ULTRALUMINOUS X-RAY SOURCES IN NEARBY GALAXIES: CLUES ON THEIR NATURE FROM X-RAY TIMING AND NEW OPTICAL DATA

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ABSTRACT

We present results from new optical and X-ray data of two selected ULXs. A recent VLT observation of NGC 1313 X-2 shows that it is a high mass X-ray binary with a very massive donor, while a new *XMM* plus archival *XMM*/*RXTE* data of M 82 X-1 represent the most revealing timing data for a ULX to date.

Key words: galaxies: individual: M82, NGC 1313; X-rays: individual: M82 X-1, NGC 1313 X-2.

1. INTRODUCTION

First revealed by *Einstein*, the population of ultraluminous X-ray sources (ULXs) has increasingly grown up in the last decade mainly thanks to the observations of *ROSAT* (e.g. Colbert & Ptak 2002), *XMM-Newton* (e.g. Foschini et al. 2002a) and *Chandra* (e.g. Liu & Bregman 2005; Swartz et al. 2004). About 150 ULXs are included in the recent *Chandra* catalogue of Swartz et al. (2004). These point-like sources have X-ray luminosities $L_X \geq 10^{39}$ erg s^{-1}, in excess of that of a $\sim 10 M_\odot$ compact object accreting at the Eddington limit. Variability in the X-ray flux on timescales of months is observed in about half of the *ROSAT* ULXs with multiple observations (Colbert & Ptak 2002), while about 5-15% of the *Chandra* ULXs show variability during a single observation (average exposure time $\sim$ 40 ks, Swartz et al. 2004). For several sources with sufficiently good statistics, the best fit to the X-ray spectrum is obtained with a two-component model, a soft multicolor disk (MCD) blackbody plus a power law. Some ULXs show typical temperatures of the MCD component 5-10 times lower than those of Galactic X-ray binaries. The high luminosity, the very soft thermal component (if it represents the emission from a cool accretion disk) and the variability suggest that these sources may be powered by accretion onto an Intermediate Mass Black Hole (IMBH) of 100-1000 $M_\odot$. Nevertheless, many of the ULX properties can be explained if they do not emit isotropically (King et al. 2001) or are dominated by emission from a relativistic jet (e.g. Kaaret et al. 2003). In this case, they may harbor stellar mass BHs and may be similar to Galactic black hole binaries.

Multiwavelength observations are definitely a powerful tool to investigate the nature of ULXs. Radio emission, when present, gives important clues on the geometry, energetics and lifetime of ULXs (Kaaret et al. 2003; Miller et al. 2005). Optical follow-ups are crucial to identify ULX counterparts and clean up the population from the significant contamination of background AGNs and interacting SNe (Foschini et al. 2002b; Masetti et al. 2003; Swartz et al. 2004). Up to now only a very small number of ULXs have been convincingly associated with stellar objects of known spectral type (e.g. Liu et al. 2002, 2004; Kaaret et al. 2004). All these ULXs are hosted in star-forming regions and their optical counterparts have properties consistent with those of early type O-B stars. Some ULXs are also associated with extended optical emission nebulae (Pakull & Mirioni 2002).

Another approach to study the nature of ULXs is through time variability. The analysis of the aperiodic variability in the X-ray flux of X-ray binaries is a powerful tool to study the properties of the inner regions of the accretion disk around compact objects (for a review see van der Klis 2005). In particular, Quasi-Periodic Oscillations (QPOs) provide well-defined frequencies, which can be linked to specific time scales in the disk. QPOs can be broadly divided into three classes: (a) QPOs at very low frequencies (<0.02 Hz), probably associated to oscillations and instabilities in the accretion disk (see Morgan et al. 1997; Belloni et al. 1997, 2000); (b) Low-Frequency (LF) QPOs, with typical frequencies between 0.1 and 10 Hz, probably connected to similar oscillations in neutron star systems (see e.g. Belloni et al. 2002; Remillard et al. 2002a; van der Klis 2005; Casella, Belloni &

