Weighing the black holes in ultraluminous X-ray sources through timing

P. Casella\textsuperscript{1*}, G. Ponti\textsuperscript{2,3,4}, A. Patruno\textsuperscript{1}, T. Belloni\textsuperscript{5}, G. Miniutti \textsuperscript{6} and L. Zampieri\textsuperscript{7}

\textsuperscript{1}Astronomical Institute “Anton Pannekoek”, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
\textsuperscript{2}IPPC Université Paris 7 Denis Diderot, 75205 Paris Cedex 13, France
\textsuperscript{3}Dipartimento di Astronomia, Università degli Studi di Bologna, via Zamboni, 40127 Bologna, Italy
\textsuperscript{4}INAF-IASF Bologna, via Gobetti 101, 40129 Bologna, Italy
\textsuperscript{5}INAF-Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122, Padova, Italy
\textsuperscript{6}Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
\textsuperscript{7}INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate (LC), Italy

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ABSTRACT

We describe a new method to estimate the mass of black holes in Ultraluminous X-ray Sources (ULXs). The method is based on the recently discovered “variability plane”, populated by Galactic stellar-mass black-hole candidates (BHCs) and supermassive active galactic nuclei (AGNs), in the parameter space defined by the black-hole mass, accretion rate and characteristic frequency. We apply this method to the two ULXs from which low-frequency quasi-periodic oscillations have been discovered, M82 X-1 and NGC 5408 X-1. For both sources we obtain a black-hole mass in the range 100 \sim 1300 M_\odot, thus providing evidence for these two sources to host an intermediate-mass black hole.

Key words: black hole physics – accretion – X-ray: binaries – X-rays: individual: M82 X-1, NGC 5408 X-1

1 INTRODUCTION

Ultraluminous X-ray Sources (ULXs) are point-like, off-nuclear sources which have luminosities greater than \sim 10^{39} \text{ erg s}^{-1}, in excess of that of a \sim 10 M_\odot compact object accreting at the Eddington limit. The high luminosity, the very soft thermal component often observed in many sources (interpreted as emission from a cool accretion disc, see e.g. Miller et al. 2003, and references therein; for different interpretations of the soft X-ray excess see e.g. Stobbart et al. 2006, and references therein) and the variability on timescales from months to hours (Swartz et al. 2004, Mucciarelli et al. 2007) suggest that (some of) these sources may be powered by accretion onto an Intermediate Mass Black Hole (IMBH) of 100-1000 M_\odot. Nevertheless, many of the ULXs properties can be explained if they do not emit isotropically (geometrically beamed emission, see King et al. 2001), are dominated by emission from a relativistic jet (e.g. Kaaret et al. 2003, are accreting at a supercritical rate (Begelman 2002, Ebisawa et al. 2003, Begelman et al. 2006), or a combination of all these. In this case, they may harbor stellar mass black holes and may be similar to Galactic black-hole binaries.

A possible approach to study the nature of ULXs is through fast 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 disc around compact objects, since observed frequencies might be linked to specific time scales in the accretion disc. The best way to do this is by studying the analogies of timing features in ULXs with those in stellar-mass black holes. Measurements of the mass of the black hole in ULXs can then be derived by applying scaling arguments.

Low-frequency quasi-periodic oscillations (QPOs) have been observed in the X-ray light curves of two ULXs, M82 X-1 (Strohmayer & Mushotzky 2003) and NGC 5408 X-1 (Strohmayer et al. 2007). The properties of these QPOs (as, e.g., fractional amplitude, variability, coherence, amplitude and frequency of the underlying noise, frequency-flux correlation, etc.; for a thorough discussion see e.g. Mucciarelli et al. 2006, Strohmayer et al. 2007) are reminiscent of those of the most common low-frequency QPO in BHCs (type-C QPO, Remillard et al. 2002, see Casella et al. 2005 and references therein). This association, assuming an inverse scaling of the QPO frequency with the BH mass, allows for an estimate of the black-hole masses in the range of a few tens of M_\odot to 1000 M_\odot. In order to further constrain the mass of the black hole in these two ULXs, several authors explore different possible scaling relations. Fong & Kaaret (2007) use the correlation between power-law luminosity and QPO frequency in BHCs to estimate a black-hole mass of around 10^3 M_\odot for both ULXs.

