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

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ABSTRACT
We analyzed the longest phase-connected photometric dataset available for NGC 1313 X-2, looking for the ~6 day modulation reported by Liu et al. (2009). The folded B band light curve shows a 6 day periodicity with a significance slightly larger than 3σ. The low statistical significance of this modulation, along with the lack of detection in the V band, make its identification uncertain.

Key words: stars: individual (NGC 1313 X-2) – X-rays: binaries – X-rays: individuals (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. 2002; Liu & Bregman 2005; Liu & Mirabel 2005; Walton et al. 2011; Swartz 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 \(\approx 10^2 - 10^4M_\odot\) (Colbert & Mushotzky 1999), to massive stellar BHs of \(\approx 25 - 80M_\odot\) formed from the direct collapse of low-metallicity massive stars (Mapelli et al. 2004; Zampieri & Roberts 2009), to stellar-mass BHs (\(\approx 20M_\odot\)) 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 the 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 1993).

To date a single dedicated monitoring campaign was performed on NGC 1313 X-2 with 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 and \(\sim 10^{40}\) erg/s in the 0.3-10 keV band (e.g. Mucciarelli et al. 2007; Feng & Kaaret 2006). 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 make 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. 2008; 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 sig-
significant galactic and extra-galactic reddening (Grisé et al. 2006).

The optical counterpart of NGC 1313 X-2 was first identified on an 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. 2002). 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′′ (Mucciarelli et al. 2003). Further refinement in the astrometry and accurate modelling of the optical emission indicated that object C1 was the more likely counterpart (Liu et al. 2006; Mucciarelli et al. 2007; Patruno & Zampieri 2008).

However, this was established beyond any doubt by the detection of the HeII 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 colors $(B-V)_0 \sim -0.15$ 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±5 Myr (Pakull et al. 2006; Ramsey et al. 2008; 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 et al. 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 $\approx 10^{52-53}$ erg or $\approx 4 \times 10^{39}$ erg/s, 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 mechanical energy comes from the ULX wind/jet activity, the same calculation provides the masses also for the BH, which is in between 20 and ~100 $M_\odot$ (Patruno & Zampieri 2011; 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±0.16 days in a monitoring campaign of the optical counterpart of NGC 1313 X-2 performed with the Hubble Space Telescope (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, 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+FOR1 and HST+WFPC2 photometric observations of NGC 1313 X-2 obtained during the years 2007-2008, 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 2003-2004 because they cannot be phase-connected to the more recent ones. In § 2 we present the data reduction procedure that we have adopted, while in § 3 we show the results of the statistical analysis. § 4 summarizes our conclusions.

2 VLT AND HST OBSERVATIONS

NGC 1313 X-2 was observed with VLT+FOR1 between October 2007 and March 2008 (11 epochs; Grisé et al. 2008) and with HST+WFPC2 between May and June 2008 (20 epochs; Liu et al. 2009). During the VLT observations the sky was clear and the average seeing was in the range 0.8"-1.2". 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 re-analyzed the whole dataset 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 dataset, 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 photometer the objects, we used AIDA (Astronomical Image Decomposition and Analysis; 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. 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.

Analyzing VLT and HST measurements together requires attention to be paid to the systematics 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). The color correction term was computed adopting the $(B-V)$ color reported in Mucciarelli et al. (2003). In spite of this, residual systematic differences between the two photometric systems might still be present and affect our measurements. In particular the color 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 BVRI 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 root mean square