Stella 2005), over whose origin there is no consensus; in Black Hole Candidates (BHCs) 3 main different types of LF QPOs have been identified (Casella, Belloni & Stella 2005 and references therein); (c) "hecto-Hertz" QPOs, with a typical frequency of 100-300 Hz, in two cases observed to appear in pairs (Strohmayer 2001a,b). It is currently unclear whether these QPOs show a constant frequency for each source (see Homan et al. 2001; Remillard et al. 2002b), and whether they do appear in pairs obeying particular frequency ratios (see Remillard et al. 2002b). However, since they identify the highest frequencies observed in these systems, they are the best candidates for association with, e.g., the keplerian frequency at the innermost stable orbit, or relativistic precession frequencies. Whatever their physical nature, as they originate in the inner regions of accretion disks around black holes, these features are expected to be produced also in ULXs. However, if ULXs contain IMBHs of 100-1000 $M_\odot$, the frequencies involved are much smaller.

Here we present a follow-up study of the optical counterpart of NGC 1313 X-2 (based on photometric archive data obtained with the ESO VLT telescope) and a timing analysis of a new 105 ks *XMM-Newton* observation of M82 X-1 plus archival *RossiXTE* observations of the same field.

2. NGC 1313 X-2

NGC 1313 X-2 is a prototypical ULX (see Miller et al. 2003; Zampieri et al. 2004 and references therein). With a luminosity $L_X \sim 10^{40}$erg s^{-1} in the 0.2-10.0 keV band, it is a good candidate for harboring an IMBH ($M \geq 100 M_\odot$). Such an option is corroborated by the presence of a very soft X-ray spectral component ($T \sim 200$ eV) which points to a compact object of mass definitely larger than those of Galactic Black Hole candidates. Moreover, the object exhibits X-ray variability on a timescale of months. On the basis of a 19 ks *Chandra* exposure and accurate astrometry of field objects, Zampieri et al. (2004) (Z04 hereafter) derived the source position with an uncertainty of 0.7$''$ (RA=03:18:22.34, DEC=–66:36:03.7; 1σ confidence level). Inside the *Chandra* error box a faint optical candidate was found on a R band image taken with the ESO 3.6 m telescope in January 2002.

We analyzed archive ESO VLT+FORS1 images (BVR) and spectra of NGC 1313 X-2 taken between December 2003 and January 2004 (Program ID 072.D0614). For details on the data reduction and analysis we refer to Mucciarelli et al. (2005a). Figure 1 shows the R and B images. Z04 give the *R* magnitude of a number of objects around NGC 1313 X-2 and of the proposed counterpart (object C in their paper). The latter was close to the limit of detectability on their image and appeared as a single object. Thanks to the higher resolution of the VLT image, in the R and V exposures we are able to resolve object C in two distinct point sources, C1 and C2. Both are inside the *Chandra* error box (see Figure 1). Object C2 is not

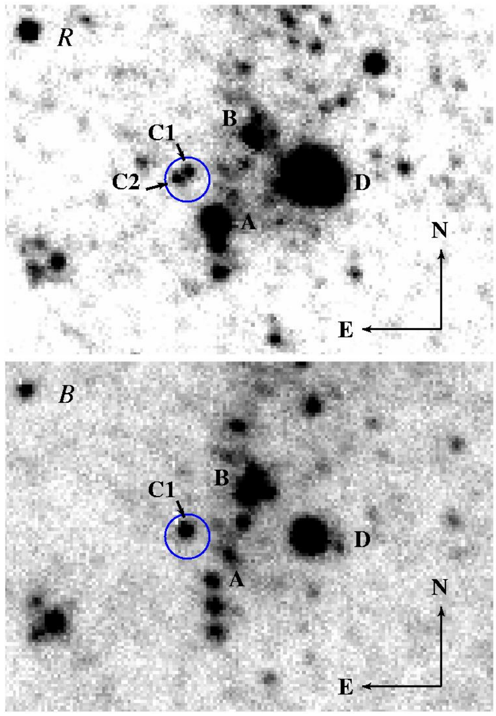

Figure 1. R (upper panel) and B (lower panel) VLT+FORS1 images of the field around NGC 1313 X-2 (30$''$×20$''$). The circle is the 2σ Chandra error-box (1.4$''$). In the R frame, the counterpart is clearly resolved in two point sources, C1 and C2.