From the correlation between the spectral photon index and the QPO frequency (known to exist in BHCs, see e.g. Vignarca et al. 2003, Fiorito & Titarchuk 2004) derived for the BH in M82 X-1 a mass of the order of 10^3 M_\odot. From the same
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where Mc Hardy et al. (2006) has shown that soft-state BHCs and active black holes in active galactic nuclei (AGNs).

2 THE VARIABILITY PLANE

Mc Hardy et al. (2006) has shown that soft-state BHCs and active galactic nuclei (AGNs) populate a plane in the parameter space defined by the black-hole mass, accretion rate and characteristic frequency in the PDS. Körding et al. (2007) recently showed evidence for this variability plane to extend to the hard-states BHCs, with a constant offset for the frequencies (see Fig. 1):

$$\log \nu_t = \log M - 2 \log \dot{M} - 14.7 - 0.9 \theta$$ (1)

where $\theta$ goes from 0 for the soft state to 1 for the hard state (from eq. 6 of Körding et al. 2007). The existence of such a variability plane across different spectral states, if confirmed, would suggest that accretion on BHs is scale invariant. If this is the case, we can thus use the correlation to measure the mass of the black holes thought to be hosted in ULXs. The frequencies and the luminosities observed in ULXs are somewhat intermediate between those in BHCs and in AGNs. Hence it is reasonable and relatively straightforward to put them in the variability plane. The strength of this method is that it uses a relation which appears to hold for many orders of magnitude in frequency, luminosity and black-hole mass. Either ULXs follow the same relation of all the accreting black holes, thus yielding constraints on the masses of the black holes they host, or they do not, thus demonstrating that their accretion flow is somewhat different than in BHCs and AGNs.

2.1 Estimate of the characteristic frequency

In order to use the variability plane to measure the mass of a black hole, we must correctly identify the characteristic frequencies in the PDS of the X-ray light curve of the black hole itself. The relatively robust identification of the QPOs in M82 X-1 and NGC 5408 X-1 with the “type-C” QPO in BHCs (see Sec. 1), helps us in this. The frequency of the type-C QPO is known to correlate with other characteristic frequencies measured in the PDS of BHCs (Wijnands & van der Klis 1999; Psaltis et al. 1999; Belloni et al. 2002; Klein-Wolt & van der Klis 2007, and references therein). In particular, the frequency of the component used in Körding et al. (2007) (the lower high-frequency Lorentzian $\nu_L$) is found to be a factor of ~10 higher than the centroid frequency of the type-C QPO (see Fig. 2 and Eq. 2). In Figure 2, we report data from Belloni et al. (2002) and the best fit power-law to them, after removal of points which do not belong to the plot (because of a different and/or dubious identification of the two frequencies, see § 4.3 of Belloni et al. 2002).

If we assume that this correlation holds also for ULXs, we can use it to estimate $\nu_t$ for M82 X-1 and NGC 5408 X-1 from the QPO frequency $\nu_{QPO}$:

$$\nu_t \approx 12.37 \times (\nu_{QPO})^{1.023}$$ (2)

It must be noted however, that this relation is obtained by extending to the ULXs the relation in Fig. 2, which is known to hold only for

Figure 1. Variability plane for stellar-mass BHCs and AGNs. The lines indicate $\nu \propto M \dot{M}^{-2}$. The upper line is a fit to soft-state objects, the lower is a fit to the hard-state BHCs only (from Körding et al. 2007).

