Period doubling and non-linear resonance in the black hole candidate IGR J17091-3624?

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ABSTRACT

The two high frequency quasi periodic oscillations (HFQPOs) recently reported in the black hole candidate IGR J17091-3624 are in a 5:2 frequency ratio (164 Hz to 66 Hz). This ratio is strongly suggestive of period doubling and nonlinear resonance analogous to phenomena known in RV Tauri-type pulsating stars (and recently discovered also in oscillations of RR Lyrae-type and of BL Herculis-type variables). An interpretation of the frequency ratio in terms of nonlinear interactions and a comparison with the HFQPOs reported in GRS 1915+105 may imply a mass of about six solar masses for the black hole in IGR J17091-3624.

Key words. accretion, accretion disks – black hole physics – X-rays: binaries – asteroseismology

Introduction

The source IGR J17091-3624 has received some notoriety as a possibly low mass ($M \sim 3 M_\odot$) black hole candidate (Altamirano et al. 2011). The suspected low mass value has been questioned by Altamirano & Belloni (2012) who discovered two high frequency quasi periodic oscillations (HFQPOs) with frequencies 66 Hz (at 8.5 sigma) and 164 Hz (at 4.5 sigma). We point out that the two frequencies are in a 5:2 ratio.

If the underlying fundamental mode of oscillations corresponds to that responsible for the pair of HFQPOs in a 5:3 ratio previously observed in another black hole transient (GRS 1915+105), then the black hole in IGR J17091-3624 would have a run-of-the-mill mass, with a value comparable to that of XTE J1550-564 (which is reported to have $9.10 \pm 0.61 M_\odot$, Orosz et al. 2011). The 5:2 ratio further strengthens the case for non-linear resonance of accretion disk oscillations as the source of HFQPOs.

The resonance interpretation was first suggested by Kluźniak & Abramowicz (2001a,b), who argued that the QPO phenomenon (van der Klis 2000) cannot be of a kinematic origin but must be due to accretion disk oscillations, and that the twin-peak HFQPOs are due to resonances between particular modes of disk oscillations. These authors (Abramowicz & Kluźniak 2001) also noticed that the 450 Hz frequency in the X-ray flux of the black hole candidate GRO J1655-40 discovered by Strohmayer (2000) was in a 3:2 ratio to the previously known 300 Hz frequency of a HFQPO in the same source.

Subsequently, Kluźniak & Abramowicz (2002) noted that “a 2:3 ratio [is] in agreement with the 300 and 450 Hz frequencies reported in GRO J1655-40 and the 184 and 276 Hz frequencies reported in XTE J1550-564. […] a 5:3 ratio [is] in agreement with the 69.2 and 41.5 Hz frequencies reported in GRS 1915+105”, and interpreted the observations in terms of parametric resonance of epicyclic oscillations in general relativity (GR).

Specifically, a rotation supported (slender) fluid torus about a black hole has modes of oscillation with eigenfrequencies corresponding to the radial and vertical epicyclic frequencies in the Kerr metric. In parametric resonance these eigenfrequencies are in a 3:2 ratio, and the first overtone of the vertical mode adds a third frequency for a sequence of ratios of 5:3:2. A more general discussion of possible 3:2 orbital resonances, and the resulting spin estimates for microquasar black holes is given in Török et al. (2005). The epicyclic modes are always among fundamental modes of oscillation of fluid disks and tori around black holes and neutron stars (see, e.g., Blaes et al. 2007; Blaes et al. 2006, and references quoted there). However, as higher frequencies in a 3:2 ratio were subsequently reported in GRS J1915+105 (McClintock & Remillard 2006; Remillard & McClintock 2006), the identification of the 69.2 Hz oscillation with the overtone of parametric epicyclic resonance was abandoned (Kato 2004).

In this Letter, we would like to present a unified scheme for the HFQPOs in IGR J17091-3624 and GRS J1915+105, and their frequency ratios, which is not necessarily tied to any specific theoretical model of accretion disk oscillations.

2. Period doubling and half-integer frequencies

We would like to suggest a simple interpretation of the 5:3 and 5:2 ratios of the reported frequencies in black hole transients that has a direct analogue in phenomena observed in certain pulsating
one of the black hole mass in GRS 1915+105, which was reported to be 14 ± 4 \( M_\odot \) (Greiner 2001). Thus, the black hole in IGR J17091-3624 should have a mass of about 6 \( M_\odot \) (modulo the unknown spin).