detected in the B band frame. Magnitudes, colors and astrometric positions of the two candidate counterparts, C1 and C2, and of objects A, B, and D (following Z04) are reported in Table 1. The photometric errors are the 2σ statistical errors on the measurements with the different Landolt standards. For object C2, we quote an upper limit to the B band magnitude using the plate limit ($B = 25.2$).

In addition to the images, we also analyzed four VLT+FORS1 spectra (λ_c=5900 A, $\lambda/\Delta\lambda$=440 at λ_c) of objects C1+C2 taken in different nights. In these VLT+FORS1 spectra the two sources (C1 and C2) are not spatially resolved. The 2D spectrum taken on 15 January 2004 shows nebular emission lines of [OII] λ 3727 A, H$_\gamma$, H$_\beta$, [OIII] $\lambda\lambda$ 4959-5007 A, [OI] λ 6300 and 6364 A, H$_\alpha$, [NII] λ 6583 A and [SII] $\lambda\lambda$ 6717-6731 A. Note that this is the first detection of a [OII] line from this nebula. A one dimensional spectrum was extracted over an aperture of 2.2$''$ centered on object C1+C2 from each of the four combined spectra. After subtracting the nebular emission (see Mucciarelli et al. 2005a), the source spectra show no evident emission or absorption lines. Residuals are present in coincidence with some nebular lines (expecially [OIII] and H$_\alpha$), with an upper limit to the equivalent width of $\sim$ 30 A. In particular the residual flux in the [OIII] line is a non negligible fraction of the nebular flux. This appears to be caused by an increased emission of the nebular line around the position of object C1+C2.

Table 1. Astrometric positions, magnitudes and colors of the sources around NGC 1313 X-2 (see Figure 1).

Source	RA	DEC	B	V	R	B-V	V-R
A	03:18:21.97±0.05	-66:36:06.4±0.3	23.5±0.15	21.7±0.05	20.6±0.05	1.8±0.15	1.1±0.1
B	03:18:21.57±0.05	-66:36:00.8±0.3	22.4±0.15	22.7±0.05	22.5±0.05	-0.3±0.15	0.2±0.1
C1	03:18:22.26±0.05	-66:36:03.3±0.3	23.5±0.15	23.6±0.15	23.7±0.15	-0.1±0.2	-0.1±0.2
C2	03:18:22.36±0.05	-66:36:03.8±0.3	≥25.2	24.1±0.15	23.6±0.15	≥1.1	0.5±0.2
D	03:18:20.96±0.05	-66:36:03.6±0.3	20.3±0.15	18.9±0.05	18.1±0.05	1.4±0.15	0.8±0.1

It is not clear if this is simply induced by a change in the rather irregular spatial profile of the nebular line or by a variation of the physical conditions produced by the presence of the nearby ULX. Finally, marginal evidence of an excess in emission may be seen at 4686 A, corresponding to HeII emission, but the line is not statistically significant.

3. M82 X-1

The first and, to date, only ULX where a QPO has been discovered is M82 X-1 (Strohmayer & Mushotzky 2003). The QPO has a frequency of 54.4 mHz and a FWHM of 11.4 mHz, leading to a quality value $Q = \nu/\Delta\nu \sim 5$. The total fractional rms of the QPO in the 2-10 keV band is 8.4%. Recently, Fiorito & Titarchuk (2004) reported the identification of another QPO at 106 mHz in the power spectrum of M82 X-1 from *RossiXTE* data, arguing that it may be a harmonic of the QPO at 54 mHz.