Figure 2. The QPO centroid frequency ($\nu_{QPO}$, which corresponds to the QPO observed in M82 X-1 and NGC 5408) versus the lower high-frequency Lorentzian ($\nu_L$, which is the one used for the variability plane in Körding et al. 2007) in neutron stars and BHCs (adapted from Belloni et al. 2002). The solid line shows the power-law fitted to the data (Eq. 2), while the two dotted lines show the correspondent uncertainty of ±0.5 dex we adopt in our estimate of $\nu_t$ (see Sect. 2.1).
stellar-mass compact objects. This extension appears to us reasonable, given the fact that the relation appears rather tight over a very broad range of frequencies (which includes the frequencies of the QPOs observed in M82 X-1) and compact-object masses, but it is not certain and will need to be confirmed by the next generation of X-ray satellites, which will be able to detect the high-frequency component \( \nu_\ell \) in ULXs.

### 2.2 Estimate of the accretion rate

Another key point is of course how to estimate the accretion rate from the X-ray luminosity. To do this, we need to know how efficient is the accretion in ULXs. Many observational evidences suggest that M82 X-1 and NGC 5408 X-1 are in a somewhat intermediate state (see e.g. Maccarone et al. 2006). The main indication for this is the high amplitude of the QPOs observed in these sources, since BHCs do not show strong QPOs in their soft state (see e.g. Belloni et al. 2005). This means that, a priori, the accretion can be either efficient (soft-state like) or inefficient (hard-state like), or, most probably, intermediate between the two. We can calculate the accretion rate under the two extreme hypotheses, thus deriving a range for the mass of the black hole.

#### 2.2.1 Efficient case

In case ULXs are efficiently accreting sources (\( \eta \sim 0.1 \)), we can measure the accretion rate directly from the bolometric luminosity:

\[
M = \frac{L_{\text{bol}}}{0.1 c^2} > \frac{L_X}{0.1 c^2}.
\]

Where the lower limit is due to the fact that we don’t know the conversion factor from \( L_X \) to \( L_{\text{bol}} \). Applying Eq. (3) to the Eq. (1) for the soft-state case (\( \theta = 0 \)), we can thus derive an expression for the mass of the black hole:

\[
\log \left( \frac{M}{M_\odot} \right) > \frac{1}{2} \log \left( \frac{L_X}{0.1 c^2} \right) - \frac{1}{1.95} \log \nu_{\text{QPO}} - 7.9 \quad (4)
\]

#### 2.2.2 Inefficient case

If the accretion is inefficient, the accretion rate is not linearly related to the X-ray luminosity. However, inefficiently accreting black holes are known to lie on the so-called “fundamental plane” (Merloni et al. 2003; Falcke et al. 2004) defined by X-ray luminosity, radio luminosity and mass. This relation holds for many order of magnitude in masses, connecting the Galactic stellar-mass BHCs to the extragalactic supermassive black holes in AGNs. Under the reasonable assumption that inefficiently-accreting BHS in ULXs would also lie on the fundamental plane (see the Discussion), we can estimate the accretion rate from the 2-10 keV X-ray luminosity:

\[
\dot{M} \approx 0.12 \left( \frac{L_X}{0.1 c^2} \right)^{0.5} M^{0.43} \left( \frac{0.1}{\eta_{\text{acc}}} \right) \quad (5)
\]

where \( \eta_{\text{acc}} \) is the total efficiency of the accretion flow, including both radiative emission and kinetic energy of any ejected matter (from eq. 8 of Körding et al. 2006).

Using again Eq. (1), this time for the hard-state case (\( \theta = 1 \)), and replacing \( \nu_{\ell} \) and \( M \) with our Eqs. (2) and (5) we derive the expression for the mass of the black hole for the inefficient-accretion case:

\[
\log M = \frac{1}{3.14} \log L_X - \frac{1}{1.55} \log \nu_{\text{QPO}} - 11.226. \quad (6)
\]

Eq. (4) and (6) give the bounds for the mass values for a black hole in a ULX with an X-ray luminosity \( L_X \) and a characteristic frequency \( \nu_{\ell} \) in the PDS.