So far, we have been referring to period doubling in the sense of its purely observational consequences of alternating higher and lower maxima and deeper and shallower minima in the light curve or, equivalently, the presence of subharmonics in the frequency domain. However, the term “period doubling” is used to denote a bifurcation in a dynamical system, a transition from one periodic state to another, period doubled one. In some cases this is followed by a cascade of doublings, which can lead to chaos (and quasi-periodicity). In the case of pulsating stars, numerical models display the period doubling bifurcation. It can also be demonstrated that the original periodic solution looses its stability at the onset of bifurcation. Such an analysis has not yet been performed for accretion disk oscillations, so our suggestion of period doubling in the two black hole systems does not have the strong theoretical underpinning that period doubling has in BL Her, RR Lyr, and RV Tau type stars. One has to be open to the possibility that the 5:2 and 5:3 frequency ratios in IGR J17091-3624 and GRO J1915+105 may be a manifestation of a direct resonance between two modes of oscillation (Klužniak & Abramowicz 2001a,b; Abramowicz & Klužniak 2002; Török et al. 2005), which does not necessarily lead to period doubling. For instance, a 3:2 coupling will lead to period doubling if the higher frequency mode is resonantly driven by the lower frequency mode (Moskalik & Buchler 1990), but not vice versa.

3. Properties of stellar and disk oscillators

We have referred to three classes of stellar pulsators, RV Taurus-type stars, RR Lyrae-type stars and BL Herculis-type stars, in which the growth rates of the oscillations (e.g., thousands of days in RR Lyrae) are much shorter than other characteristic timescales, such as the thermal timescale (10^8 years in RR Lyrae), but much longer than their periods. The amplitudes of the oscillation have reached saturation. Thus the oscillations are often essentially strictly periodic (or multiperiodic). The subharmonic oscillations typically have amplitudes much lower than the harmonics, but they are not always periodic: in RR Lyrae the main oscillation is amplitude modulated and period doubling is present in some stretches of data, but not in others (Szabó et al. 2010; Kolenberg et al. 2011), thus leading to a finite width of the.
subharmonics in the frequency domain. In RV Tauri type stars, the subharmonics also have a finite width.

The excitation and damping mechanism of the accretion disk oscillations (Kato 2001; Wagoner 2002) is without doubt very complex. While we have reinterpreted the observation of the HFQPOs in the black hole candidate IGR J17091-3624, it is important to note that simple harmonics of the presumed fundamental at 27 Hz have not yet been reported in that source.

The black hole HFQPOs can only be extracted from the data upon integration of the X-ray signal for thousands of oscillation periods, the resulting average Lorentzian profiles fitted to the data have widths comparable to the frequency (quality factor, Q). These values are not so different from those in oscillating red giants: in ° of a few) – it is not clear whether this reflects an intrinsically low coherence of black hole disk oscillations or whether the frequencies shift during the integration time. We note that in neutron stars, where the signal is stronger, at least some HFQPOs have been shown to have a larger coherence, with a quality factor of 200 (Barret et al. 2005; Mukherjee & Bhattacharya 2011).

These values are not so different from those in oscillating red giants; in ° with a lifetime of possibly 3 days, for a quality factor value of 10 (Barban et al. 2007), and in another source, CoRoT 101034881 the corresponding numbers are about 6 h, and 50 days, for a Q ~ 200 (De Riddier et al. 2009). In the Sun, the 5 min oscillations have a Q ~ 103, e.g., the 4.9 min period oscillation has a lifetime of 0.7 days for a Q = 270, while the 8.2 min period corresponds to a lifetime of 17.1 days, for a Q = 3000 (Liberbichler 1988).

4. Discussion and conclusions

In this Letter we suggest a possible interpretation of the recently observed HFQPOs in the black hole candidate IGR J17091-3624. By analogy with stellar oscillations, we interpret HFQPOs in the black hole oscillations a challenging task. If we were to search for similar behavior in stellar systems, we would look to red giants and solar type stars, where short-lived oscillations are stochastically excited by turbulent convection (e.g., De Riddier et al. 2009; Goldreich & Keely 1977; Houdek 2010). Period doubling has not (yet?) been reported in those stars.

With only two HFQPOs recently discovered in IGR J17091-3624 it is too early to be confident about the presence of a subharmonic series similar to the one observed in the pulsating stars, even though the 5/2 subharmonic is much weaker than the presumed fundamental at 66 Hz. While we have reinterpreted the GRS 1915+105 QPO frequencies in light of the newly discovered ones in J17091-3624, it is important to note that simple harmonics of the presumed fundamental at 27 Hz have not yet been reported in that source.

If confirmed, period doubling in black hole QPOs could be the first such detection in a stochastically driven astrophysical system. A more detailed investigation of the full spectrum of QPOs in IGR J17091-3624 is eagerly awaited, as it could reveal a sequence of harmonics and subharmonics with amplitudes of non-linear interactions that match observations, and lead to a reasonable mass estimate (of about 6 0) for IGR J17091-3624 on the assumption that the 66 Hz oscillation corresponds to the 27 Hz oscillation in GRS 1915+105. The common denominator between accretion disks and stars is that they are fluid bodies near hydrostatic equilibrium (although with different accuracy: RR Lyrae can be considered stationary on a timescale of 10^4 years, while the state of the disk in a black hole transient change in minutes). The fact that in one case GR effects are important while in the other they are not, may be relevant in the discussion of the nature of the fluid oscillations, but it does not affect the simple period doubling phenomenon.

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