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Kilohertz QPOs, the marginally stable orbit, and the mass of the central sources – a maximum likelihood test

T. Bulik[1], **W. Kluźniak**[1], **and W. Zhang**[2]

[1] Copernicus Astronomical Center, Bartycka 18, 00-716 Warszawa, Poland
[2] Laboratory for High Energy Astrohysics NASA/GSFC, Greenbelt, MD 20771, USA

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Abstract. Kilohertz quasi perodic oscillations (QPOs) have been detected in more than a dozen LMXBs. We show that the observations are consistent with the assumption that the maximum-frequency QPOs occur in the innermost (marginally) stable orbit allowed by general relativity. On this assumption, taking the masses of the compact objects to be randomly distributed in some interval, we use the maximum likelihood method to determine the minimum and maximum mass in the parent distribution of kHz QPO sources. At the 99% confidence level, we find the mass range of the accreting compact objects to be $(1.55\,M_\odot, 2.40\,M_\odot)$, in remarkable agreement with the expected mass range of neutron stars in LMXBs.

Key words: stars: binaries: general – stars: oscillations – X-rays: stars

1. Introduction

Kilohertz quasi periodic oscillations have been discovered in 1996 by Rossi X-ray Timing Explorer, in observations of the low-mass X-ray binaries (LMXBs) Sco X-1, and 4U1728-34 (Strohmayer et al. 1996a; van der Klis et al. 1996a). By now, kHz QPOs have been found in more than a dozen of sources which are thought to contain accreting neutron stars. They usually come in pairs, in some sources the difference between the two QPO frequencies in a pair changes noticeably with the X-ray flux. A third frequency is observed in X-ray bursts with a value similar to the difference between frequencies in the pair, or in some cases double this value. For a review see van der Klis, 1998.

It is natural to expect that there is a highest frequency to be observed in LMXBs, the orbital frequency at the marginally stable orbit (Kluźniak et al. 1990). Indeed, Zhang et al. (1998b) noted that in 4U1820-30, at high count rates, the QPO frequency saturates at a value of about 1.06 kHz, and interpreted this as evidence for orbital motion in the marginally stable orbit. However, such a saturation is not clear in other sources, and it has been shown that there may exist a correlation between the QPO frequency and the position along the track traced out in the color-color diagram (Jonker et al. 1998; Mendez et al. 1998). Such correlations depend on a particular model of the source of kHz QPOs, yet in this paper we only assume that the QPO frequency has to be bounded from above by the frequency of the marginally stable orbit.

If the highest QPO frequency is interpreted as the orbital motion around a moderately rotating compact object (stellar remnant), then a value of the mass of the object can be inferred (Kluźniak et al. 1990). Assuming this interpretation for all the sources known, we find the mass range of the central objects, and show that this mass range is compatible with neutron stars. This reinforces the identification of the highest value of the QPO frequencies with the general-relativistic orbital frequency close to the marginally stable orbit (Kaaret et al. 1997; Zhang et al. 1998b; Kluźniak 1998).

In Sect. 2 we decribe the data set used for this analysis, in Sect. 3 we present the model for QPO, which is subjected to a K-S test (Sect. 4). Sect. 5 introduces the likelihood function formalism. The results and their discussion follow in Sects. 6 and 7.

2. The data

Kilohertz QPOs in steady emission have been observed from eighteen sources. We present a list of the sources and the highest frequencies of their QPOs in Table 1. The top thirteen entries in the table represent the points that are likely to be close to the maximal frequency from the given source. We think that the bottom five sources have not yet been observed for a time sufficiently long to establish the correct maximum frequency of the QPO.

The five sources listed in the bottom of the table are those for which there are serious doubts as to whether the maximum frequency has already been observed. In the case of GX 349+2 the highest frequency observed listed in the table is 978 Hz. There was however a hint of a higher frequency in another observation, Kuulkers & van der Klis (1998) reported a possible 2.6σ detection at the frequency of 1020 Hz. The observation of GX 5-1 where the 895 Hz QPO was found was quite short

Send offprint requests to: T. Bulik (bulik@camk.edu.pl)

and hence it is likely that the QPO frequency was not at the maximum. In the case of Aql X-1 only one kilohertz QPO is seen, and therefore it is likely that we see only the lower peak. The last entry in Table 1 is GX 340+02, where the highest QPO frequency is only 820 Hz. The QPO frequency has been found to increase along the Z-track in this object (Jonker et al. 1998), with a simultaneous decrease of the rms amplitude. The difference between the upper and lower peaks is consistent with a constant 325 Hz, and there is a measurement of the lower QPO at ≈ 650 Hz. It is likely that with a longer exposure the upper peak would be seen at the frequency $650 + 325 = 975$ Hz, or even higher when the source is further along its Z-track.