### 2.3 Uncertainties

The uncertainties on the mass values given from Eq. (4) and (6) mainly come from the intrinsic scatter of the three correlations we used to derive the mass estimates. These scatters are larger than the observational uncertainties in the measurements of fluxes and QPO frequencies.

From Fig. 2, we see that the full scatter in \( \nu_{\ell} \) is always smaller than half a decade. We can thus associate a very conservative uncertainty of 0.5 dex (i.e. 1 dex scatter) to the values of \( \nu_{\ell} \) obtained from the measurement of \( \nu_{\text{QPO}} \) (Eq. 4). In other words, given a measurement of \( \log(\nu_{\text{QPO}}) \), the derived value of \( \log(\nu_{\ell}) \) will have a symmetric uncertainty \( \Delta_{\nu_{\ell}} = 0.5 \). This uncertainty obviously dominates the one on the direct measurement of \( \nu_{\text{QPO}} \) (which is of the order of \( \sim 1\% \)).

The uncertainty on the accretion rate estimate is dominated from the scatter in the fundamental plane which, to be conservative, we estimate to be of the order of \( \sim 0.5 \) dex (see fig. 4 of Körding et al. 2006), which translates in a symmetric uncertainty \( \Delta_{\nu_{\ell}} = 0.25 \) dex.

Since we use the variability plane to estimate the black-hole masses, the intrinsic scatter of the plane itself gives in fact an important contribution to the uncertainty on the mass values. Körding et al. (2007) extensively discuss the uncertainties of the variability plane, and conclude estimating an overall error on the normalization of 0.22 dex. The dependent variable in the variability plane is \( \nu_{\ell} M^2 \), which translates in a scatter (full range) of 0.11 dex on the mass (i.e., a symmetric uncertainty \( \Delta_K = 0.055 \) dex). An uncertainty of \( \sim 10\% \) (\( \Delta L = 0.1 \)) can be associated to the measurement of the X-ray luminosity.

These uncertainties are clearly independent, hence we can propagate them quadratically through the Eq. (4) and (6). We do not associate any error to the estimate of the accretion rate for the efficient case. As we do not convert the X-ray luminosity in bolometric luminosity, we are considering a lower limit for \( M \).

The total uncertainties \( \Delta_M \) on the values of \( \log(M) \) are thus:

\[
\Delta_M \approx \sqrt{\left( \frac{\Delta L}{3.14} \right)^2 + \left( \frac{\Delta \nu_{\ell}}{1.55} \right)^2 \Delta_K^2 + \Delta_F^2} = 0.36
\]

for the efficient case (Eq. 4), and:

\[
\Delta_M \approx \sqrt{\left( \frac{\Delta L}{3.14} \right)^2 + \left( \frac{\Delta \nu_{\ell}}{1.55} \right)^2 \Delta_K^2 + \Delta_F^2} = 0.41
\]

for the inefficient case (Eq. 5).

### 3 THE CASES OF M82 X-1 AND NGC 5408 X-1

Let us now apply these arguments to the two ULXs for which a QPO has been discovered: M82 X-1 and NGC 5408 X-1.

#### 3.1 M82 X-1

The QPO in M82 X-1 was observed at 54 mHz and 112 mHz in two XMM-Newton observations in 2001 (Strohmayer & Mushotzky).
Table 1. Values of the characteristic frequencies, luminosities and inferred masses for M82 X-1 and NGC 5408 X-1.

| Source      | $v_{QPO}$ (mHz) | $L_X$ (ergs/s) | Black-hole mass ($M_\odot$) |
|-------------|-----------------|----------------|-----------------------------|
|             | $a$             | Ineff. accr.   | Eff. accr.                  |
| M82 X-1 (2001) | 54±1            | 130±13        | 240$^{+380}_{-150}$ 700$^{+905}_{-305}$ |
| M82 X-1 (2004) | 113±2           | 170±17        | 165$^{+380}_{-150}$ 550$^{+710}_{-310}$ |
| NGC 5408 X-1  | 20±0.5          | 30±3          | 295$^{+465}_{-180}$ 570$^{+735}_{-320}$ |

$\times 10^{38}$, in the 2-10 keV range.

