Super-Spinning Compact Objects and Rapid Variability of Galactic Microquasars

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Abstract

In our previous work we applied several models of high-frequency quasi-periodic oscillations (HF QPOs) to estimate the spin of the central compact object in three Galactic microquasars. We also assumed the possibility that the central compact body is a super-spinning object with external spacetime described by Kerr geometry with a dimensionless spin parameter $a \equiv cJ/GM^2 > 1$. Here we extend our consideration, and in a consistent way investigate implications of a set of ten resonance models so far discussed only in the context of $a < 1$. For these models, there is the possibility of recognizing a direct observational signature of presence of a super-spinning compact object. Epicyclic forced resonance models predict that $a \sim 1$ and more pairs of different 3:2 commensurable frequencies can be expected within a single source. This issue can be resolved using the data available from the next generation of X-ray observatories including technologies such as the proposed concept of Large Area Detector.

QPO Models under Consideration

Several variations of resonance models have been assumed by Török et al. (2005, A&A 436) who estimated the spin of the central black hole ($-1 \leq a \leq 1$) in three Galactic microquasars. These comprehend both parametric and forced non-linear resonances, in particular the 3:2 parametric resonance, and the 3:1, 2:1, 5:1, 5:2, 5:3 forced resonances. In the recent paper of Kotrlová et al. (2014, A&A 572, arXiv:1410.6129) we have assumed the possibility that the central compact body is a super-spinning object ($a > 1$). Two most popular alternatives of resonance models have been under the consideration. These are represented by the 3:2 "epicyclic resonance" (Ep) model dealing with radial and vertical epicyclic oscillations, and the 3:2 "Keplerian resonance" (Kep) model assuming a resonance between the orbital Keplerian motion and the radial epicyclic oscillations.

Here we explore the predictions of 10 forced resonance models (Kep1–Kep5 and Ep1–Ep5). The list of these models together with associated relations giving observable QPO frequencies is given in Table 1.

Table 1: Frequency relations corresponding to individual epicyclic and Keplerian forced resonance models.

Model	Type of resonance	Relations		ν_K/ν_r or ν_θ/ν_r
Ep1	epicyclic 3:1 forced	$\nu_L = \nu_\theta - \nu_r$	$\nu_U = \nu_\theta$	3/1
Kep1	Keplerian 3:1 forced	$\nu_L = \nu_K - \nu_r$	$\nu_U = \nu_K$	3/1
Ep2	epicyclic 2:1 forced	$\nu_L = \nu_\theta$	$\nu_U = \nu_\theta + \nu_r$	2/1
Kep2	Keplerian 2:1 forced	$\nu_L = \nu_K$	$\nu_U = \nu_K + \nu_r$	2/1
Ep3	epicyclic 5:1 forced	$\nu_L = \nu_\theta - \nu_r$	$\nu_U = \nu_\theta + \nu_r$	5/1
Kep3	Keplerian 5:1 forced	$\nu_L = \nu_K - \nu_r$	$\nu_U = \nu_K + \nu_r$	5/1
Ep4	epicyclic 5:2 forced	$\nu_L = \nu_r$	$\nu_U = \nu_\theta - \nu_r$	5/2
Kep4	Keplerian 5:2 forced	$\nu_L = \nu_r$	$\nu_U = \nu_K - \nu_r$	5/2
Ep5	epicyclic 5:3 forced	$\nu_L = \nu_\theta - \nu_r$	$\nu_U = \nu_r$	5/3
Kep5	Keplerian 5:3 forced	$\nu_L = \nu_K - \nu_r$	$\nu_U = \nu_r$	5/3

Results

For various individual models of the observed 3:2 HF QPOs with frequencies $\nu_U/\nu_L = 3/2$ we have explored behaviour of the $M \times \nu_U(a)$ quantity and determined spin intervals based on the HF QPO independent mass estimates (Kotrlová et al., 2014, A&A 572, arXiv:1410.6129). Based on the assumption of a rapid decrease of spin due to accretion for $a \gg 1$, one may expect that for a favoured model there should be only small deviation of spin estimate from $a = 1$, $a \gtrsim 1$. All the investigated models except for two models (Ep and Kep model) are incompatible with such requirement.