The presence and absence of kHz QPOs are correlated with source position on the color-color diagram (Zhang et al. 1998b; Méndez et al. 1999). To the extent that repeated disappearance of QPOs have been observed at the same position on the color-color diagram, or at similar total count rate, we can be sure that the apparently highest frequency has been observed for that particular source–this is the case for many of the top thirteen sources in the table. Therefore an empirical determination of whether or not the highest possible QPO frequency may have been observed for a given source, critically depends on the length of observation. The partition of the table into two sections is determined by taking into account of the exposure time.

We consider two sets of data: one, $\mathcal{S}_1$, where we take only the top thirteen entries in Table 1, and the second, $\mathcal{S}_2$, where we use all eighteen frequencies. Our main conclusions are the same for both data sets.

Table 1. Kilohertz QPO highest frequencies

Object	f_{max} [Hz]	Reference
4U 1636-536	1220	Zhang et al. (1997a)
KS 1731-260	1207	van der Klis et al. (1997)
4U 1702-43	1156	Markwardt et al. (1999)
4U 1728-34	1150	Zhang et al. (1997b); Strohmayer et al. (1996b)
4U 1735-44	1149	Wijnands et al. (1996)
4U 0614+09	1145	Ford et al. (1997)
Sco X-1	1130	van der Klis et al. (1996a)
4U 1608-52	1125	Mendez et al. (1998)
X 2123-058	1123	Homan et al. (1999)
GX 17+2	1087	Wijnands et al. (1997)
4U 1705-44	1075	Ford et al. (1998)
4U 1820-30	1066	Smale et al. (1997)
Cyg X-2	1020	Wijnands et al. (1998)
GX 349+2[1]	978	Zhang et al. (1998c)
GX 5-1[2]	895	van der Klis et al. (1996b)
Aql X-1[3]	830	Zhang et al. (1998a)
GX 340+02[4]	820	Jonker et al. (1998)
XTE J1723-376[2]	816	Marshall & Markwardt (1999)

[1] also a 2.6σ detection of a 1020 Hz frequency (Kuulkers & van der Klis 1998).
[2] a short observation
[3] only one peak observed,therefore it is likely that we do not see the real highest frequency QPO
[4] probably not the maximal frequency yet

3. Kilohertz QPOs–the model

We consider an interpretation of the kHz QPOs in which they occur at the orbital frequency in the inner accretion disk around the compact central object whose stellar radius is smaller than the innermost (marginally) stable circular orbit allowed in general relativity (GR). It is expected that the accretion disk in such cases terminates close to the radius of the marginally stable orbit, and hence, that the orbital frequency–and the kHz QPO with it–will have an upper cutoff. Such a cutoff may already have been observed in 4U 1820-30, where the kHz QPO frequency saturated at a certain X-ray flux level, and remained constant with increasing flux (Zhang et al. 1998b). However this saturation is not robust in most sources (Kaaret et al. 1999) and, as already remarked above, the cutoff frequency is more apparent in the color-color diagram.

The complex phenomenology of the QPOs (van der Klis 1998) and the lack of two- or three-dimensional theoretical solutions for the structure of the inner accretion disk in LMXBs make the above interpretation uncertain. Here, we wish to test whether the observed frequency distribution of the maximum QPO frequency in the thirteen well observed sources is consistent with this interpretation.

We make an additional assumption that the masses of the central object have a flat distribution between M_0 and M_1. Such a distribution may appear for example if kHz QPOs first appear at a definite mass of the accreting object (e.g. when its surface dips below the marginally stable orbit) and we observe each object exhibiting a QPO at a random moment of its accretion history; then, if the mean accretion rate is approximately constant over the lifetime of the kHz QPO sources their expected distribution in mass is uniform. Hence, we take the probability density $p(M)$ to be

$$p(M) = \begin{cases} (M_1 - M_0)^{-1}, & \text{if } M_0 < M < M_1, \\ 0 & \text{elsewhere} \end{cases} . \quad (1)$$