1 http://www.stsci.edu/software/tinytim/tinytim.html
2 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+Instr. | $\Delta B$ | $\sigma_B$ | $\Delta V$ | $\sigma_V$ |
|------|------------|---------|--------------|------------------|------------|------------|------------|------------|
| 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 | 54496.070381 | 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      | 4.759      | 0.043      |
| 13   | 2008-05-25 | 54607.927094 | 400+700     | $HST+$WFPC2     | 3.098      | 0.072      | 4.824      | 0.045      |
| 14   | 2008-05-26 | 54607.043761 | 500×2       | $HST+$WFPC2     | 3.058      | 0.071      | 4.816      | 0.044      |
| 15   | 2008-05-27 | 54607.058344 | 400+700     | $HST+$WFPC2     | 3.192      | 0.074      | 4.841      | 0.045      |
| 16   | 2008-05-28 | 54610.056955 | 400+700     | $HST+$WFPC2     | 3.190      | 0.074      | 4.855      | 0.046      |
| 17   | 2008-05-29 | 54611.040983 | 500×2       | $HST+$WFPC2     | 3.241      | 0.075      | 4.917      | 0.047      |
| 18   | 2008-05-30 | 54611.120150 | 400+700     | $HST+$WFPC2     | 3.226      | 0.075      | 4.815      | 0.045      |
| 19   | 2008-05-31 | 54613.179178 | 500×2       | $HST+$WFPC2     | 3.185      | 0.074      | 4.877      | 0.046      |
| 20   | 2008-05-32 | 54613.245150 | 400+700     | $HST+$WFPC2     | 3.063      | 0.072      | 4.850      | 0.045      |
| 21   | 2008-05-33 | 54615.177789 | 500×2       | $HST+$WFPC2     | 3.110      | 0.071      | 4.775      | 0.043      |
| 22   | 2008-05-34 | 54616.097233 | 500×2       | $HST+$WFPC2     | 3.178      | 0.075      | 4.854      | 0.046      |
| 23   | 2008-05-35 | 54617.109039 | 500×2       | $HST+$WFPC2     | 3.326      | 0.077      | 4.762      | 0.043      |
| 24   | 2008-05-36 | 54618.708344 | 400+700     | $HST+$WFPC2     | 3.200      | 0.075      | 4.835      | 0.045      |
| 25   | 2008-05-37 | 54619.173622 | 500×2       | $HST+$WFPC2     | 3.189      | 0.074      | 4.788      | 0.043      |
| 26   | 2008-05-38 | 54619.238205 | 400+700     | $HST+$WFPC2     | 3.071      | 0.072      | 4.899      | 0.046      |
| 27   | 2008-05-39 | 54620.105567 | 500×2       | $HST+$WFPC2     | 3.101      | 0.072      | 4.888      | 0.046      |
| 28   | 2008-05-40 | 54620.164594 | 400+700     | $HST+$WFPC2     | 3.316      | 0.077      | 4.913      | 0.046      |
| 29   | 2008-05-41 | 54623.163206 | 400+700     | $HST+$WFPC2     | 3.419      | 0.080      | 4.872      | 0.045      |
| 30   | 2008-05-42 | 54624.034733 | 500×2       | $HST+$WFPC2     | 3.257      | 0.075      | 4.899      | 0.047      |
| 31   | 2008-05-43 | 54625.100706 | 500×2       | $HST+$WFPC2     | 3.285      | 0.075      | 4.833      | 0.045      |

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variability ($\sim 0.05$ mag in the VLT and $\leq 0.02$ 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.

Figures 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 ($\Delta B = B_B - B_{C1}$, $\Delta V = V_B - V_{C1}$) 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 (n. 24 and 31) that differ by 0.1 mag.
Figure 1. Joint VLT+HST light curve of NGC 1313 X-2 in the $B$ band. The squares are 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 $\sim 7.5$ months. The solid (cyan) line is the best fitting sinusoid with a period $P = 5.68$ days.

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

| Sample            | $<\Delta B>$ | $<\Delta V>$ | $\sigma^a$ | $P^a$ (days) | $A^a$   | $\phi^a$ | $\chi^2$(dof) |
|-------------------|--------------|--------------|-------------|-------------|---------|-----------|---------------|
| VLT+HST$^b$ (B band) | 3.198        | 0.078        | $5.68^{+0.01}_{-0.01}$ | $0.06^{+0.02}_{-0.03}$ | $270.5^{+20.0}_{-31.0}$ | $21.0$ (28) |
| VLT (B band)      | 3.201        | 0.038        | $6.01^{+0.01}_{-0.01}$ | $0.06^{+0.03}_{-0.03}$ | $950.5^{+25.0}_{-23.0}$ | $21.9$ (28) |
| HST (B band)      | 3.196        | 0.094        | $6.1^{+0.18}_{-0.17}$  | $0.10^{+0.02}_{-0.02}$ | $800^{+13.0}_{-13.0}$   | $13.4$(17) |
| VLT+HST (V band)  | 4.843        | 0.047        |             |             |        |           |               |

$^a$ Standard deviation

$^b$ Parameters of the two deepest minima.

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 ($\sim 1$ day) variability. As can be seen from Figure 1 the $B$ band HST data have larger root mean square variability than the $B$ band VLT ones. Similarly, comparing Figures 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 (Figure 2), whereas the $HST$ $B$ band dataset shows an approximately sinusoidal modulation with a period of 6 days (Figure 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:

$$\Delta B = <\Delta B> + A \sin(2\pi(t - t_1)/P + \phi),$$

(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% confidence level, they are in agreement at the 3-\( \sigma \) level. Furthermore, the \( \chi^2 \) surface for the VLT+HST dataset has several (at least 5) pronounced minima in the range \( \sim 5.7-7.1 \) days (5.7, 6.0, 6.2, 6.7, 7.1 days, respectively), with similar values of the \( \chi^2 \). The 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. (2004).

