Discovery of a 450 Hz QPO from the Microquasar GRO J1655-40 with RXTE

Tod E. Strohmayer
Laboratory for High Energy Astrophysics, NASA’s Goddard Space Flight Center, Greenbelt, MD 20771; stroh@clarence.gsfc.nasa.gov

ABSTRACT

We report the discovery with the proportional counter array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE) of a 450 Hz quasiperiodic oscillation (QPO) in the hard X-ray flux from the galactic microquasar GRO J1655-40. This is the highest frequency QPO modulation seen to date from a black hole. The QPO is detected only in the hard X-ray band above $\sim 13$ keV. It is both strong and narrow, with a typical rms amplitude of 4.5 % in the 13 - 27 keV range, and a width of $\sim 40$ Hz (FWHM). For two observations in which we detect the 450 Hz QPO a previously known $\sim 300$ Hz QPO is also observed in the 2 - 13 keV band. We show that these two QPO sometimes appear simultaneously, thus demonstrating the first detection of a pair of high frequency QPO in a black hole system. Prior to this, pairs of high frequency QPO have only been detected in neutron star systems. GRO J1655-40 is one of only a handful of black hole systems with a good dynamical mass constraint. For a non-rotating black hole with mass between 5.5 - 7.9 $M_\odot$ the innermost stable circular orbit (ISCO) ranges from 45 - 70 km. For any mass in this range the radius at which the orbital frequency reaches 450 Hz is less than the ISCO radius, indicating that if the modulation is caused by Kepler motion, the black hole must have appreciable spin. If the QPO frequency is set by the orbital frequency of matter at the ISCO then for this mass range the dimensionless angular momentum lies between 0.15 < $j$ < 0.5. Moreover, if the modulation is caused by oscillation modes in the disk or Lense-Thirring precession, then this would also require a rapidly rotating hole. We briefly discuss the implications of our findings for models of X-ray variability in black holes and neutron stars.

Subject headings: black hole physics - stars: individual (GRO J1655-40) - stars: oscillations - X-rays: stars

Accepted for publication in Astrophysical Journal Letters
1. Introduction

The Galactic microquasar GRO J1655-40 is one of a handful of black hole systems in which high frequency quasiperiodic X-ray brightness oscillations have been recently observed with RXTE. Remillard et al. (1999) reported the presence of a weak, broad $\sim 300$ Hz QPO at times when the X-ray spectrum was hardest (dominated by a power law component) and the luminosity above $\sim 0.2L_{\text{Edd}}$. Recently, high frequency QPOs have also been observed in three black hole transients; 4U 1630-47 at 184 Hz, XTE J1858+226 at 170 Hz, and XTE J1550-564 between 100 - 283 Hz (see Remillard & Morgan 1998; Markwardt et al. 1999; Remillard et al. 1999a; Homan et al 2000). A stable 67 Hz QPO has also been observed from the Galactic microquasar GRS 1915+105 (Morgan, Remillard & Greiner 1997). The high frequencies of these QPO combined with their X-ray origin argue forcefully that they are produced in the innermost region of the accretion flow close to the black hole event horizon. If their production mechanism can be understood they stand to provide a wealth of information on black hole mass and spin as well as the structure of strongly curved spacetime. Their behavior may also provide tests of General Relativity (GR) in the strong field limit. A number of different models have been proposed to explain these oscillations, but all of them require that strong-field GR effects be taken into account (see Milsom & Taam 1997; Nowak et al. 1997; Wagoner 1998; Stella, Vietri & Morsink 1999; Merloni et al. 1999). Although pairs of simultaneously present high frequency QPOs have been observed ubiquitously from neutron star systems (see the review by van der Klis 2000), until now no black hole system has revealed a pair of simultaneous high frequency ($\nu \geq 50$ Hz) QPO.

