**Astronomy
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Mass estimate of the *Swift* J 164449.3+573451 supermassive black hole based on the 3:2 QPO resonance hypothesis

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ABSTRACT

A dormant *Swift* source J 164449.3+573451 (Sw 164449+57) recently experienced a powerful outburst, caused most probably by a tidal disruption of a star by the supermassive black hole at the center of the source. During the outburst, a quasi periodic oscillation (QPO) was detected in the observed X-ray flux from Sw 164449+57. We show that if the observed QPO belongs to a "3:2 twin peak QPO" (with the second frequency not observed), the mass of the black hole in Sw 164449+57 is rather low, $M \sim 10^5\ M_\odot$, and the source belongs to a class of intermediate mass black holes. The low mass of the source has been pointed out previously by several authors.

Key words. black hole physics – X-rays: bursts

The *Swift* source Sw 164449+57 at redshift $z = 0.3543$ is believed to be a super-massive dormant black hole at the center of an inactive galaxy. During a recent X-ray outburst (probably activated by a tidal disruption of a star), the source was in many respects similar to a small-scale blazar; see e.g. Bloom et al. (2011). In particular, it displayed a relativistic jet (Burrows et al. 2011; Zauderer et al. 2011). If one accepts (as we do) theoretical and observational arguments that link relativistic jets with a high black hole spin (discussed by Narayan & McClintock 2012, and many other authors), then the presence of a jet suggests that the black hole in Sw 164449+57 is rotating rather rapidly ($a > 0.6$, say). However, one should also note that this evidence of jets being powered by the black hole rotation is not unanimously accepted. Using much of the same data, Fender et al. (2010) came to very different conclusions – that even the relatively simple radio-loud versus radio-quiet dichotomy in AGN may be due to the AGN states rather than to spins. In this context it is also relevant to note that McKinney et al. (2012) discuss the possibility of exciting QPOs through a disk-jet coupling.

During the outburst, Reis et al. (2012) detected a firm (statistically significant) QPO[1] with the centroid frequency $f_{obs} = 4.8(1 + z)$ mHz. In this short article we examine the possibility that this frequency may correspond to a lower (or upper) frequency of the "twin peak" QPOs in which the two frequencies are in the 3:2 ratio. Such twin peaks are observed in several microquasars and other black hole sources (see e.g. Török et al. 2005).

It has been argued by Kluźniak & Abramowicz (2001) that the phenomenon of the 3:2 twin peak QPOs in the black hole sources is due to a nonlinear parametric resonance in two eigenmodes of accretion disk oscillations. According to the simplest

version of the 3:2 resonance model, the observed QPO twin peak frequencies should be identified with the vertical epicyclic and radial epicyclic frequencies, which in the Kerr geometry are given by

$$f_{ver} = \frac{\Omega_K}{2\pi}\left[1 - 4ax^{-3/2} + 3a^2 x^{-2}\right]^{1/2}, \tag{1}$$

$$f_{rad} = \frac{\Omega_K}{2\pi}\left[1 - 6x^{-1} + 8ax^{-3/2} - 3a^2 x^{-2}\right]^{1/2}, \tag{2}$$

$$\Omega_K = \left(\frac{GM}{r^3}\right)^{1/2}\left[1 + x^{-3/2}a\right]^{-1}, \tag{3}$$

where M is the black hole mass, a its dimensionless spin ($0 \leq |a| \leq 1$), and the dimensionless radial coordinate is defined by

$$x = \frac{r}{GM/c^2}. \tag{4}$$

Here G is the Newtonian gravitational constant and c the speed of light. The 3:2 epicyclic resonance occurs at the "resonance radius" $x_{3:2} = x_{3:2}(a)$, defined by the condition

$$\frac{3}{2} = \left[\frac{1 - 4a(x_{3:2})^{-3/2} + 3a^2(x_{3:2})^{-2}}{1 - 6(x_{3:2})^{-1} + 8a(x_{3:2})^{-3/2} - 3a^2(x_{3:2})^{-2}}\right]^{1/2}. \tag{5}$$

For a nonrotating black hole ($a = 0$), this implies $x_{3:2}(0) = 54/5$, which is approximately twice the radius of ISCO.

