 8 | 2008-01-31 | 54496.073081 | 242 × 2 | VLT+FORS1 | 3.162 | 0.058 | | |
| 9 | 2008-03-02 | 54527.059338 | 242 × 2 | VLT+FORS1 | 3.215 | 0.066 | | |
| 10 | 2008-03-05 | 54530.053776 | 242 × 2 | VLT+FORS1 | 3.172 | 0.053 | | |
| 11 | 2008-03-08 | 54533.056052 | 242 × 2 | VLT+FORS1 | 3.244 | 0.065 | | |
| 12 | 2008-05-21 | 54607.911122 | 500 × 2 | *HST*+WFPC2 | 3.217 | 0.075 | | |
| | 2008-05-21 | 54607.927094 | 400+700 | *HST*+WFPC2 | | | 4.759 | 0.043 |
| 13 | 2008-05-22 | 54608.043761 | 500 × 2 | *HST*+WFPC2 | 3.098 | 0.072 | | |
| | 2008-05-22 | 54608.059733 | 400+700 | *HST*+WFPC2 | | | 4.824 | 0.045 |
| 14 | 2008-05-23 | 54609.042372 | 500 × 2 | *HST*+WFPC2 | 3.058 | 0.071 | | |
| | 2008-05-23 | 54609.058344 | 400+700 | *HST*+WFPC2 | | | 4.816 | 0.044 |
| 15 | 2008-05-24 | 54610.040983 | 500 × 2 | *HST*+WFPC2 | 3.192 | 0.074 | | |
| | 2008-05-24 | 54610.056955 | 400+700 | *HST*+WFPC2 | | | 4.841 | 0.045 |
| 16 | 2008-05-25 | 54611.038900 | 500 × 2 | *HST*+WFPC2 | 3.190 | 0.074 | | |
| | 2008-05-25 | 54611.054872 | 400+700 | *HST*+WFPC2 | | | 4.855 | 0.046 |
| 17 | 2008-05-26 | 54612.104178 | 500 × 2 | *HST*+WFPC2 | 3.241 | 0.075 | | |
| | 2008-05-26 | 54612.120150 | 400+700 | *HST*+WFPC2 | | | 4.917 | 0.047 |
| 18 | 2008-05-27 | 54613.179178 | 500 × 2 | *HST*+WFPC2 | 3.226 | 0.075 | | |
| | 2008-05-27 | 54613.245150 | 400+700 | *HST*+WFPC2 | | | 4.815 | 0.045 |
| 19 | 2008-05-28 | 54614.178483 | 500 × 2 | *HST*+WFPC2 | 3.185 | 0.074 | | |
| | 2008-05-28 | 54614.243761 | 400+700 | *HST*+WFPC2 | | | 4.877 | 0.046 |
| 20 | 2008-05-29 | 54615.177789 | 500 × 2 | *HST*+WFPC2 | 3.063 | 0.072 | | |
| | 2008-05-29 | 54615.243066 | 400+700 | *HST*+WFPC2 | | | 4.850 | 0.045 |