Main New Findings [Kotrlová et al., 2017, A&A, in press, arXiv:1708.04300]

Here we extend our consideration, and in a consistent way investigate implications of a set of 10 resonance models so far discussed only in the context of $a < 1$. For 5 of these models that involve Keplerian and radial epicyclic oscillations (Kep1–Kep5) we find the existence of a unique specific QPO excitation radius. Consequently, there is a simple behaviour of dimensionless frequency $M \times \nu_U(a)$ represented by a single continuous function having solely one maximum close to $a \gtrsim 1$. Only one of these models is compatible with the expectation of a small deviation from $a = 1$, $a \gtrsim 1$ (see Table 2 and Figure 1). The other 5 models that involve the radial and vertical epicyclic oscillations (Ep1–Ep5) however imply the existence of multiple resonant radii for a given spin (see Figure 2). There is thus a more complicated behaviour of $M \times \nu_U(a)$ that cannot be represented by single functions. Each of these 5 models is compatible with the expectation of $a \gtrsim 1$ (see Table 2 and Figure 3).

For these models, there is the possibility of recognizing a direct observational signature of presence of a super-spinning compact object. Each individual model predicts that more pairs of different 3:2 commensurable frequencies can be expected within a single source (see Figure 3). This issue can be resolved using the large amount of high quality data available from the next generation of X-ray observatories including technologies such as the proposed concept of Large Area Detector (Feroci et al., 2012, ExA 34).

Results for Keplerian Models

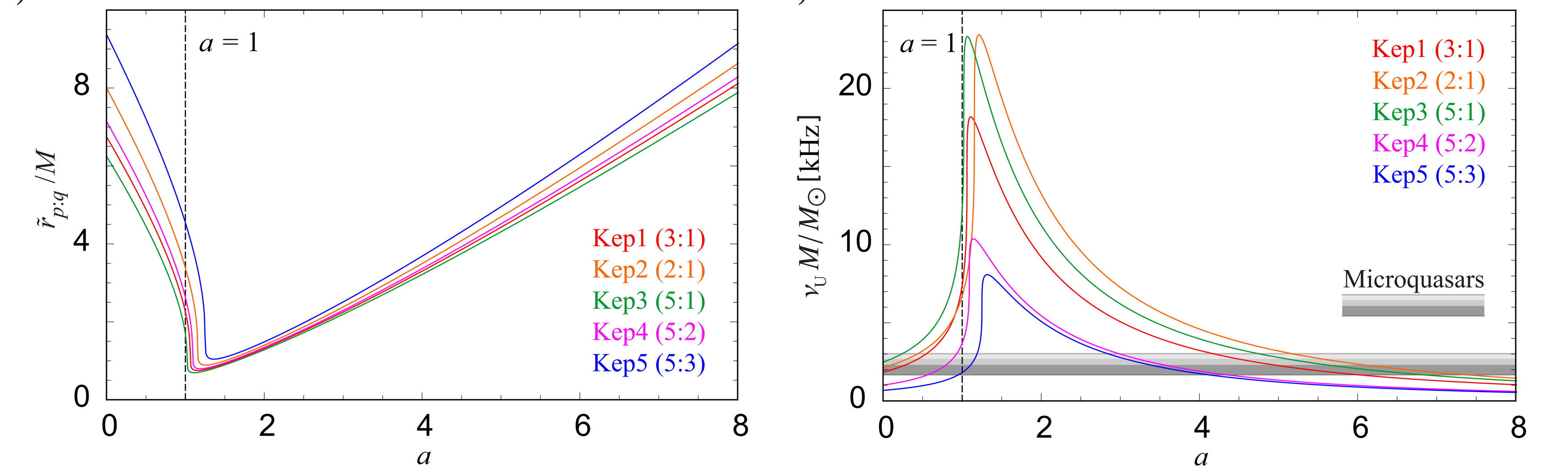

Figure 1: a) Resonant radii of Kep models calculated in Kerr spacetimes. b) Resonant frequencies of Kep models calculated in Kerr spacetimes. The shaded region corresponds to observational values of $\nu_U \times M$ determined for Galactic microquasars.