Here we report the results from a timing analysis of a 105 ks *XMM-Newton* observation of M82 X-1 performed in April 2004 (Observation ID 0206080101, PI: P. Ranalli) and of archival *XMM* and *RossiXTE* observations of the same field. For details on the X-ray data reduction of these observations we refer to Mucciarelli et al. (2005b). For the timing analysis of the *XMM* data we avoided intervals with high background radiation and limited the extraction to the longest (nearly) uninterrupted segment of data (66 ks) free from solar flares with count rate higher than 30 count s^{-1}. To minimize galactic contamination, source counts were extracted from a circular region of 8$''$ radius and at energies > 2 keV. We produced a light curve from pn+MOS data with a time binning of 0.5 s. A few gaps of typical duration of $\sim$100 s were present in the light curve and were filled with a Poissonian realization around the mean value of counts before and after the gap. We produced a power spectrum (normalized after Leahy et al. 1983) from the resulting light curve and rebinned it by a factor of 256 reaching a frequency resolution of 3.9 mHz. A rather strong QPO peak is present in the power spectrum. We fitted the power spectrum with a model consisting of a constant (for the Poissonian level) plus two Lorentzian components (see Belloni et al. 2002): one zero-centered for the broad band-limited noise and one for the QPO peak. The characteristic frequency for the band-limited noise component (see Belloni et al. 2002 for a definition) is 39.4±8.6 mHz and its integrated fractional rms is $\sim$22% (after subtracting the contribution of the host galaxy). The parameters of the QPO can be seen in Table 2. The quality value Q, defined as the ratio of the centroid frequency over the FWHM of the QPO, is 4.3±0.5. We repeated the analysis in two separate energy bands, 2-4 keV and 4-10 keV. The fractional rms of the QPO in these bands resulted to be 13.8% and 23.9% respectively.

In order to investigate the possible variability of the QPO during the observation, we produced a spectrogram, by aligning power spectra obtained from consecutive stretches of data 2048 seconds long. A trend towards lower QPO frequencies is apparent, correlated with the source count rate. In order to quantify the decrease in centroid frequency, we divided the 66 ks interval in two segments of 33 ks each and repeated the power spectral analysis described above. A fit with the same model used for the total power spectrum confirms that the centroid frequency of the QPO decreased by 10.8±4.0% (see Table 2). In order to investigate the variability of the QPO frequency on longer time scales, we extracted from the *RXTE* public archive all 30 public observations of M82, spanning over the year 1997. For each observation, we accumulated PCA light curves in the channel range 0-35, corresponding to 2-13 keV, with a 0.5 s bin size and produced power spectra in the same way as for the *XMM* data. We detected a significant QPO in seven observations, including the three reported by Strohmayer & Mushotzky (2003) and Fiorito & Titarchuk (2004). The timing history of these detections is shown in Figure 2, where also the *XMM* detections are indicated. Although the frequencies are variable, they are roughly consistent with three groups in harmonic 1:2:3 ratio, as recently suggested by Fiorito & Titarchuk (2004). In order to calculate the significance of such an harmonic relation we did a numerical simulation and found the nine QPO frequencies (the seven from RXTE data plus the two from XMM) to be consistent at 2.8 σ with being harmonics of a fundamental frequency of 54.9 Hz. However, this is not sufficient to completely rule out that such a distributions occurs by chance. More detections are clearly needed in order to address this issue.

4. DISCUSSION

4.1. NGC 1313 X-2

The superb quality of the VLT images reveals that two distinct objects, C1 and C2, are visible inside the *Chandra* error box of NGC 1313 X-2 in the *R* and *V* bands.

Table 2. M82 X-1. Parameters of the XMM QPO (1σ errors).