To first order in the rotation rate of the star, the orbital frequency in the marginally stable orbit is

$$\nu_{ms} = 2198\,\mathrm{Hz}(M_\odot/M_*)(1 + 0.748j) \quad (2)$$

where M_* is the mass of the central object and $j = cJ/GM^2$ is the dimensionless angular momentum of the star (Kluźniak & Wagoner 1985; Kluźniak et al. 1990). We will continue the discussion in terms of the masses, M, obtained for non-rotating stars ($j = 0$), but the results can be reinterpreted for moderately rotating stars (at least down to 3 ms periods) with the understanding that, through first order in j, the true gravitational mass of the star is $M_* \approx M(1 + 0.75j)$. The probability density in the frequency space is easily obtained from Eqs. 1 and 2:

$$p(f) = \begin{cases} 2198 f^{-2}(M_1 - M_0)^{-1}, & \text{if } \dfrac{2198}{M_1} < f < \dfrac{2198}{M_0}, \\ 0 & \text{elsewhere} \end{cases}$$

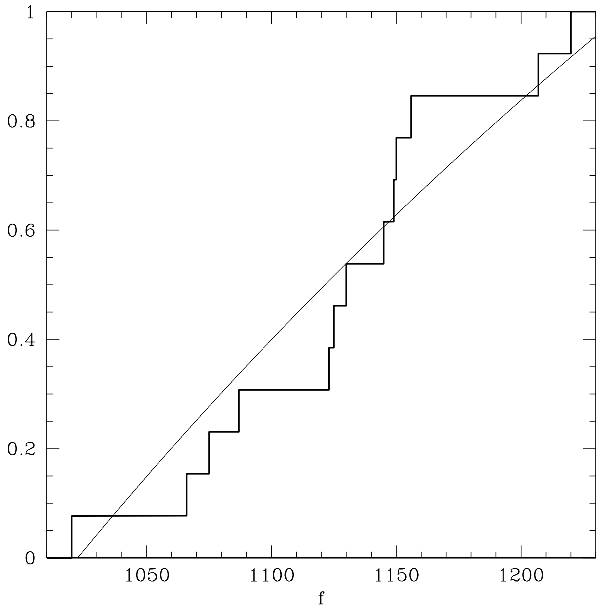

Fig. 1. Cumulative distribution of the data set $\mathcal{S}_1$ and the model for $M_0 = 1.77\,M_\odot$ and $M_1 = 2.15\,M_\odot$ (Eq. 3). In our model the highest observed QPO frequencies are orbital frequencies in the marginally stable orbit for static stars uniformly distributed in mass in the range (M_0, M_1). The probability that the observed distribution has been drawn from the one given by the model is 63%.

(3)

where f is the QPO frequency in Hz and M is the stellar mass in units of solar mass, $M_\odot$.

4. A test of the model

Thirteen sources, for most of which the maximum frequency has already been observed, provide a sufficeintly large data set for testing the null hypothesis that the maximum QPO frequency is given by the model of Eq. (3). We find that the model fits the data reasonably well.

For instance, comparison of the actually observed distribution of frequencies with the one expected on the model can be made for several choices of the minimum and maximum stellar mass, M_0 and M_1. Fig. 1 exhibits one such comparison, for the values $M_0 = 1.77 M_\odot$, $M_1 = 2.15 M_\odot$, which happen to be close to the most likely ones (Sects. 5, 6 and Fig. 2). Application of the Kolmogorov–Smirnov test, shows that the two distributions are in fair agreement, and the probability that they come from the same distribution is 63% (the null hypothesis cannot be rejected). This provides a quantitative basis for assuming that the maximum QPO frequency is attained in the marginally stable orbit.

To learn more about the sources, we wish to find the most likely interval, (M_0, M_1), of masses of the compact objects exhibiting the phenomenon of kHz QPOs. We will find the mass range using the maximum likelihood method.

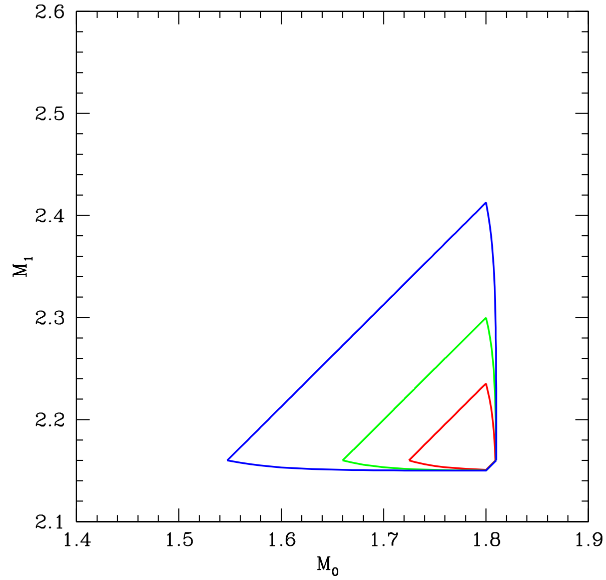

Fig. 2. Probability density contours in the M_0, M_1 plane. The contours encircle regions containing 67%, 90%, and 99% probablity.