From these frequencies we derive a $v_\nu$ of 0.54 Hz and 1.12 Hz, respectively (see Sec. 2.1). After correcting for crowding, Feng & Kaaret (2007) estimate a 2-10 keV source luminosity of $1.3 \times 10^{40}$ ergs s$^{-1}$ and $1.7 \times 10^{40}$ ergs s$^{-1}$ for the 2001 and 2004 observation, respectively. By inserting these numbers in Eq. (4) we obtain, for the efficient case, a black-hole mass $700^{+905}_{-305} M_\odot$ (2001) and $550^{+710}_{-310} M_\odot$ (2004). If we assume an inefficient accretion, we instead obtain a black-hole mass value of $243^{+380}_{-148} M_\odot$ (2001) and $165^{+260}_{-100} M_\odot$ (2004) from Eq. (6).

From these values we see that we can put a lower limit for the black hole in M82 X-1 of 95 $M_\odot$ (smaller values would not be consistent with the 2001 observation) and an upper limit of 1260 $M_\odot$ (higher values would not be consistent with the 2004 observation).

3.2 NGC 5408 X-1

The QPO in NGC 5408 X-1 was observed at 20 mHz (Strohmayer et al. 2007), which yields to a $v_\nu = 0.20$ Hz. We reanalyzed the public XMM-Newton data and obtained a 2-10 keV unabsorbed luminosity of $3.0 \times 10^{40}$ ergs s$^{-1}$. Using these values, we derive a black-hole mass of $295^{+465}_{-180}$ $M_\odot$ for the inefficient-accretion case and $570^{+735}_{-320}$ $M_\odot$ for the efficient-accretion case. This translates in a lower limit of $115 M_\odot$ and an upper limit of $1300 M_\odot$ for the mass of the black hole in this source.

4 DISCUSSION

In Table 1 we report the inferred values for the mass of the black holes in M82 X-1 and NGC 5408 X-1. It is evident that this method supports the identification of both black holes as “intermediate-mass black holes”. Since we do not know the efficiency of the accretion in the two sources, we cannot further constrain the masses. However, a comparison with BHCs can give some hints on this.

QPOs similar to those discovered in these two ULXs are often observed in BHCs during their intermediate state. The frequency of these QPOs usually increases, and their amplitude decreases, as the source becomes brighter and the energy spectrum softens (see e.g. Casella et al. 2004; Belloni et al. 2003; Homan & Belloni 2005). This softening is usually due to a steepening of the hard power law and to an increase of the soft, thermal disc flux. The increase of the disc flux might be also the origin of the decrease of the QPO amplitude, in case the QPO itself arises from the hard power law. Hence, the high amplitude of the QPOs observed in the X-ray light curve of M82 X-1 and NGC 5408 X-1, as well as the presence of a very weak disc in their energy spectra, suggest that these two sources are on the hard side of the intermediate state. However, in case these two sources host an intermediate-mass black hole, a relatively low-temperature disc is expected (Miller et al. 2003 and references therein).

The QPO in M82 X-1 has already been observed at two different frequencies. Over this small data set the source has shown to follow several correlations known to exist in BHCs. Namely, the QPO frequency increases and its amplitude decreases as the source becomes brighter. This means that during the 2004 observation (see Table 1) the source was probably in a slightly softer, more efficient state than in 2001. If we use, for the 2004 observation, the same luminosity-to-accretion rate conversion than in 2001, we are actually underestimating the accretion rate. This is consistent with the fact that we obtain slightly lower ranges of mass values for the 2004 observation than for the 2001 one.