GRO J1655-40 is unique amongst these QPO sources in that it is the only one whose mass is known with reasonable precision. Orosz & Bailyn (1997) observed the source in quiescence, modelled the observed ellipsoidal variations using both quiescent and outburst data and obtained a mass $M = 7.02 \pm 0.22 M_\odot$. More recently, Shabaz et al. (1999) used radial velocity observations in quiescence to constrain the black hole mass to the range $5.5 - 7.9 M_\odot$. Since these results were obtained using only quiescent data they should be free from systematic effects due to X-ray heating of the secondary which can bias the mass determination (Phillips, Shahbaz & Podsiadlowski 1999). These mass constraints make GRO J1655-40 arguably the best object in which to test different models for the high frequency X-ray oscillations and thus to learn how to infer fundamental properties of black holes from X-ray variability measurements.

In this Letter we report the discovery in archival RXTE data of a strong and narrow $\sim 450$ Hz QPO in the hard X-ray flux from GRO J1655-40. We show that this QPO is present at the same time as a previously discovered 300 Hz QPO (Remillard et al. 1999), however, the 450 Hz QPO is not always seen when the 300 Hz QPO is detected and vice
versa. This result is the first detection of a pair of high frequency QPO in a black hole system, and is also the highest frequency modulation yet seen from a black hole. We discuss the implications of our findings for models of X-ray variability in neutron star and black holes systems as well as the implications for black hole spin in GRO J1655-40.

2. Data Analysis

GRO J1655-40 is one of the best studied Galactic ‘microquasars’, a class of black hole binaries which produce superluminal radio jets and correlated X-ray activity (Mirabel & Rodriguez; Hjellming & Rupen 1994). The source was discovered by BATSE in July, 1994 (Harmon et al. 1995). A new outburst of GRO J1655-40 was discovered in April, 1996 by the All-Sky Monitor (ASM) aboard RXTE (Remillard et al. 1996). The outburst lasted more than 450 days and an extensive set of RXTE pointed observations were conducted. Remillard et al. (1999) reported an extensive timing analysis of 52 RXTE observations. They reported four types of QPO behavior spanning the range from 0.1 - 300 Hz. They found that the 300 Hz QPO as well as a 0.1 Hz QPO appeared only when the X-ray spectrum was dominated by a hard power law component.

We began investigating the X-ray timing properties of GRO J1655-40 as part of an effort to compare systematically the variability properties of black holes and neutron stars in the RXTE archive. The data we discuss here were obtained from August through November, 1996 as part of proposal P10255 (PI: Remillard) and are now public. The data modes employed for most of these observations included a high time resolution (sampling rate of 65,536 Hz) event mode recording events above PCA channel 35 (∼13 keV) and a single bit mode covering the lower energies in a single band from 2 - 12 keV. As part of our analysis we computed power spectra for each observation and data mode separately. We used 32 s intervals and 8 Hz frequency resolution in the range from 1 - 2048 Hz. We then averaged the individual spectra for each observation. We found almost immediately that some of the average power spectra computed using only the high energy event mode data contained a significant feature near 450 Hz. Figure 1 shows the power spectrum for observation 10255-01-10-00 (UT date, 09/09/96, Observation 13 in Table 2 of Remillard et al. 1999) in which we first saw the 450 Hz feature.

To estimate the significance of this feature we first rescaled the power spectrum so that the local mean near 450 Hz was 2 (the value expected for a Poisson process), and then computed the probability of obtaining a power $P = P_{\text{max}} \times 512 \times 256$ from a $\chi^2$ distribution with $2 \times 512 \times 256$ degrees of freedom. Here $P_{\text{max}}$ is the highest power in the QPO feature. We used this $\chi^2$ distribution because we averaged in frequency by a factor of 512 and averaged...
256 individual power spectra. This gives a chance probability of $2 \times 10^{-8}$ for the highest bin within the QPO profile, better than a $5\sigma$ deviation. We note that this is also a conservative estimate since the QPO feature has not been averaged into a single bin at this frequency resolution.

We next modelled the power spectrum using a Gaussian profile and a power law component in the 100 - 1200 Hz range. The QPO is well fit by a Gaussian centered at $\nu_0 = 449.3 \pm 5$ Hz and a width of $\delta \nu = 19.6 \pm 4$ Hz. This gives a coherence value $Q = \nu / \delta \nu = 23$. The rms amplitude in the 13 - 27 keV band is $4.8 \pm 0.6\%$.