Spin Intervals implied by QPO Models

In Kerr geometry, the relevant frequencies are for geodesic motion dependent solely on the mass M and spin a of the central compact object. For a particular QPO model and source with an independently estimated mass that displays HF QPOs, it is then possible to calculate the spin of the central object as predicted by the concrete model.

Table 2: Spin intervals inferred for the three microquasars (GRS 1915+105, XTE J1550−564, and GRO J1655−40) from the individual Ep and Kep models.

Model	GRS 1915+105		XTE J1550−564		GRO J1655−40	
Ep	0.68 – 0.99		0.89 – 0.99		0.96 – 0.99	
	1.00229 – 1.00972	3.84 – 5.38	1.00431 – 1.00939	3.88 – 4.48	1.00582 – 1.00703	
					1.00746 – 1.00931	3.88 – 4.11
Ep1	< 0.61		0.32 – 0.59		0.50 – 0.59	
	1.00052 – 1.00217	5.25 – 7.40	1.00088 – 1.00116		1.00107 – 1.00116	
			1.00125 – 1.00210	5.29 – 6.13	1.00171 – 1.00209	5.30 – 5.61
Ep2	< 0.44		0.11 – 0.42		0.31 – 0.42	
	1.00059 – 1.00207	5.81 – 8.14	1.00111 – 1.00200	5.86 – 6.77	1.00151 – 1.00199	5.87 – 6.20
Ep3	< 0.29		< 0.27		0.13 – 0.26	
	0.99978 – 1.00006		0.99980 – 1.00002		0.99981 – 0.99992	
	1.00020 – 1.00076	6.28 – 8.85	1.00042 – 1.00074	6.34 – 7.34	1.00059 – 1.00073	6.35 – 6.72
Ep4	0.60490 – 1.00818	3.68 – 5.23	0.84716 – 1.00337		0.93259 – 1.00233	
			1.00474 – 1.00794	3.71 – 4.32	1.00647 – 1.00788	3.72 – 3.94
Ep5	0.86756 – 1.03363	3.05 – 4.34	0.99257 – 1.03363	3.08 – 3.59	1.01310 – 1.01590	
					1.02148 – 1.03363	3.08 – 3.27
Kep	0.79 – 1.17	3.81 – 5.41	1.03 – 1.17	3.84 – 4.47	1.12 – 1.16	3.85 – 4.08
Kep1	< 0.55	4.17 – 5.99	0.29 – 0.54	4.21 – 4.92	0.45 – 0.53	4.22 – 4.48
Kep2	< 0.44	5.17 – 7.34	0.12 – 0.43	5.22 – 6.06	0.31 – 0.42	5.23 – 5.54
Kep3	< 0.24	4.75 – 6.81	< 0.23	4.79 – 5.59	0.11 – 0.22	4.80 – 5.09
Kep4	0.57 – 0.93	2.98 – 4.33	0.80 – 0.93	3.01 – 3.54	0.88 – 0.92	3.02 – 3.21
Kep5	0.95615 – 1.18902	2.84 – 4.10	1.11049 – 1.18574	2.87 – 3.36	1.16028 – 1.18489	2.87 – 3.05