Parameter	Total observation	First half	Second half
ν_0 (mHz)	113±2	120±3	107±4
$FWHM(mHz)$	26±3	21±4	19±3
Frac % rms	18.3±1.0	17.5±1.1	17.3±1.1
Signif. (σ)	8.9	8.3	8.2

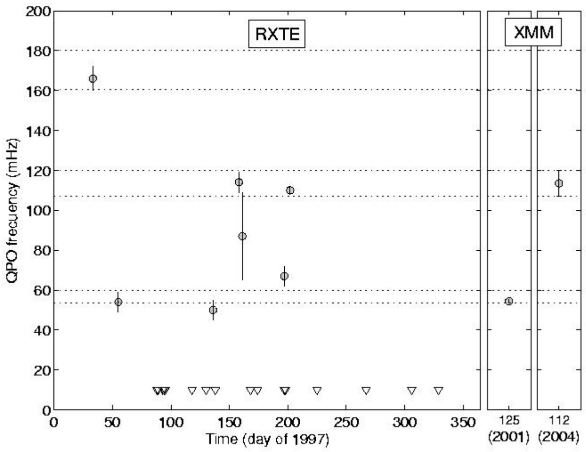

Figure 2. Time history of the centroid frequencies detected from M82 X-1 in the XMM and RXTE data. The triangles indicate the times of RXTE observations when no significant QPO was detected. The pairs of dotted lines indicate the range of frequencies detected by XMM in 2004 and the corresponding intervals at half and 1.5 times the frequency.

From the astrometric positions reported in Table 1, we infer a separation of $0.75''$ and a position angle (C2 with respect to C1) of ~131°.

The possibility that either C1 or C2 may be a background AGN appears very unlikely. In fact, no statistically significant emission line at wavelengths longer than H_α is observed in the optical spectrum nor any other feature that may be identified with a highly redshifted emission line (for a thorough discussion see Mucciarelli et al. 2005a). Within the photometric errors, the colors of object C1 appear to be consistent with those of a A3-O9 I or a A2-B0 V star, while those of C2 with a G8-G7 I star (see e.g. Cox 2000). Unfortunately, the optical continuum does not provide useful information for assessing the spectral type because the light from both objects contributes to it. Observationally, the slope of the continuum can be caracterized by a power law, $\lambda^{-1.8}$. The absence or extreme weakness of the HeII λ 4686 A emission line in the optical spectrum suggests that X-ray irradiation is not dominant. Taking Galactic absoption into account and assuming $A_V \simeq 0.3$ (Cardelli et al. 1989 exctinction law with $R_V = A_V/E_{B-V} = 3.1$ has been used throughout), the unreddened colors of object C1 are $(V-R)_0 = -0.2\pm0.2$ and $(B-V)_0 = -0.2\pm0.2$, consistent with those of a B8-O I or A0-O5 V star. For object C2 it is $(V-R)_0 = 0.4\pm0.2$ and $(B-V)_0 \geq 1.0$, consistent only with a G4 I star. Recently, Liu et al. (2005) performed a 6.4 m Magellan/Baade observation of the field around NGC 1313 X-2 and found a $I = 23.3$ mag object in coincidence with the position of C1+C2 (that appear unresolved in their I frame). Assuming that the flux in the I band originates mainly from the redder object C2, we then obtain $(R - I) = 0.3 \pm 0.2$, consistent with our tentative spectral classification.