In Section 2.2 we use the fundamental plane of accreting BHs to convert the X-ray luminosity in accretion rate for the inefficient case. This method is based on the assumption that ULXs lie on the same radio/X-ray correlation as BHCs and AGN do. To date, radio counterparts have been found only for a few ULXs (see e.g. König et al. 2005 and references therein). A full discussion about the radio-to-X-ray luminosity ratio of ULXs has already been started by other authors, and is beyond the aim of this Letter. Here we only note that NGC 5408 X-1 is one of the few ULXs for which a steady radio counterpart has been detected. König et al. 2005 used the values of X-ray and radio luminosity of this source to measure the mass of the hosted black hole, obtaining a value of $\sim 1000 M_\odot$, which is roughly consistent with the values we found. It must be noted, however, that the observed steep, inverted radio spectrum is consistent with a thin synchrotron emission, and not with the steady flat radio spectrum observed in hard-state BHCs (for a discussion see Soria et al. 2006). The slope of the radio emission in NGC 5408 X-1 suggests that the source is on the soft side of the intermediate state, when thin synchrotron radio emission is often observed in BHCs. This would imply that the mass of the BH in this source is closer to the values obtained in the efficient case. A bright, variable radio counterpart has been reported also for M82 X-1. Its strong variability clearly rules out the possibility to use the radio flux to place the source on the fundamental plane, since the latter is valid only for steady states. The upper limit for the steady emission, however, is still consistent with the source lying on the plane and a BH of a few hundreds of solar masses.

4.1 Non-standard accretion flow

The method described in this Letter is based on the initial assumption that the accretion flow in ULXs follows the same general rules as the one in stellar-mass and supermassive BHs does. If the accretion onto the black holes in ULXs does not follow general scale-invariant relations, the method described here, as well as many other scaling arguments, loses validity. Let us thus discuss possible alternative scenarios.

For example, it has been proposed for the ULXs to be sources similar to SS433, but with a different viewing angle. In this scenario, most of the X-ray luminosity emitted from a supercritical accretion disc (Begelman 2002) would be geometrically collimated (Begelman et al. 2006; Poutanen et al. 2007). The main concern, when invoking a beamed emission (either geometric or relativistic) is whether QPOs can be preserved. Any physical interpretation of the ULXs involving beaming will need to demonstrate that relatively coherent oscillations in the X-ray flux do not get smeared out by the beaming itself.

Without applying any beaming correction, i.e. remaining under the assumption of roughly isotropic emission, there are only
two possible ways for a stellar-mass BH (\(\lesssim 20 \, M_\odot\)) to reach X-ray luminosities as high as \(10^{40}\) ergs sec\(^{-1}\): either the accretion rate is super-Eddington, or the accretion rate is still below the Eddington limit, but the accretion flow is extremely efficient, as to produce such high luminosities. For example, it has been suggested that ULXs host super-Eddington accreting, stellar-mass black holes, somewhat similar to the microquasars in our Galaxy, as GRS 1915+105 (see e.g. King 2002). However, GRS 1915+105 itself lies on many of the relations used here and in literature to measure the black-hole mass in ULXs, as well as other very luminous microquasars do. The very highly, sometimes super-Eddington accreting Galactic microquasars appears to follow the same general relations of the sub-Eddington accreting black holes.

To discuss the case of extremely efficient accretion, let us take the most extreme case of an efficiency of 50% (maximally rotating Kerr BH) and of a bolometric luminosity equal to the X-ray luminosity. Under these extreme assumptions, from Eq. (4) we would obtain \(M = 300_{-0.200}^{+400} \, M_\odot\) (for the 2004 observation of M82 X-1). This demonstrate that, even in case of an extremely efficient accretion, the method presented in this Letter yields a BH mass higher than 130 \(M_\odot\).

More observations are clearly needed in order to test the validity of the method described here. Detecting more QPOs from M82 X-1 and NGC 5408 X-1, hopefully at different frequencies and/or luminosities, will show whether these two sources lie on the variability plane or not. The current data strongly argue for M82 X-1 and NGC 5408 X-1 to host intermediate-mass black holes, both with a mass from \(\sim 100\) to \(\sim 1300 \, M_\odot\).

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