Having found a significant QPO in one of the observations we then searched the remaining set of observations for a similar feature. We detected the 450 Hz QPO in four additional observations (10255-01-06-01 on 8/16/96, 10255-01-07-00 on 8/22/96, 10255-01-09-00 on 9/4/96, and 10255-01-17-00 on 10/27/96). Power spectra from the three observations with the strongest detections are shown in figure 2 (left panel). We modelled the QPO in each observation in which it was detected and found that its centroid did not change significantly over those observations. Thus, to within the precision of the measurements the frequency appears to be stable. Finally, we computed an average power spectrum for all observations which contained the 450 Hz QPO (see figure 2).

### 3. Discussion and Summary

The detection of a 450 Hz QPO in GRO J1655-40 has many important implications and also raises many interesting questions. One of the most important questions bears on the relationship, if any, between the 300 Hz QPO discovered by Remillard et al. (1999) and the 450 Hz QPO reported here? We detected the 450 Hz QPO in three observations in which Remillard et al. (1999) detected the 300 Hz QPO; 10255-01-06-01 on 8/16/96, 10255-01-07-00 on 8/22/96, 10255-01-09-00 on 9/4/96, and 10255-01-17-00 on 10/27/96. Note that for the latter observation, Remillard et al. report a possible occurrence of the 300 Hz QPO. To investigate whether both QPOs can appear simultaneously we computed an average power spectrum by combining these three observations. We computed two power spectra, one using only the 2 - 12 keV single bit data, and the other using just the 13 - 27 keV event data. Our resulting power spectra are shown in figure 3. We clearly detect both the 300 Hz QPO in the 2 - 12 keV band and the 450 Hz QPO in the hard band. We also investigated the average power spectra of each observation individually. Both the 300 Hz and 450 Hz QPOs are detected in the 8/16/96 and 8/22/96 data. The 450 Hz QPO is detected in the 10/27/96, but the 300 Hz QPO is only marginally detected, consistent with the findings of Remillard et al. (1999). During the 8/22/96 observation we were able to detect the 450 Hz QPO in several subintervals and
we confirm that during this observation the 450 Hz frequency did not drift significantly. Although in this observation we can not track the frequency of the 300 Hz QPO with the same temporal resolution as the 450 Hz QPO, it’s stability on timescales of several hours is evident in other observations (for example 10255-01-04-00 on 8/1/96). This evidence, combined with the observed sharpness of both QPOs in the average power spectrum (see figure 3), provides strong evidence that the pair of peaks could not be produced by a single feature which drifted substantially in frequency.

Remillard et al. (1999) report 300 Hz QPO in three additional observations in which we did not detect the 450 Hz QPO. We also investigated the average power spectra of these observations. The results confirm the 300 Hz detections but also show no evidence for the 450 Hz QPO. This indicates that the two QPOs are not always detected together. Interestingly, the pairs of kilohertz QPO seen in neutron star systems are also not always detected at the same time (see van der Klis 2000).

The 300 Hz QPO has a typical amplitude in the 2 - 12 keV band of $\sim 0.8\%$. Such an amplitude would not be detectable in the 13 - 27 keV data. If the amplitude increased to about 1.7% in the hard band then we would have been able to just detect the signal, so we can place a limit on the amplitude of the 300 Hz signal in the 13 - 27 keV band of about 1.7%. Similarly, if the 450 Hz QPO amplitude stayed the same down into the soft band then we would have detected it easily, so its amplitude must be a strong function of energy, and in fact, it cannot be much larger than about 0.4 % in the 2 - 12 keV band or it would have been detected. Not only are two high frequency signals present but they appear to have very different energy dependencies as well, perhaps indicating different physical mechanisms or production sites for each oscillation.