| 21 | 2008-05-30 | 54616.097233 | 500 × 2 | *HST*+WFPC2 | 3.110 | 0.071 | | |
| | 2008-05-30 | 54616.113205 | 400+700 | *HST*+WFPC2 | | | 4.775 | 0.043 |
| 22 | 2008-05-31 | 54617.109039 | 500 × 2 | *HST*+WFPC2 | 3.178 | 0.075 | | |
| | 2008-05-31 | 54617.170150 | 400+700 | *HST*+WFPC2 | | | 4.854 | 0.046 |
| 23 | 2008-06-01 | 54618.692372 | 500 × 2 | *HST*+WFPC2 | 3.326 | 0.077 | | |
| | 2008-06-01 | 54618.708344 | 400+700 | *HST*+WFPC2 | | | 4.762 | 0.043 |
| 24 | 2008-06-02 | 54619.173622 | 500 × 2 | *HST*+WFPC2 | 3.200 | 0.075 | | |
| | 2008-06-02 | 54619.238205 | 400+700 | *HST*+WFPC2 | | | 4.835 | 0.045 |
| 25 | 2008-06-03 | 54620.105567 | 500 × 2 | *HST*+WFPC2 | 3.189 | 0.074 | | |
| | 2008-06-03 | 54620.166678 | 400+700 | *HST*+WFPC2 | | | 4.788 | 0.043 |
| 26 | 2008-06-04 | 54621.171539 | 500 × 2 | *HST*+WFPC2 | 3.071 | 0.072 | | |
| | 2008-06-04 | 54621.236122 | 400+700 | *HST*+WFPC2 | | | 4.899 | 0.046 |
| 27 | 2008-06-05 | 54622.104178 | 500 × 2 | *HST*+WFPC2 | 3.101 | 0.072 | | |
| | 2008-06-05 | 54622.164594 | 400+700 | *HST*+WFPC2 | | | 4.888 | 0.046 |
| 28 | 2008-06-06 | 54623.102789 | 500 × 2 | *HST*+WFPC2 | 3.316 | 0.077 | | |
| | 2008-06-06 | 54623.163206 | 400+700 | *HST*+WFPC2 | | | 4.913 | 0.046 |
| 29 | 2008-06-07 | 54624.034733 | 500 × 2 | *HST*+WFPC2 | 3.419 | 0.080 | | |
| | 2008-06-07 | 54624.091678 | 400+700 | *HST*+WFPC2 | | | 4.872 | 0.045 |
| 30 | 2008-06-08 | 54625.100706 | 500 × 2 | *HST*+WFPC2 | 3.257 | 0.075 | | |
| | 2008-06-08 | 54625.161122 | 400+700 | *HST*+WFPC2 | | | 4.899 | 0.047 |
| 31 | 2008-06-09 | 54626.611817 | 500 × 2 | *HST*+WFPC2 | 3.285 | 0.075 | | |
| | 2008-06-09 | 54626.627789 | 400+700 | *HST*+WFPC2 | | | 4.833 | 0.045 |