Results for Epicyclic Models

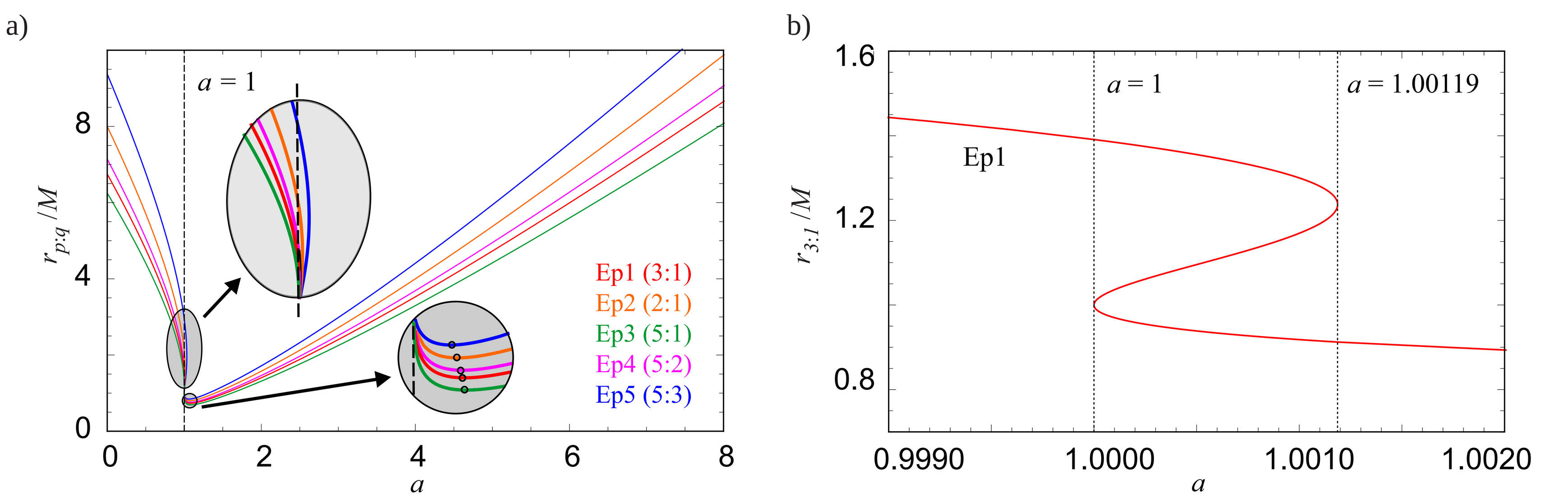

Figure 2: a) Resonant radii of Ep models calculated in Kerr spacetimes. The enlarged area emphasizes a region close to $a = 1$ where each $a(r_{p:q})$ function exhibits both a local minimum and a local maximum. Global minima of $r_{p:q}(a)$ functions are denoted by circles. b) Detailed view of the behaviour of the $r_{3:1}(a)$ relation for $a \approx 1$. The global minimum of $r_{3:1}$ is not shown since it occurs only for a higher value of spin, $a_{3:1} = 1.08471$.