The detection of a 450 Hz QPO in GRO J1655-40 has interesting implications for black hole spin in this source. A black hole whose mass lies between $5.5 - 7.9 M_\odot$, the 95 % confidence limits from Shahbaz et al. (1999), must have a non-zero angular momentum in order for the orbital frequency at the ISCO to be greater than or equal to 450 Hz (see Bardeen, Press & Teukolsky 1972 for a discussion of the ISCO radius). In figure 4a (left) we have plotted the ISCO radii as a function of dimensionless angular momentum $j = cJ/GM^2$ using the mass limits for GRO J1655-40 from Shahbaz et al. (1999) and Orosz & Bailyn (1997). For each mass limit we also show the corresponding radii at which the orbital frequency would be 450 Hz. Even at the lower mass limit of Shahbaz et al. (1999) one requires $j \geq 0.15$ in order for the orbital frequency at the ISCO to be 450 Hz. Indeed, if the 450 Hz QPO is set by the orbital frequency at the ISCO, then $j$ could range from about 0.15 to 0.5. Only with $M \leq 4.8 M_\odot$ would a non-rotating hole be able to produce a 450 Hz orbital frequency at the ISCO.
Although the 450 Hz QPO may not actually be produced by Kepler motion of matter at some radius, the Kepler frequency is generally the highest characteristic variability frequency at a given radius. For example, the lowest order diskoseismic modes discussed by Perez, Silbergleit & Wagoner (1999), some of which have been suggested as the mechanism for high frequency black hole QPOs (Nowak et al. 1997), all have characteristic frequencies below that of the Kepler frequency at the ISCO. Therefore, if one of these modes is responsible for the 450 Hz oscillation the conclusion that the black hole has appreciable spin is unchanged, in fact, in such a case it would have to be spinning even faster than suggested by the orbital frequency at the ISCO. Moreover, Cui, Zhang, & Chen (1998) suggested that the 300 Hz QPO in GRO J1655-40 could be associated with the Lense-Thirring precession frequency close to the ISCO radius. For GRO J1655-40 this could only be achieved with a nearly maximally rotating black hole. With the discovery of a 450 Hz QPO it is now even less obvious which frequency should be associated with Lense-Thirring precession (see Mendez, Belloni & van der Klis 1998). If 300 Hz is indeed the precession frequency, then the 450 Hz QPO cannot be due to Kepler motion at the same radius as this would have a much higher frequency. However, if either of the QPO can be associated with Lense-Thirring precession the black hole must be nearly maximally rotating. Although controversial, spectral analysis by Zhang, Cui & Chen (1997) suggests that the inner accretion disk of GRO J1655-40 is hot and compact, perhaps requiring rapid black hole spin (see however, Merloni, Fabian & Ross 2000; Sobczak et al. 1999).

There has been much recent work directed at investigating the relationship between high frequency QPOs and characteristic noise frequencies in neutron stars and black holes. For example, Psaltis et al. (1999) showed that a correlation could be found between a pair of QPO frequencies across a broad range of source types and luminosities, including both neutron star and black hole systems. In the neutron star systems the pair of frequencies are the lower frequency kilohertz QPO and the 20 - 50 Hz QPO most commonly referred to as a horizontal branch oscillation (HBO). For the black hole systems the situation is a bit less certain because of the lack of high frequency features with properties unambiguously similar to the neutron star kHz QPO. In the so called relativistic precession models the observed QPO frequencies have been identified with the Keplerian, the periastron precession and nodal precession frequencies at some characteristic radius in the accretion disk (see Stella, Vietri & Morsink 1999; Psaltis & Norman 2000; Markovic 2000; Markovic & Lamb 2000). Psaltis et al. (1999) tentatively identified the 300 Hz QPO from GRO J1655-40 with the lower kHz QPO in neutron stars. Our detection of a higher frequency QPO in GRO J1655-40 (perhaps the analog to the upper kHz QPO in neutron stars?) would at first glance seem to strengthen this association. To test this we investigated whether the pair of high frequency QPO and the lower frequency (\sim 18 Hz) QPO could be consistently associated with the
Keplerian, periastron precession and nodal precession frequencies of a $\sim 7M_\odot$ black hole. We show in figure 4b a plot of the radial epicyclic frequency vs the Kepler frequency for the mass range appropriate for GRO J1655-40 and several different values of the dimensionless angular momentum $j$ (curved traces). In the relativistic models the frequency difference between the pair of high frequency QPOs is identified with the radial epicyclic frequency. We also plot the nodal precession frequency for the same set of angular momenta and mass range. The QPO data from GRO J1655-40 are shown with diamond symbols. A black hole with $0.4 < j < 0.6$ could account for the high frequency QPOs, but then the predicted nodal precession frequency is uncomfortably high to be associated with the $\sim 18$ Hz QPO. Whether or not hydrodynamic corrections can mitigate this apparent discrepancy remains to be seen (see Psaltis 2000).