sinusoidal modulation with a period of 6 days (Fig. 1). The maximum peak-to-peak variation in the $B$-band light curve is 0.36 mag.

## 3 RESULTS

Following Liu et al. (2009), we fitted the *HST* and VLT+*HST* $B$-band light curves with a sinusoid:

$$\Delta B = \langle \Delta B \rangle + A \sin(2\pi(t - t_1)/P + \phi), \qquad (1)$$

where $A$, $P$ and $\phi$ are the amplitude, period and phase, respectively, and $t_1 = 54390$ is a reference epoch. The best-fitting parameters of the fit are reported in Table 2. Although the values of the period and phase of the *HST* and VLT+*HST* fits are not consistent at the 90 per cent confidence level, they are in agreement at the $3\sigma$ level. Furthermore, the $\chi^2$ surface for the VLT+*HST* data set has several (at least five) pronounced minima in the range of ~5.7–7.1 d (5.7, 6.0, 6.2, 6.7 and 7.1 days, respectively), with similar values of $\chi^2$. The

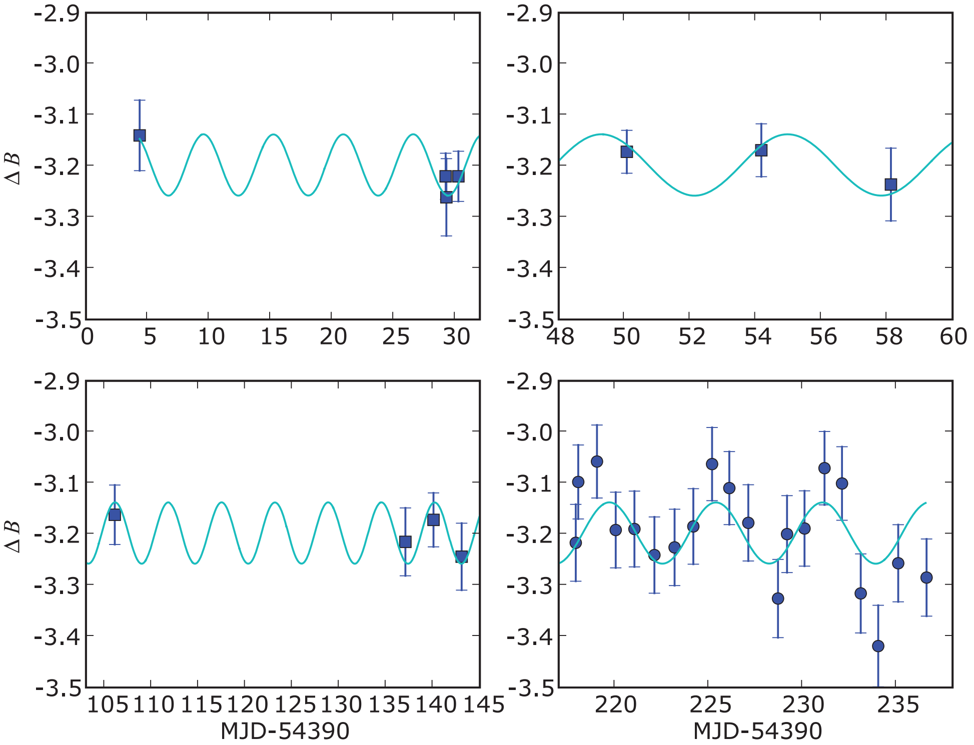

**Figure 1.** Joint VLT+*HST* light curve of NGC 1313 X-2 in the *B* band. The squares represent the VLT+FORS1 data, while the circles represent the *HST*+WFPC2 observations. The magnitudes are the difference with those of a reference field star. The data cover a period of ~7.5 months. The solid (cyan) line is the best fitting sinusoid with a period $P = 5.68$ days.

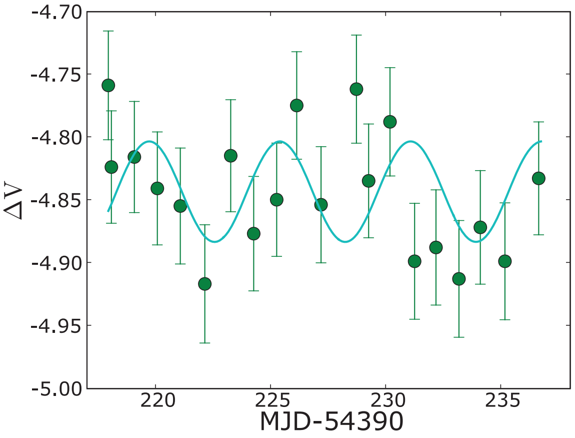

**Figure 2.** *HST* light curve of NGC 1313 X-2 in the *V* band. The magnitudes are the difference with those of a reference field star. The solid (cyan) line is a sinusoid with the same period and phase obtained from the fit of the joint VLT+*HST* *B*-band data, but with a fixed amplitude of 0.04 mag.

values reported in Table 2 refer to the two deepest minima. Considering these caveats, the fits appear to return consistent results. The value of the amplitude and period of the *HST* fit are in agreement, within the errors, with those reported by Liu et al. (2009).

The error on the period for the VLT+*HST* light curve is such that $\Delta P(T/P) \lesssim 6$ days, where $T \sim 200$ days is the interval between the first and last observations (sampling interval). This is not larger than $P$, indicating that the two data sets can be phase connected. Indeed, this represents the longest phase-connected photometric data set available for NGC 1313 X-2. A fit of the VLT data alone was also attempted and returned $P = 5.7$ days, $A = 0.04$ mag and $\phi = 28^\circ$. Computing the errors for one interesting parameter (while holding the others fixed), all these values turn out to be consistent with those reported in Table 2. However, the amplitude of the sinusoidal fit (for fixed period and phase) is consistent with zero at the 90 per cent confidence level. Therefore, it is not possible to infer evidence of periodicity from the VLT data alone, but they appear to be consistent with the sinusoidal modulation observed in the *HST* observations.