5. Likelihood function

Suppose that we have a set, $\mathcal{S}$, of experimentally measured values of a variable y, and a model giving the probability density $p(y)$, which depends on parameters α, β. The set of measurements $\mathcal{S}$ contains N elements. The probablity density $p(y)$ determines the Poisson density $\mu(y) = N p(y)$.

A very convenient way to estimate the values of the parameters that correspond to the measurements is to use the likelihood function, $\mathcal{L}$ (Loredo & Wasserman 1995). Let us first divide the space of measured values into bins, and denoting by $i = 1 \dots N$ the bins where detections occured and by $j = 1 \dots M$ the bins with nondetections. Now, for any values α, β we can calculate the likelihood of obtaining, in the framework of the model, the same values of y as in the observed set $\mathcal{S}$. This likelihood is given by the product over all the bins of the probability of detection for the bins where one of the observed values falls into the bin, and the probability of nondetections in the opposite case. Thus the likelihood function is given by

$$L = \left(\prod_{i=1}^{N} e^{-\mu(y_i)\Delta y_i} \mu(y_i) \Delta y_i \right) \times \left(\prod_{j} e^{-\mu(y_j)\Delta y_j} \right) . \quad (4)$$

Eq. 4 still contains an arbitrary parameter - the bin size Δy_i. It can be eliminated by going to the limit of infinitely small bin size (Graziani, private commnication). We obtain

$$L \to \exp(-N) \times \prod_{i=1}^{N} \mu(y_i) dy_i \propto \prod_{i=1}^{N} p(y_i). \quad (5)$$

Having computed the likelihood function we normalize it, and treat it as the probability density of the unknown parameters α, β, allowing us to find the most likely values of the parameters.

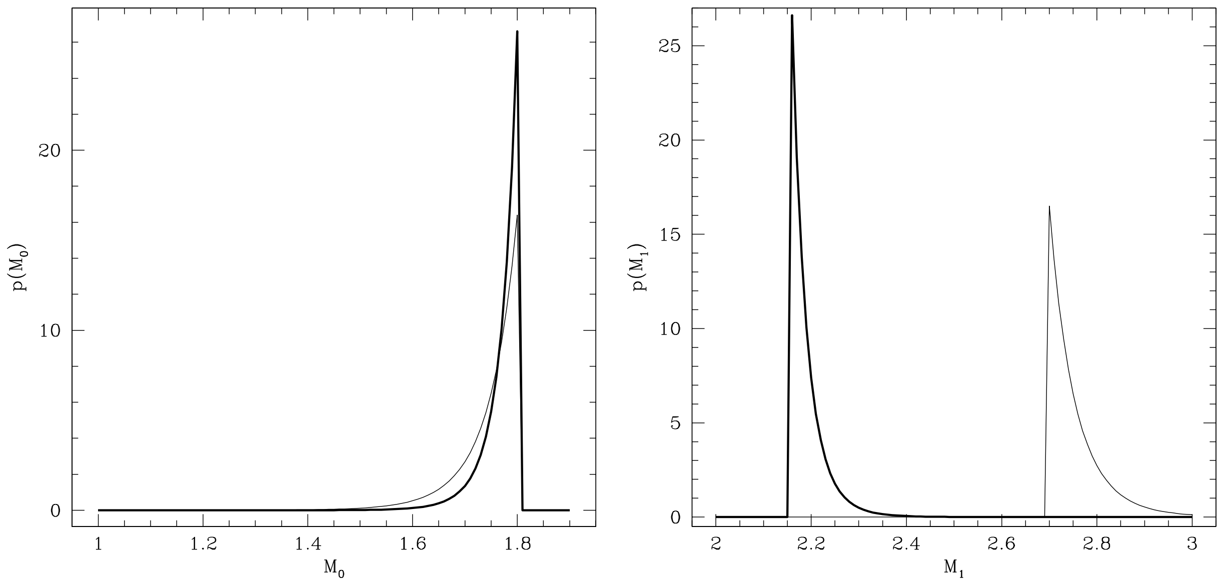

Fig. 3. The left panel shows the probability density of M_0 and the right panel shows the probability density of M_1. The thick lines are the result of dataset $\mathcal{S}_1$ analysis, and the thin lines correspond to $\mathcal{S}_2$.