The epicyclic resonance hypothesis allows for an accurate estimate of the black hole mass and spin, as first discussed by Abramowicz & Kluźniak (2001) for the microquasar GRO J1655-40. Applying this idea to Sw 164449+57, we first assume that $f_{obs} = 4.8(1 + z)$ mHz corresponds to the *lower* of the twin peak frequencies, i.e. to the *radial* epicyclic frequency

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[1] It should be mentioned that Miller & Strohmayer (2011) note the possibility of a QPO in Sw 164449+57.

in the Kluźniak & Abramowicz resonance model[2]. After a few lines of simple algebra we may write, in this case,

$$\frac{M}{M_\odot} = A \frac{\left[1 - 6(x_{3:2})^{-1} + 8a(x_{3:2})^{-3/2} - 3a^2(x_{3:2})^{-2}\right]^{1/2}}{(x_{3:2})^{3/2} + a}$$

$$A = \frac{c^3}{2\pi G f_{obs} M_\odot} = 4.97 \times 10^6, \tag{6}$$

where $M_\odot$ is the solar mass. Similarly, if we assume the other possibility, i.e. that $f_{obs} = 4.8(1 + z)$ mHz corresponds to the *upper* of the twin peak frequencies, i.e. to the *vertical* epicyclic frequency, we may write

$$\frac{M}{M_\odot} = A \frac{\left[1 - 4a(x_{3:2})^{-3/2} + 3a^2(x_{3:2})^{-2}\right]^{1/2}}{(x_{3:2})^{3/2} + a}. \tag{7}$$

Because for a non rotating black hole it is $x_{3:2}(0) = 54/5$, in this case from Eqs. (6) and (7) it follows that

$$\frac{M}{M_\odot} = \begin{cases} 9.34 \times 10^4 & \text{if } f_{obs} = f_{rad}, \\ 1.40 \times 10^5 & \text{if } f_{obs} = f_{ver}, \end{cases} \quad \text{for } a = 0. \tag{8}$$

Similarly, one may calculate that in the two extreme cases, corresponding to $a = \pm 1$. We consider both the corotating ($a \geq 0$) and counter-rotating ($a \leq 0$) cases, because the star may come to the vicinity of Sw 164449+57 from a random direction before being tidally disrupted, and the stellar debris can form either a corotating or a counter-rotating accretion disk. We have

$$\frac{M}{M_\odot} = \begin{cases} 3.16 \times 10^5 & \text{if } f_{obs} = f_{rad}, \\ 4.74 \times 10^5 & \text{if } f_{obs} = f_{ver}, \end{cases} \quad \text{for } a = +1, \tag{9}$$

$$\frac{M}{M_\odot} = \begin{cases} 5.60 \times 10^4 & \text{if } f_{obs} = f_{rad}, \\ 8.40 \times 10^4 & \text{if } f_{obs} = f_{ver}, \end{cases} \quad \text{for } a = -1. \tag{10}$$

Mass estimates for the case of a rotating black hole for any value of the spin in Sw 164449+57 are given in Fig. 1. Figure 1 suggests that if the black hole in Sw 164449+57 is rapidly corotating with $a > 0.6$, the mass should be in the range $1.6 \times 10^5 < M/M_\odot < 3.2 \times 10^5$ if $f_{obs} = f_{rad}$ or $2.3 \times 10^5 < M/M_\odot < 4.7 \times 10^5$ if $f_{obs} = f_{ver}$. While, if the black hole is counter-rotating with $a < -0.6$, the mass would be in the range $5.6 \times 10^4 < M/M_\odot < 6.7 \times 10^4$ if $f_{obs} = f_{rad}$ or $8.4 \times 10^4 < M/M_\odot < 1.0 \times 10^5$ if $f_{obs} = f_{ver}$.