We checked possible systematic effects induced by the transformation from the VEGAMAG to the *UBVRI* system fitting the function in equation (1) directly to the *HST*-F450W-band light curve. We found values for the period and amplitude completely consistent with those of the *HST* *B*-band light curve reported in Table 2 ($P = 6.21^{+0.18}_{-0.17}$ days and $A = 0.1^{+0.02}_{-0.02}$ mag). The $\chi^2$ is 31.5 for 17 degrees of freedom (dof), corresponding to a null hypothesis probability of 0.0174. The rather large value of $\chi^2$ may indicate that, at this level of accuracy, we may be sensitive to small deviations of the light curve from a perfect sinusoidal shape. The phase is $\phi = 169^\circ \pm 14^\circ$. This is clearly different from the phase reported in Table 2 because the reference epoch (MJD 54390) is ~215 days before the *HST* observations and small difference in the period estimate (0.04 days) can accumulate to give rise to a phase shift of $\sim 0.04\ \mathrm{days} \times (220/6) \sim 1.4\ \mathrm{d} \sim 80^\circ$.

We tried to assess the statistical significance of the apparent *B*-band modulation in two different ways. First, we performed a Lomb–Scargle periodogram analysis of all the unevenly sampled time series, including both the VLT and *HST* observations. The maximum power is at a frequency of $1.93 \times 10^{-6}$ Hz, corresponding to a period of 6 days. However, the null hypothesis probability is quite large (16.5 per cent), meaning that the statistical significance of the modulation is low. Second, in order to increase the signal-to-noise ratio, we then decided to bin the light curve in $M = 6$ bin intervals and perform an epoch-folding period search. The peak of

**Table 2.** Average magnitudes, standard deviation and best-fitting parameters of sinusoidal fits to different samples of data.

| Sample | $\langle \Delta B \rangle$ | $\langle \Delta V \rangle$ | $\sigma^{a}$ | $P^{b}$ (d) | $A^{b}$ | $\phi^{b}$ | $\chi^2$ (dof) |
|---|---|---|---|---|---|---|---|
| VLT+*HST*$^{c}$ (*B* band) | 3.198 | | 0.078 | $5.68^{+0.01}_{-0.01}$ | $0.06^{+0.02}_{-0.03}$ | $27^{0}{}^{+29^{0}}_{-31^{0}}$ | 21.0 (28) |
| | | | | $6.01^{+0.01}_{-0.01}$ | $0.06^{+0.03}_{-0.03}$ | $95^{0}{}^{+25^{0}}_{-23^{0}}$ | 21.9 (28) |
| VLT (*B* band) | 3.201 | | 0.038 | | | | |
| *HST* (*B* band) | 3.196 | | 0.094 | $6.17^{+0.18}_{-0.17}$ | $0.10^{+0.02}_{-0.02}$ | $86^{0}{}^{+13^{0}}_{-13^{0}}$ | 13.4 (17) |
| VLT+*HST* (*V* band) | | 4.843 | 0.047 | | | | |

$^{a}$Standard deviation.
$^{b}$Errors are 90 per cent confidence intervals.
$^{c}$Parameters of the two deepest minima.

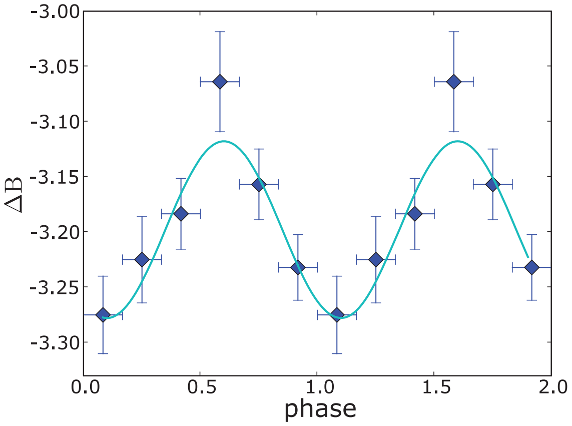

**Figure 3.** Binned light curve (six bins) of the *B*-band VLT+*HST* data set of NGC 1313 X-2, folded over the best estimate of the period (6 days). The best-fitting sinusoid is also shown. The phase is measured from MJD 54390.