At the distance of NGC 1313 ($d = 3.7$ Mpc; Tully 1988) the V magnitudes of C1 and C2 (reported in Table 1) translate into the absolute magnitudes $M_V \sim -4.6$ and ~ -4.1, respectively. Comparing these values with the absolute magnitudes of main sequence and supergiant stars (e.g. Cox 2000), we find that the observed value is consistent only with a B0-09 main sequence star for C1, while it is consistent with a G4 supergiant of type Ib for C2. Therefore, we conclude that both C1 and C2 are stars in NGC 1313, with C1 an early type main sequence star and C2 a supergiant. The bolometric luminosities of the two objects are $\sim 3 \times 10^{38}$ erg s^{-1} and $\sim 2 \times 10^{37}$ erg s^{-1}, respectively. Given the density of objects in the field of view ($\sim 50 - 100$ arcmin^{-2}), a significant fraction of which are supergiants in NGC 1313, the probability that C1 or C2 fall by chance inside the 2σ *Chandra* error box is not negligible (~ 0.1). However, the chance occurrence of two objects, separated by only $0.7''$, inside the X-ray error box is $\sim 5 \times 10^{-3}$, sufficiently small to be considered rather unlikely. Actually, if both C1 and C2 are stars in NGC 1313, a physical association may not be unplausible (the distance corresponding to the apparent separation on the sky is $\sim$ 10 pc). Therefore, we conclude that the ULX is most probably physically associated to either object C1 or C2. Irrespectively of which of the two objects is the actual counterpart, NGC 1313 X-2 appears to be a high mass X-ray binary with a very massive donor star.

A B0-O9 main sequence star has an initial mass of $\sim 20M_\odot$. In this respect our analysis essentially confirms the original suggestion by Z04, who proposed that the optical counterpart of NGC 1313 X-2 may be an O type main sequence star in NGC 1313. If the colors are affected by the binary interaction, the estimated mass may vary somewhat. A $\sim 20M_\odot$ donor star could easily provide the mass transfer rate required to fuel the accreting black hole through Roche-lobe overflow during the main sequence phase if the orbital separation is $\approx$ 1 AU. In these conditions, the mass transfer would be stable and the source persistent (Patruno et al. 2005; Patruno & Zampieri, in preparation).

If object C2 is the counterpart, the nature of the system remains unchanged. In this case X-ray irradiation may be significant and give a non-negligible contribution to the optical emission. The mass corresponding to a G4 supergiant is $\sim 10 M_{\odot}$. The same caveat discussed for C1 about the possibility that the colors and mass estimate are affected by binary interaction applies also in this case. The mass transfer rate provided by such a donor star throug Roche-lobe overflow is certainly adequate also for large orbital separations. Wind accretion may also be a viable alternative.

4.2. M82 X-1

M82 X-1 is at present the only ULX where a QPO has been discovered. An important issue is of course the possible identification of this QPO with one of the QPO types observed in the X-ray light curves of stellar-mass BHCs. In the following we will summarize the main properties of the QPO in M82 X-1, and discuss its similarities and differences with the QPOs observed in BHCs.

- The lowest and highest observed frequencies are 50 ± 5 mHz and 166 ± 6 respectively (Figure 2).
- The frequency distribution over this range is suggestive of a harmonic 1:2:3 ratio between them.
- In the 2004 *XMM* observation the frequency is observed to vary by ~10% in less than one day.
- The QPO peak has a quality value higher than 4 (up to ~6 in one case).
- It shows a high fractional rms (up to ~18%).
- The underlying band limited noise is strong (fractional rms ~22%) and has a characteristic frequency comparable to the QPO frequency.
- The integrated fractional rms of the QPO above 4 keV is higher than below that energy.

Let us compare now all these properties with those of the various types of QPOs observed in BHCs.

Very-low frequency QPOs. An association of the QPO in M82 X-1 with the very low frequency ($\nu \leq 0.02$ Hz) “heart-beat” QPOs observed in GRS 1915+105 is unlikely as their frequency is *lower*. This, assuming an inverse scaling with the black-hole mass, would imply a very low (~solar) mass black hole in M82 X-1, which is not in agreement with the spectral evidences (see Mucciarelli et al. 2005b).