Models for the Khz QPO in neutron star systems generally fall into two broad classes; beat frequency models (Miller, Lamb, & Psaltis 1998; Strohmayer et al. 1996), which require the spinning neutron star surface to produce a pair of frequencies; and relativistic disk models (Stella, Vietri, & Morsink 1999; Psaltis & Norman 2000; Nowak et al. 1997; Perez et al. 2000), which generate the frequencies in the disk alone and are therefore thought to be more generally applicable to both neutron star and black hole systems. Our discovery of a 2nd high frequency QPO in GRO J1655-40 proves that it is not necessary to have a hard surface (as in a neutron star) to produce a pair of high frequency peaks. This would seem to provide some support to the relativistic disk models, since this model can naturally produce pairs of peaks in either class of source, however, a straightforward application of the model seems to have some difficulty (see above). Caution regarding the identification of the QPOs in GRO J1655-40 with the better understood kHz QPO in neutron stars is warranted because of the different properties of the QPOs in GRO J1655-40 and the neutron star kHz QPOs.

We thank Craig Markwardt, Cole Miller and Jean Swank for many helpful discussions and comments on the manuscript. We thank the referee, Ron Remillard, for his comments which helped us improve the paper.
References

Bardeen, J. M., Press, W. H. & Teukolsky, S. A. 1972, ApJ, 178, 347
Cui, W., Zhang, S. N. & Chen, W. 1998, ApJ, 492, L53
Harmon, B. A. et al. 1995, Nature, 374, 703
Hjellming, R. M. & Rupen, M. P. 1995, Nature, 375, 464
Homan, J. et al. 2000, ApJ in press, (astro-ph/0001163)
Leahy, D. A. et al. 1983, ApJ, 266, 160
Markovic, D. 2000, MNRAS, submitted, (astro-ph/0009450)
Markovic, D. & Lamb, F. K. 2000, MNRAS, submitted, (astro-ph/0009169)
Markwardt, C. B., Swank, J. H. & Taam, R. E. 1999, ApJ, 513, L37
Mendez, M., Belloni, T., & van der Klis, M. 1998, ApJ, 499, L187
Merloni, A., Fabian, A. C. & Ross, R. R. 2000, MNRAS, 313, 193
Merloni, A., Vietri, M., Stella, L. & Bini, D. 1999, MNRAS, 304, 155
Miller, M. C., Lamb, F. K. & Psaltis, D. 1998, ApJ, 508, 791
Milsom, J. A., & Taam, R. E. 1997, MNRAS, 286, 359
Mirabel, I. F. & Rodriguez, L. F. 1994, Nature, 371, 46
Morgan, E. H., Remillard, R. A. & Greiner, J. 1997, ApJ, 482, 993
Nowak, M. A., Wagoner, R. V. Begelman, M. C. & Lehr, D. E. 1997, ApJ, 477, L91
Orosz, J. A. & Baillyn, C. D. 1997, ApJ, 477, 876
Perez, C. A., Silbergleit, A. S., Wagoner, R. V. & Lehr, D. E. 1997, ApJ, 476, 589
Phillips, S. N., Shahbaz, T. & Podsiadlowski, P. 1999, MNRAS, 304, 839
Psaltis, D. 2000 ApJ, submitted, (astro-ph/0010316)
Psaltis, D., Belloni, T. & van der Klis, M. 1999, ApJ, 520, 262
Psaltis, D. & Norman, C. 2000, ApJ, in press (astro-ph/0001391)
Remillard, R. A., et al. 1996, IAU Circ. 6393
Remillard, R. A., Morgan, E. H., McClintock, J. E., Bailyn, C. D. & Orosz, J. A. 1999, ApJ, 522, 397