the distribution is $\chi^2 = 17.2$ at $P = 6$ days. For $\nu = M - 1 = 5$ dof, this corresponds to a significance level of $2.8\sigma$. No other significant peaks were found in the interval between 3 and 9 days. As the validity of the $\chi^2$ distribution is limited to large samples, following Davies (1990) we also estimated the significance of the 6-day period using the *L* statistics, which is statistically sound for all sample sizes. The peak of the distribution is $L = 6.75$ for $\nu_1 = M - 1 = 5$ and $\nu_2 = N - M = 25$ dof, where $N = 31$ is the number of observations. This corresponds to a null hypothesis probability of 0.0004 or a significance level of $3.6\sigma$. In Fig. 3 we show the folded light curve along with its best-fitting sinusoid ($P = 6.0$ days, $A = 0.08$, $\phi = 54°$). The parameters of the sinusoid are consistent with those of the second best fit of the unbinned light curve (see Table 2).

In contrast with the *B* band, the *V*-band light curve shows a rather stochastic variability (although the first six and seven observations appear to follow a sinusoidal behaviour). We also tried a sinusoidal fit of this data set and found an acceptable minimum with a periodicity $P = 10.8^{+1.2}_{-1.0}$ days that, however, is not statistically meaningful (significance from a Lomb–Scargle periodogram analysis ∼56 per cent). As shown in Fig. 2, a sinusoidal modulation with the same period and phase obtained from the fit of the *B*-band data and an amplitude $\lesssim$0.04 mag may be marginally consistent, within the errors, with the *V*-band data (reduced $\chi^2 \lesssim 1.4$).

Repeating a similar analysis on the F450W-band measurements of Liu et al. (2009) (their table 1), we found that the maximum power in the Lomb–Scargle periodogram corresponds to a period $P = 6.13$ days and to a null hypothesis probability of 16 per cent. The peak of the $\chi^2$ distribution after binning and folding the light curve as described above is $\chi^2 = 15.8$ at $P = 6.3$ days. Adopting the *L* statistics, this corresponds to $L = 13.8$ for $\nu_1 = 5$ and $\nu_2 = 14$ dof, or to a significance level of $4\sigma$ (a null hypothesis probability of 0.000054). This value is very close to that estimated from our measurements, indicating that the main reason for the difference with the significance level ($6\sigma$) reported by Liu et al. (2009) relies on the statistical treatment of the data and not on the different photometric analyses.

## 4 DISCUSSION AND CONCLUSIONS

We re-analysed the longest phase-connected photometric data set available for NGC 1313 X-2 using VLT+FORS1 and *HST*+WFPC2 observations taken between 2007 October and 2008 June. *B*-band differential photometry with respect to a nearby isolated and non-saturated field star confirms the 6-day modulation detected by Liu et al. (2009) in the *HST*-F450W data alone. No significant periodic variability was found in the *V* band. Binning the *B*-band light curve, the statistical significance of the 6-day modulation turns out to be slightly larger than $3\sigma$. No other significant oscillations were found.

Although much of the work presented in this paper is a re-reduction and analysis of previously published data (Grisé et al. 2009; Liu et al. 2009), we emphasize that there are two important differences in the approach that we followed here. We adopted differential photometry with respect to a reference field star (instead of absolute photometry) and, most importantly, we performed a full statistical analysis of the significance of the modulation. Differential photometry allows us to minimize the effects of absolute calibration uncertainties and leads to small differences in the flux measurements. All but two *V*-band measurements are in agreement with those reported previously in the literature. However, the major improvement of our work consists in a careful statistical re-analysis of the data, which includes binning the light curve and using the *L* statistics for small sample sizes (Davies 1990). While excluding the VLT observations from the analysis does not significantly affect our conclusions, we find that they can be phase connected to the *HST* data set and are consistent with it. They also show that the optical luminosity of the counterpart is quite steady on time-scales of months–years and that the accretion disc does not have a large stochastic variability, which is encouraging for photometric studies of this nature. At the same time, they also show that detecting periodic optical variability in ULX counterparts is possible from both space and the ground, if 8+ metre class telescopes are available. A necessary condition in the latter case is to have optimal seeing and rather isolated counterparts.