No direct measurement of the mass of the black hole in Sw 164449+57 has been reported. If the outburst was powered by a tidal disruption of a solar-type main sequence star, the black hole mass must be $M \lesssim 10^8 \, M_\odot$ (Rees 1988). If a white dwarf was disrupted, as suggested by Krolik & Piran (2011a), the black hole mass would correspond to the intermediate mass range,
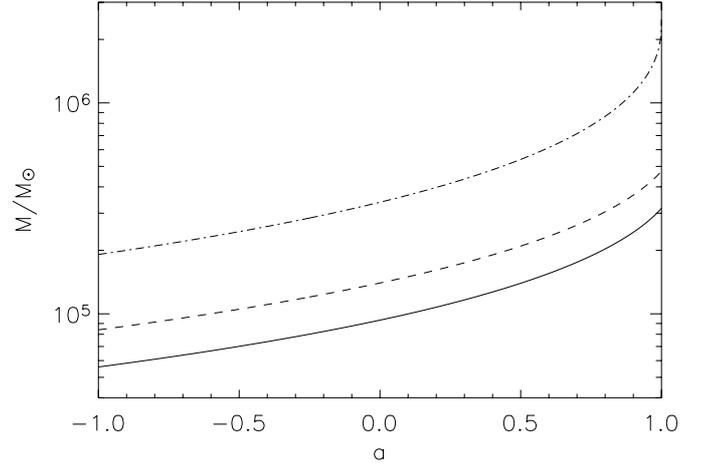
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[2] Reis et al. (2012) also report a less certain QPO with the centroid frequency about $f_2 \sim 6.2(1 + z)$ mHz. They give no estimate of error in the determination of this value, but if it is about 16%, then it could be that $f_2/f_{obs} \sim 3/2$, which would strengthen the case for $f_{obs} = f_{rad}$.

Fig. 1. Mass estimate for the supermassive black hole in the *Swift* source Sw 164449+57, based on the assumption that the observed QPO frequency $f_{obs} = 4.8(1 + z)$ mHz corresponds either to the radial epicyclic (solid line), $f_{obs} = f_{rad}$, or to the vertical epicyclic (dashed line), $f_{obs} = f_{ver}$, frequency, in accordance with the twin peak QPO 3:2 resonance model. For a comparison, we also show the mass estimate based on an assumption that $f_{obs} = \Omega_K/2\pi$ is the Keplerian frequency at ISCO (dash-dotted line).

$M \lesssim 10^5 \, M_\odot$ (but see also Krolik & Piran 2012b). Because the host galaxy of Sw 164449+57 is not resolved and the host morphology is unknown, the bulge luminosity cannot be determined. Therefore, the empirical relation (black hole mass – bulge luminosity) (Magorrian et al. 1998) cannot be used directly to estimate the black hole mass. By employing the relation of black hole mass and bulge luminosity to the total luminosity of host galaxy, an upper limit of black hole mass $M \lesssim 10^7 \, M_\odot$ has been given in the literature; see Bloom et al. (2011); Burrows et al. (2011); Zauderer et al. (2011); Levan et al. (2011). The "fundamental plane" of the black hole accretion, described by a relation between radio luminosity, X-ray luminosity, and black hole mass may be used to determine mass from the observed radio and X-ray luminosities. This way, Miller & Gültekin (2011) estimate the black hole mass of Sw 164449+57: to be $\log(M/M_\odot) = 5.5 \pm 1.1$.

Reis et al. (2012) noticed that Sw 164449+57 is a beamed source and therefore its accretion disk must be viewed at very low inclination (nearly face-on). This excludes the possibility that the disk oscillations are modulated directly by the relativistic Doppler effect and by the light trajectory bending, as these effects work only for highly inclined disks (Bursa et al. 2004). It is not obvious what the modulation mechanism is in the case of the black hole disks that are seen nearly face-on, in particular whether the disk oscillations may modulate (with the same frequencies) the properties of the disk. This is an interesting issue for further theoretical studies. In this context we would like to note that McKinney et al. (2012) discuss the possibility of exciting QPOs through a disk-jet coupling (see also Krolik & Piran 2012b, who discuss the jet issue specifically for Sw 164449+57).

We conclude that the hypothesis that the QPO frequency observed in Sw 164449+57 is one of the twin peak 3:2 frequencies, and the hypothesis of the high spin in this source, are together consistent with the above-mentioned low mass estimates ($M \sim 10^5 \, M_\odot$), implying an intermediate-mass black hole in Sw 164449+57.

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