Remillard, R. A. & Morgan, E. H. 1998, in The Active X-ray Sky, ed. L. Scarsi, H. Bradt, P. Giommi, & F. Fiore (Amsterdam: Elsevier), 316

Remillard, R. A., Morgan, E. H., McClintock, J. E., Bailyn, C. D. & Orosz, J. A. 1998, in Proc. 18th Texas Symp. on Relativistic Astrophysics, ed. A. Olinto, J. Frieman, & D. Schramm (Singapore: World Scientific), 750

Shahbaz, T., van der Hooft, F., Casares, J., Charles, P. A. & van Paradijs, J. 1999, MNRAS, 306, 89

Sobczak, G. J., McClintock, J. E., Remillard, R. A., Bailyn, C. D. & Orosz, J. A. 1999, ApJ, 520, 776

Stella, L., Vietri, M. & Morsink, S. M. 1999, ApJ, 524, L63

Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, A. P., Titarchuk, L., Day, C. & Lee, U. 1996, ApJ, 469, L9

van der Klis, M. 2000, ARAA, in press [astro-ph/0001167]

Zhang, S. N., Cui, W. & Chen, W. 1997, ApJ, 482, L155
4. Figure Captions

Figure 1: Average power spectrum for observation 10255-01-10-00 in the 13 - 27 keV energy band. The spectrum was computed by averaging a total of 256 individual spectra each computed from a 32 second interval. The frequency resolution is 16 Hz and the spectrum has been normalized following Leahy et al. (1983). The QPO at 450 Hz is clearly visible.

Figure 2: Average power spectra from three observations with the most significant detections of the 450 Hz QPO (top three traces). The spectra were computed in the same way as for figure 1. The centroid of the 450 Hz peak did not change significantly over these observations. The spectra have been shifted vertically for clarity. The average power spectrum at 2 Hz frequency resolution of all observations in which the 450 Hz QPO was detected is shown in the bottom trace. The lower frequency ∼ 18 Hz QPO can also be seen.

Figure 3: Power spectra computed from the three observations in which we detected the 450 Hz QPO and in which Remillard et al. reported either detections or evidence of the 300 Hz QPO. The upper spectrum was computed from the 2 - 12 keV single bit mode data only while the lower spectrum was computed using only the 13 - 27 keV event mode data. Both the 300 and 450 Hz QPO are clearly detected simultaneously.

Figure 4: The radius of the inner most stable circular orbit (ISCO) as a function of dimensionless black hole angular momentum, $j$, for the mass limits for GRO J1655-40 of Shahbaz et al. (1999) and Orosz & Bailyn (1997) (left panel). The curves denoting the ISCO radii are labelled with the corresponding mass (5.5, 6.8, 7.2, or 7.9 $M_\odot$). Also shown for each mass are the corresponding radii at which the orbital frequency is equal to 450 Hz. Curves corresponding to a particular mass are plotted with the same line style (ie. solid, dashed, etc.). For example, for a 5.5 $M_\odot$ black hole one requires $j \sim 0.15$ in order for the Kepler frequency at the ISCO to be 450 Hz. The Radial epicyclic frequency (curved lines) and the nodal precession frequency (diagonal lines) vs Keplerian frequency for the Shahbaz et al. mass limits for GRO J1655-40 and for several different values of the dimensionless angular momentum $j$ (right panel). the solid, dotted and dashed curves correspond to $j = 0.2, 0.4,$ and 0.6, respectively. The curves for $j = 0.2$ are labelled with their corresponding masses in order to indicate the sense of the mass dependence. The difference frequency between the 300 and 450 Hz QPO and the low frequency (∼ 18 Hz) QPO are plotted with diamonds. Note that the error bars are smaller than the symbol size.
Fig. 1.— Figure 1
Fig. 2.— Figure 2
Fig. 3.— Figure 3
Fig. 4.— Figure 4a
Fig. 5.— Figure 4b