The observed optical emission of NGC 1313 X-2 originates from the intrinsic emission and X-ray heating of the donor star and the accretion disc (e.g. Patruno & Zampieri 2008). From the maximum amplitude of the sinusoid that is marginally consistent with the VLT data, we infer a maximum rms sinusoidal variability of 0.03 mag for the VLT data, much smaller than that of the *HST* observations ($\sim$0.07 mag), indicating that there are different levels of optical activity whose origin is unclear. This is confirmed by the analysis of previous observations of NGC 1313 X-2 performed in 2003 and 2004, when the *B*-band light curve showed an intermediate level of variability (standard deviation $\sim$0.056 mag) with respect to the two data sets considered here. There may be different reasons for this behaviour. Some B stars have intrinsic variability on a time-scale of a few hours that may be different from one cycle to the next, even though the baseline is constant (e.g. $\beta$ Cep stars; Saesen et al. 2010). This variability may be superimposed to a short-term stochastic variability from the disc, and appear random because the time-scale is too short compared to the time resolution of our observations. However, if we consider the standard deviation of the residuals with respect to the sinusoidal fit, the behaviour of the VLT and *HST* data sets is more similar (standard deviation $\sim$0.05 mag for VLT and $\sim$0.06 mag for *HST*). Therefore, it is likely that the extra variability observed in the *B*-band *HST* data comes from the regular sinusoidal modulation. If it is so and if the changing view of the X-ray-irradiated/non-irradiated donor surface gives a significant contribution to the modulation of the optical flux, an increased amplitude of the modulation would imply an increment in the X-ray heating and, in turn, in the average optical luminosity. We know that the X-ray flux of NGC 1313 X-2 is indeed quite variable (e.g. Mucciarelli et al. 2007). A recent *Swift* monitoring campaign of the source, performed in 2009, seems to show a bimodal distribution of the fluxes which may in fact suggest rapid and recurrent X-ray flares (with variations of a factor of 3 and 4; Grisé et al., in preparation), although the correlation with optical variability is not yet firmly established.

At first glance, interpreting the extra *HST* variability as caused by increased X-ray heating does not appear to be consistent with the observed average $\Delta B$ reported in Table 2, which is not significantly different in the VLT and *HST* observations. On the other hand, as already mentioned, note that there may be possible residual systematic uncertainties in the conversion between the VEGAMAG and *UBVRI* photometric systems. In particular, in performing the conversion, we applied a colour correction (to both objects C1 and D) estimated from the colours reported in Mucciarelli et al. (2005). However, we know that the colour of object C1 is variable and is likely to become bluer if X-ray heating increases. Furthermore, we found that the inferred $(B - V)$ colour of the reference object D in the *HST* data turns out to be slightly redder (1.6 instead of 1.4 mag) than that reported in Mucciarelli et al. (2005) (although they are in agreement within the errors). Both effects would tend to change the average $\Delta B$ of the *HST* data and shift them upwards in Fig. 1, as expected if X-ray irradiation has increased. For an error and/or variation in the colours of 0.15 mag, the average $\Delta B$ would vary by 0.035 mag, which is significant in comparison with the amplitude of the modulation. Even assuming that the average luminosity does not vary much between the two data sets, one may still think of some particular conditions under which the modulated fraction of the emission varies without significant changes in $\langle \Delta B \rangle$. For example, when X-ray irradiation is higher, the disc may be partly obscured by material blown off from the inner regions. Or a change in the height of the outer accretion disc may partly induce variations in the obscuration of the companion. While the total solid angle of disc+star seen by the source (and hence the fraction of intercepted X-ray photons) remains constant, the relative contribution of star and disc may change, inducing variations in the modulated fraction of the emission. Clearly, no definite conclusion can be reached without further accurate observations.