Further, $\mathcal{L}$ can be collapsed to the probability density of one parameter by integrating out the remaining parameters,

$$p(\alpha) = \int \mathcal{L}(\alpha, \beta)\, d\beta. \tag{6}$$

Finally, it allows to find credible region of the parameters by ploting regions with the likelihood larger than a given value.

6. Results

We have calculated the probability density of the parameters M_0 and M_1 with the two sets of data points described in Sect. 2. We present the contour plot of the probability density for the case of the restricted data set $\mathcal{S}_1$ in Fig. 2.

The probability density $p(M_0)$ for the lower mass, M_0, and the probability density for M_1 are shown in Fig. 3. The thin lines show the results obtained using the full data set $\mathcal{S}_2$ (eighteen frequencies). Clearly, the width of the distribution depends on all the points.

The probabilities are very strongly peaked at the value of $M_0 = 1.78\,M_\odot$ and $M_1 = 2.16\,M_\odot$. When M_0 increases slightly above $1.78\,M_\odot$, or when M_1 decreases below $2.16\,M_\odot$, the probability density drops to zero. This is because for the highest frequency in Table 1, namely 1220 Hz, Eq. (2) requires $M_* \leq 1.78 M_\odot$, while for the lowest (1066 Hz) the implied mass is $M_* \geq 2.16 M_\odot$. The values at which the probability peaks directly reflect the assumed relation between maximum QPO frequency and the stellar mass (Eq. [2], with $j = 0$).

For the set $\mathcal{S}_1$ (thirteen sources), we find the stellar masses to be in the range $1.55 M_\odot \leq M \leq 2.40 M_\odot$, at the 99% confidence level. However, these values (of M_0 and M_1 at a given confidence level) have to be treated with caution, as the width of the peak in the probability function is sensitive to the assumed prior mass distribution of the sources (Eq. [1]).

7. Discussion

If the hypothesis (that the maximum frequency of the QPOs in LMXBs is the one in the marginally stable orbit) is to be accepted, it must not only pass a formal statistical test (Sect. 4), it must also give physically meaningful results.

Without any assumptions as to the internal structure of the compact objects in the LMXBs exhibiting kHz QPOs, we have found a mass range for these objects. A reasonable conclusion based on the masses thus derived, $1.55 M_\odot \leq M \leq 2.40 M_\odot$, would be that the sources are neutron stars which have accreted for a long time. This, of course, agrees with the standard explanation of what LMXBs are (see Bhattacharya & van den Heuvel, 1991, for a review).

The high value of the maximum mass found restricts the equation of state (e.o.s.) of ultradense matter. It has already been noted that an interpretation of a 1.1 kHz frequency as the orbital frequency in the marginally stable orbit about a neutron star requires a stellar mass exceeding $2 M_\odot$, and that only a couple of e.o.s. allow this value (Kaaret et al. 1997; Zhang et al. 1998b; Kluźniak 1998), e.g., e.o.s. AV14+UVII of Wiringa et al. (1988). Raising the maximum mass to $2.40 M_\odot$ poses no further restriction.

Although our model and the data are too crude to permit placing a constraint on the e.o.s. based on the value for the minimum mass in the model, we note that already among the e.o.s. considered by Arnett & Bowers (1977) a few are consistent with the presence of the marginally stable orbit in the mass range (M_0, M_1). E.g., for nonrotating models based on e.o.s. L (mean field, Pandharipande, Pines & Smith 1976), the neutron star is within the marginally stable orbit for $M \geq 1.7 M_\odot$, up to the maximum mass of $2.7 M_\odot$. For e.o.s. N (relativistic mean field, Walecka 1974) this mass range is $(1.43 M_\odot, 1.96 M_\odot)$, while for e.o.s. AV14+UVII of Wiringa et al. (1988), which was preferred by Kaaret et al. (1997), the corresponding values are $1.3M_\odot$ and $2.1M_\odot$. Kluźniak (1998) suggested that e.o.s. L and AU14+UVII are compatible with the then observed lowest reported value of the maximum kHz QPO frequency of 1.15 kHz. For rotating stars, all these values increase.

Note that objects more massive than $3M_\odot$ are clearly excluded–this supports the notion that the Z sources present in our sample are not likely to be black holes, as their mass is not systematically larger in our analysis than that of X-ray bursters (which must have a stellar surface on which the burst occurs, and so are already known not to be black holes). Again, this agrees with the accepted view of what the Z sources are–their status has long been that of neutron star candidates: "the source Sco XR-1 (...) corresponds to a neutron star in a state of accretion" (Shklovsky 1967).