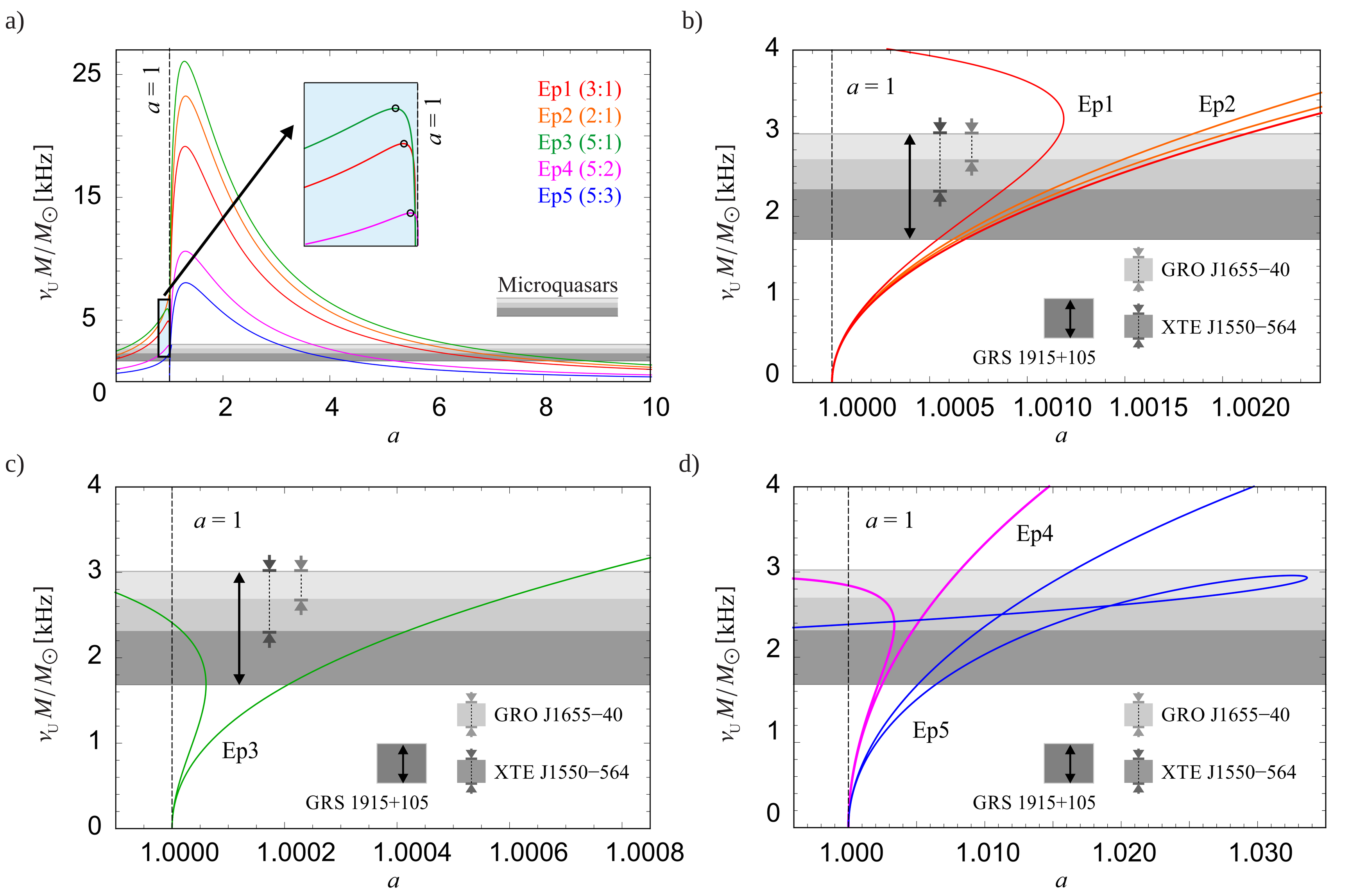

Figure 3: Resonant frequencies of the Ep models calculated in Kerr spacetimes. The enlarged area emphasizes the existence of maxima of the $\nu_U \times M$ curves in the case of the Ep1, Ep3, and Ep4 models in BH spacetimes. The shaded region corresponds to the observational values of $\nu_U \times M$ determined for Galactic microquasars. a) Behaviour of resonant frequencies of the whole group of models on a large scale of a. b) Detailed view of behaviour of the resonant frequencies for the Ep1 and Ep2 models for $a \approx 1$. The individual horizontal grey-scaled areas denote the observational values of $\nu_U \times M$ determined for each of the Galactic microquasars. c) Detailed view of the behaviour of resonant frequencies for the Ep3 model for $a \approx 1$. d) Detailed view of the behaviour of resonant frequencies for the Ep4 and Ep5 models for $a \approx 1$.

Acknowledgements

We would like to acknowledge the Czech grant GAČR 17-16287S and the INTER-EXCELLENCE project No. LTI17018 which supports international activities of the Silesian University in Opava (SU) and Astronomical Institute in Prague (ASU). We also acknowledge two internal SU grants, SGS/14,15/2016 and IGS/2/2016. ZS acknowledges the Albert Einstein Center for Gravitation and Astrophysics supported by the Czech Science Foundation grant No. 14-37086G. We are grateful to Marek Abramowicz (Nicolaus Copernicus Astronomical Center in Warsaw – CAMK & SU), Wlodek Kluźniak (CAMK), Maciek Wilgus (CAMK), Jiří Horák (ASU), and Pavel Bakala (SU) for many useful discussions. Furthermore we would like to acknowledge the hospitality of CAMK. We express our sincere thanks to the concierges of the Mlýnská hotel in Uherské Hradiště, Czech Republic for their kind help and participation in organizing frequent workshops of SU and ASU.