Also, the smaller variability and absence of a detectable modulation in the *V* band is puzzling. Model calculations of the irradiated plus donor disc emission show that at longer optical wavelengths the donor spectrum declines more rapidly than the irradiated disc spectrum. Therefore, the contamination from the disc is comparatively stronger in the *R* and *V* bands with respect to the *B* and *U* bands (Patruno & Zampieri 2010). As the emission from the accretion disc is not orbitally modulated, any variation in the donor star emission would induce a slightly smaller change in the *R* and *V* bands than in the *B* and *U* bands. Perhaps the irregular variability comes more from the disc, while the phase-modulated variability comes more from the irradiated star. However, our analysis indicates an upper limit of 0.04 mag on the *V*-band modulation, significantly lower than the inferred amplitude of the modulation in the *B* band (0.09 mag). Furthermore, ellipsoidal modulations are also likely to be important in these conditions (e.g. Bochkarev, Karitskaia & Shakura 1979), with two maxima/minima per orbital revolution. If they dominate, no significant wavelength dependence of the modulation is expected and the observed 6-day periodicity would correspond to an orbital period of 12 days. In case both X-ray irradiation and ellipsoidal modulation contribute to the observed variability, the combined effect may be an asymmetric light curve with two minima of different depth (not easily detectable with the accuracy of present measurements). However, even in this case, the light curve may show a single maximum/minimum at superior/inferior conjunction, if the X-ray flux at the stellar surface is sufficiently high. Further observations and a detailed joint modelling of the irradiated accretion disc and ellipsoidally distorted donor are required to assess this point. We note that any signature of X-ray irradiation/reprocessing in the optical data would provide evidence against beaming, as in that case the fraction of X-ray photons intercepted by disc and the star would be small.

Another possibility for explaining the smaller *V*-band variability may be the contribution of emission lines. The *B* band contains both the He II $\lambda$4686 and H$\beta$ lines, while the *V* band has only the continuum. If irradiation and/or orbital effects are causing the lines to vary in addition to the continuum, perhaps they may induce an extra *B*-band variability. But the observed strength of the excess *B*-band variability ($\sim$5 per cent over the continuum) requires significant line emission and hence a very high equivalent width. Roberts et al. (2010) found that the equivalent width of the He II $\lambda$4686 line displays variations between 2 and 11 Å, not large enough to explain the observed variability. Finally, changes in the absorbing column towards the source may also contribute to induce differential variations in the *B* and *V*-bands light curves [e.g. $E(B - V)$ variability of $\sim$0.01 mag would cause $\Delta B$ and $\Delta V$ variability of $\sim$0.04 and $\sim$0.03 mag, respectively].

If the modulation is real and represents the orbital period of the ULX, it would place rather compelling constraints on the properties of the system and also on the donor and BH masses. Patruno & Zampieri (2010) have shown that imposing the 6-day periodicity and using all the other constraints available for this source from X-ray and optical observations (mass transfer rate, position on the colour–magnitude diagram, characteristic ages of the parent stellar cluster and the surrounding bubble nebula), the system would be consistent with a $\sim$50–100 $M_\odot$ black hole accreting from a 12–15 $M_\odot$ star that fills its Roche lobe at terminal-age main sequence. At this stage of the binary evolution, such a star would have a radius of $\sim 8$–$9 \times 10^{11}$ cm and a separation from the BH of $\sim 4 \times 10^{12}$ cm, and so it will intercept a fraction of $\sim$10–15 per cent of the X-ray photons assuming isotropic emission. Note, however, that the fraction of photons intercepted by the disc exceeds that from the donor star (which is also partly screened by it).

Finally, the detection of the orbital modulation would open the way to perform a direct dynamical measurement of the BH mass in NGC 1313 X-2, the first time ever for a ULX, although a recent Gemini spectroscopy campaign failed to reveal regular modulations (Roberts et al. 2010). The binned light curve suggests that the periodicity may be there, but the low statistical significance of the *B*-band modulation, along with the lack of detection in the *V* band, makes its identification uncertain. A dedicated photometric monitoring campaign under homogeneous observing conditions to minimize systematic uncertainties is needed to confirm it.

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