A&A 374, L19–L20 (2001)
DOI: 10.1051/0004-6361:20010791

Astronomy & Astrophysics

Letter to the Editor

A precise determination of black hole spin in GRO J1655-40

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Received 21 May 2001 / Accepted 5 June 2001

Abstract. We note that the recently discovered 450 Hz frequency in the X-ray flux of the black hole candidate GRO J1655-40 is in a 3:2 ratio to the previously known 300 Hz frequency of quasi-periodic oscillations (QPO) in the same source. If the origin of high frequency QPOs in black hole systems is a resonance between orbital and epicyclic motion of accreting matter, as suggested previously, the angular momentum of the black hole can be accurately determined, given its mass. We find that the dimensionless angular momentum is in the range $0.2 < j < 0.67$ if the mass is in the (corresponding) range of 5.5 to 7.9 solar masses.

Key words. equation of state – relativity – stars: black holes – X-rays

We have previously suggested that "twin" kHz QPOs in accreting neutron stars arise as a result of non-linear 1:2 or 1:3 resonance between the radial epicyclic motion and the orbital motion of matter in a nearly Keplerian accretion disk. As a corollary, we have noted (Kluźniak & Abramowicz 2001) that the same phenomenon should also arise in accreting black holes, where only a single high frequency had been observed. Strohmayer (2001) now reports the discovery of a second QPO in GRO J1655-40, a well known black hole candidate in a low-mass X-ray binary, with the mass of the compact X-ray source determined from optical studies to be in the range $5.9 < M/M_{\odot} < 7.9$ (Shabhaz et al. 1999). There are time intervals, when both QPOs are present at the same time.

The two QPOs now known in the source occur at frequencies 300 Hz and 450 Hz, i.e., in a 2:3 ratio, strongly supporting the notion of a resonance in the system. (The effects of orbital resonances are commonly observed in the solar system − the rotation of the Moon and gaps in the rings of Saturn are well known examples.) Of all rational ratios only 2:3, 1:2 and 1:3 resonances are capable of giving a 2:3 ratio of frequencies. Specifically, if the lower frequency in the resonance is ω, and the higher frequency Ω, the only possibilities are that $\Omega = 300$ Hz and $\Omega + \omega = 450$ Hz for the 1:2 resonance, or that $\Omega = 450$ Hz and $\Omega - \omega = 300$ Hz for the 1:3 resonance.

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In the spirit of Kluźniak & Abramowicz (2001), we consider resonances between orbital and epicyclic motion in the Kerr metric. The fluid in a geometrically thin and axially symmetric accretion disk follows circular orbits, and any departures (caused by gradients of pressure) from circular geodesic motion are second order in the small parameter of characteristic thickness divided by the radius of the disk. We assume that an $n{:}m$ resonance can be excited at or near that radius where the ratio of the epicyclic frequency to the orbital frequency is $n{:}m$. The formulae for the frequencies can be found, e.g., in the review by Kato (2001) and references therein. We find, for instance, that for $j = 0.2$ (see below) the radial epicyclic frequency is in a 1:2 resonance with orbital frequency at $r = 7.22\ M$, i.e., at 3.6 Schwarzschild radii. For $j = 0.67$, the same frequencies are in a 1:3 resonance at $r = 4.1\ M$.

We only consider cases when the integers n and m have no common divisors (for instance, a 1:2 resonance and not a 2:4 resonance). Then, for the given mass range of the black hole, and for the frequencies of 300 Hz and 450 Hz, we can exclude that orbital frequency is in resonance with the epicyclic motion in "vertical" (meridional) direction. Only resonance with radial epicyclic motion can give the observed frequencies. So in the case of GRO J1655-40, ω is the radial epicyclic frequency and Ω is the orbital frequency for circular equatorial orbits in the Kerr metric. We can also exclude the 2:3 resonance between orbital and radial epicyclic frequencies, and this leaves only the 1:2 and 1:3 resonances.

We find the following angular momentum range:

$0.20 < j < 0.60$ for the 1:2 resonance, and

$0.36 < j < 0.67$ for the 1:3 resonance.

Here $j = Jc/(GM^2)$ is the Kerr parameter of the black hole, i.e., its dimensionless angular momentum.

In both cases the upper limit is for $M = 7.9\ M_\odot$, and the lower limit is for $M = 5.5\ M_\odot$. Thus, most of the uncertainty in the determination of angular momentum comes from the mass uncertainty and not from the choice of the resonance.

We conclude that the black hole in GRO J1655-40 is neither a Schwarzschild nor a maximal Kerr black hole, contrary to some reports. This is certainly expected (Kluźniak & Abramowicz 2001). On the one hand, the black hole is accreting matter from a low-mass companion in a long lived binary system, so it must have acquired considerable angular momentum in its evolution. On the other, because the companion is a low-mass star, the *fractional* mass and angular momentum accreted by the black hole cannot be large. Note that if the black hole mass is close to its "preferred" value of 6 $M_\odot$, the Kerr parameter has a moderate value of about 0.3.

The source is also one of the Galactic microquasars, so if the 450 Hz and 300 Hz QPOs are caused by an orbital resonance the presence of mass ejection in "jets" cannot be a signature of a maximally rotating black hole.

Acknowledgements. It is a pleasure to thank J.-P. Lasota and E. Gourgoulhon for helpful discussions.

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