The mass values for M_0 and M_1 given above, correspond to non-rotating stars. As noted in Sect. 3, if the stars rotate with moderate frequencies, the masses go up by the factor $(1 + 0.748j)$, i.e., go up by less than $\sim 15\%$ for rotational frequencies up to ~ 300 Hz, with the exact value of j depending on the stellar period P and on the equation of state.

Incidentally, moderately rotating ($P > 1.6$ ms) strange quark stars cannot be excluded at this stage, as their maximum masses may be as high as about $2.3M_\odot$ in the MIT bag model (if the bag constant is low enough: Bulik et al. 1999a,b; Zdunik et al. 2000).

In the extreme case of stars rotating at the equatorial mass-shedding limit (i.e., with keplerian rotation at the equator), the approximation of Eq. (2) is no longer valid, and the mass, corresponding to a given orbital frequency in the marginally stable orbit, may in fact be lower than that of the non-rotating star. For example, strange quark stars of $1.4M_\odot$ rotating at a frequency of about 1.1 kHz could have an orbital frequency in the marginally stable orbit of only 1 kHz (Stergioulas et al. 1999). In this work we ignore the possibility of such rapid rotation.

Note that our results for the masses of LMXBs are in agreement with the reported mass of Cyg X-2, as determined from the binary motion, $M > 1.88M_\odot$ (Casares et al. 1998). The exact evolutionary origin of LMXBs is not clear, but it is reasonable to expect that in these very old systems with typical lifetimes in excess of 10^8 years, the neutron star has accreted several tenths of a solar mass, and that the neutron star masses are larger than in the much younger accreting systems known as high-mass X-ray binaries (HMXBs), whose neutron star masses are mostly consistent with $1.4M_\odot$. Note that in the HMXB X-ray pulsar Vela X-1, a mass of $1.77 \pm 0.21M_\odot$ has been reported for the neutron star (Nagase 1989). Thus, the value found by us for the minimum source mass, M_0, is not surprising for LMXBs.

A confirmed discovery of a maximum QPO frequency exceeding the highest value in Table 1 (1220 Hz), would of course decrease the value of M_0 reported here (e.g., a value of 1329 Hz as reported by van Straaten et al. 2000, at a 2.4 sigma level for 4U 0614+09, and corresponding to $M = 1.65M_\odot$ according to Eq. (2), would lower the values of M_0 reported here by about $0.1M_\odot$). Further, our sample is limited to the sources showing kHz QPOs, which we have assumed to be related to the presence of the marginally stable orbit, and it is possible that these appear above a certain minimum mass–for many e.o.s. the marginally stable orbit appears outside the star only above a certain mass (Kluźniak & Wagoner 1985; Cook et al. 1994). In short, the range of masses in all persistent LMXBs may exceed the mass range found by us for the kHz QPO sample.

It is also interesting to compare the obtained masses with those measured for other binary systems containing neutron stars. For the millisecond radio pulsars, the reported masses are consistent with $1.4M_\odot$ or less, with several values clearly below $1.5M_\odot$ (Thorsett & Chakrabarty 1999). This is below the values found by us for LMXBs (and below the masses reported for Vela X-1 and Cyg X-2, see above), irrespective of whether we deal with dataset $\mathcal{S}_1$ or $\mathcal{S}_2$. The implication would be, that contrary to accepted wisdom (see Bhattacharya and van den Heuvel, 1991, for a review), millisecond pulsars are not formed in persistent LMXBs, a point already made in the literature in various other contexts (Kluźniak et al. 1992; Chen et al. 1993; Kluźniak 1998).

8. Conclusions

Using the assumption–which we show to be consistent with kHz QPO data–that the maximum QPO frequency in any persistent LMXB is the orbital frequency at the innermost stable orbit, we found the masses of the compact objects in thirteen well monitored sources to be in the range between $1.55M_\odot$ and $2.40M_\odot$ at the 99% confidence level. Note that we have made no assumption about the nature of the compact objects, yet we find a range of masses remarkably close to the one expected for neutron stars in old accreting systems.

Given a larger, or more reliable data set, the method described above can be used to further constrain the range of masses, or the models of LMXB formation and evolution. It is therefore important both to continue monitoring the known systems, and also to search for other X-ray sources which may exhibit the QPO phenomenon.

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