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 observation (sampling interval). This is not larger than \( P \), indicating that the two datasets can be phase connected. Indeed, this represents the longest phase-connected photometric dataset 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% 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, \( A = 0.1^{+0.02}_{-0.03} \) mag. The \( \chi^2 \) is 31.5 for 17 d.o.f., corresponding to a null hypothesis probability of 0.0174. The rather large value of the \( \chi^2 \) 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 \( \sim 215 \) 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 \( \sim 0.04 \) days \times (220/6) \( \sim 80^\circ \).

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 the HST observations. The maximum power is at 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%), meaning that the statistical significance of the modulation is low. In order to increase the signal-to-noise, we then decided to bin the light curve in \( M = 6 \) bin intervals and perform an epoch folding period search. The peak of the distribution is \( \chi^2 = 17.2 \) at \( P = 6 \) days. For \( \nu = M - 1 = 5 \) degrees of freedom, 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 estimated the significance of the 6 day period using also 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 \( \nu_2 = N - M = 25 \) degrees of freedom, 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 Figure 3 we show the folded light curve along with its best fitting sinusoid \( (P = 6.0 \) days, \( A = 0.08, \phi = 54^\circ \)). 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 6-7 observations appear to follow a sinusoidal behaviour). We tried a sinusoidal fit also of this dataset 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 \( \sim 56\% \)). As shown in Figure 4 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%. 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 \( \nu_2 = 14 \) degrees of freedom, or to a significance level of 4\( \sigma \) (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 reported by Liu et al. (2009) (6\( \sigma \)) relies on the statistical treatment of the data and not on the different photometric analyses.
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 (~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 2003-2004, when the B band light curve showed an intermediate level of variability (standard deviation ~0.056 mag) with respect to the two datasets considered here. There may be different reasons for this behavior. Some B stars have intrinsic variability on a timescale of a few hours that may be different from one cycle to the next, even though the baseline is constant (e.g. β 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 timescale 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 datasets is more similar (standard deviation ~0.05 mag for VLT, ~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 3-4; 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 ΔB reported in Table 4 which is not significantly different between the VLT and HST observations. On the other hand, as already mentioned, it is important to remind that there may be possible residual systematic uncertainties in the conversion between the VEGAMAG and UBVR1 photometric systems. In particular, in performing the conversion, we applied a color correction (to both objects C1 and D) estimated from the colors reported in Mucciarelli et al. (2003). However, we know that the color of object C1 is variable and is likely to become bluer if X-ray heating increases. Furthermore, we found that the inferred (B − V) color 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. (2003) (although they are in agreement within the errors). Both effects would tend to change the average ΔB of the HST data and shift them upwards in Figure 1 as expected if X-ray irradiation has increased. For an error and/or variation in the colors of 0.15 mag, the average ΔB 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

4 DISCUSSION AND CONCLUSIONS

We re-analyzed the longest phase-connected photometric dataset available for NGC 1313 X-2 using VLT+FORS1 and HST+WFPC2 observations taken between October 2007 and June 2008. 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 3σ. 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 (Liu et al. 2009; Grisé 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 what reported previously in the literature. However, the major improvement of our work consists in a careful statistical re-analysis of the data, that includes binning the light curve and using the L statistics for small sample sizes (Davis, 1990). While excluding the VLT observations from the analysis does not affect significantly our conclusions, we find that they can be phase-connected to the HST dataset and are consistent with it. They also show that the optical luminosity of the counterpart is quite steady on timescales 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 both from space and from the ground, if 8+ meter class telescope are available. Necessary condition in the latter case is having optimal seeing and rather isolated counterparts.
vary much between the two datasets, one may still think to some particular conditions under which the modulated fraction of the emission varies without significant changes in $\Delta B$. 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-flux 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 band 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 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 et al. 1973), 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 torus 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 HeII $\lambda 4686$ 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% 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 HeII $\lambda 4686$ 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 mag 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 CM 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 $8 - 9 \times 10^{11}$ cm and a separation from the BH of $4 \times 10^{12}$ cm, and so it will intercept a fraction $\sim 10 - 15\%$ 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, make its identification uncertain. A dedicated photometric monitoring campaign under homogeneous observing conditions to minimize systematic uncertainties are needed to confirm it.

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