High-frequency QPOs. The observed short-time scale variability seems to exclude an association with the high-frequency “hecto-Hertz” QPOs observed in BHCs, since the latter have been detected at rather stable frequencies. Also the presence of a strong underlying band limited noise, with a characteristic frequency comparable to the QPO frequency, is at variance with the high-frequency ”hecto-Hertz”QPOs observed in BHCs. Furthermore, the rms amplitude of the QPO itself in M82 X-1 is roughly an order of magnitude bigger than that of the ”hecto-Hertz” QPOs in BHCs, thus making the association very unlikely. For the sake of completeness we stress that the detection of the QPO at $\sim$ 166 mHz reported in this paper lowers the upper limit for the mass of the black hole in M82 X-1 (assuming that this frequency is associated with the Keplerian frequency at the innermost circular orbit around a Schwarzschild black hole) to $\sim 1.2 \times 10^4 M_{\odot}$.

Low-frequency QPOs. In the type-A and type-B QPOs observed in BHCs, the peak appears always at frequencies near 8 and 6 Hz respectively. Moreover, they are both characterized by a weak (a few %) underlying red noise component. These properties make an association with the variable, strong QPO observed in M82 X-1 unlikely. In the case of type-A QPOs, its low coherence and amplitude make the association even less likely.

The properties of the QPO in M82 X-1 are on the contrary reminiscent of those of the third type of BHCs low-frequency QPO, the type C, whose characteristic frequencies vary in the range 0.1-15 Hz. The similarities in fractional rms, variability, quality value, and underlying noise strongly suggest an association between the two features. Furthermore, in the 2004 *XMM* observation there is evidence for a positive correlation of the QPO frequency with the count-rate, and a similar correlation is often observed in type-C QPOs. However, during the 2001 *XMM* observation (when the QPO was detected at a lower frequency) the count rate was higher than during the 2004 observation. Since the count-rate vs. frequency correlation in BHCs is “outburst dependent” (which means that during different outburst a source can show similar frequencies at different count-rates) no conclusion can be derived from the observed phenomenology in M82 X-1. No information on the count-rate variability could be obtained from the *RXTE* observations, given the lack of imaging capabilities of the satellite.

Assuming that the QPO detected in M82 X-1 is a type-C QPO, and scaling the frequency inversely to the BH mass, the observed frequency range (from 50 to 166 mHz) would yield a black hole mass M_{BH} anywhere in the range 10-1000 $M_{\odot}$. However, type-C QPOs are observed in BHCs throughout the whole Hard-Intermediate State (see Homan & Belloni 2005), and their frequency is known to decrease with the hardness of the energy spectrum. At the lowest observed frequencies, the spectrum is hard and there is often no evidence for the presence of a soft thermal component. As the contribution from a disk appears and increases, the QPO frequency also increases. The *XMM* spectra of both observations in which a QPO has been detected in M82 X-1 show possible evidence for a disk contribution (see Mucciarelli et al. 2005b). To the extent that the two phenomena can be compared, the presence of a soft component would exclude that the type-C QPO in M82 X-1 is in the lowest frequency range, increasing the lower limit for M_{BH}.

5. CONCLUSIONS

We presented an analysis of archive ESO VLT photometric and spectroscopic data of NGC 1313 X-2. The superb quality of the VLT images reveals that two distinct objects, with R magnitudes 23.7 and 23.6, are visible inside the *Chandra* error box. Both are stars in NGC 1313, the first a B0-O9 main sequence star of $\sim 20M_{\odot}$, while the second a G supergiant of $\sim 10M_{\odot}$. Irrespectively of which of the two objects the actual counterpart is, this implies that NGC 1313 X-2 is a high mass X-ray binary with a very massive donor.

We reported also a complete analysis of *XMM-Newton* and *RXTE* observations of M82 X-1. The similarities in fractional rms, variability, quality value, and underlying noise strongly suggest an association between the QPO in M82 X-1 and the low-frequency, type-C QPOs observed in BHCs. This allows us for the first time to put strong constrains to the mass of the central black hole in this source, yielding to a value between a few tens to one thousand solar masses.

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