Quasi-periodic oscillations of perturbed tori

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Abstract

↪ Axisymmetric hydrodynamical simulations of perturbed tori orbiting a black hole were performed.

↪ Equilibrium tori with a constant distribution of angular momentum in a pseudo-Newtonian potential (Kluźniak-Lee) were constructed.

↪ Epicyclic motion were triggered by adding sub-sonic velocity fields; radial, vertical and diagonal to the tori.

↪ L_2 norm of density ($\|\rho\|_2$) was measured as the perturbed tori evolved in time.

↪ Power spectrum of $\|\rho\|_2$ manifested eigenfrequencies of tori modes.

Modes

Modes	Frequencies (Ω_K)	
	$r_c = 5.2\ r_g$	$r_c = 7.2\ r_g$
Radial (R)/harmonic	0.65/1.3	0.76/1.52
Vertical (V)/harmonic (V_h)	1.0/2.0	1.0/2.0
Breathing (B)	1.65	1.69
Plus (+)	0.98	1.18
x	1.18	1.26

Table 1: Modes and frequencies. From left to right the columns are, modes with labels in parenthesis and theoretical values of frequencies (Ω_K) at r_c, where $r_g = 2GM/c^2$.

Models

Model	Resolution	r/r_g	z/r_g	$r_{\rm in}/r_g$	r_c/r_g	$r_{\rm out}/r_g$	r_t/r_g	$\mathcal{M}$	r_t/r_c	Perturbation
T1a	296×228	[4.8 - 5.6]	[-0.4 - 0.4]	5.02	5.2	5.39	0.18	0.3	0.03	vertical, radial, diagonal
T1b	512×496	[4.8 - 5.6]	[-0.4 - 0.4]	5.02	5.2	5.39	0.18	0.3	0.03	vertical, diagonal
T2a	296×228	[6.8 - 7.6]	[-0.4 - 0.4]	7.02	7.2	7.39	0.18	0.3	0.02	vertical, radial, diagonal
T2b	512×496	[6.8 - 7.6]	[-0.4 - 0.4]	7.02	7.2	7.39	0.18	0.3	0.02	vertical, diagonal
T3	512×512	[4.5 - 6.0]	[-0.5 - 0.5]	4.84	5.2	5.62	0.36	0.3	0.07	vertical

Table 2: The Parameter space of the simulation. From left to right the columns are, model name, resolution, range of the radial (r) and vertical (z) domain, inner radius ($r_{\rm in}$), center of the torus (r_c), outer radius ($r_{\rm out}$), cross section of torus r_t, magnitude of velocity perturbation (in Mach number $\mathcal{M}$ at r_c) and ratio of the cross section of the torus to the distance from black hole (r_t/r_c). The type of perturbation is also listed. Models T1a-T2b are *thinner* tori and T3 *thicker* torus. For models T1a-T3, $r_g = 2GM/c^2$.

Simulations

Numerical code PLUTO was used to perform the simulations. Frequencies of various modes obtained from the simulations are accurate to the order of 0.03.

Model	Trend of perturbation	Frequencies (Ω_K)	Modes
T1a	radial	0.65/1.3, 1.01, 1.68	R/harmonic, +, B
	vertical	1.67, 1.99	B, V_h
	diagonal	0.65/1.3, 1.0, 1.68, 1.99	R/harmonic, +, B, V_h
T1b	vertical	0.65, 1.01, 1.66, 1.99	R, +, B, V_h
	diagonal	0.65/1.29, 1.0, 1.68, 1.99	R/harmonic, +, B, V_h
T2a	radial	0.77/1.53, 1.15, 1.71	R/harmonic, +, B
	vertical	1.71, 1.99	B, V_h
	diagonal	0.77/1.52, 1.16, 1.73, 1.99	R/harmonic, +, B, V_h
T2b	vertical	0.76, 1.18, 1.71/3.37, 1.99/4.03	R, +, B/harmonic, V_h/harmonic
	diagonal	0.76/1.52, 1.16, 1.72, 2.0	R/harmonic, +, B, V_h
T3	vertical	0.64, 1.02, 1.2/2.36, 1.66/3.33, 1.95/3.89	R, +, x/harmonic, B/harmonic, V_h/harmonic

Table 3: Frequencies and corresponding modes of oscillating tori. From left to right: model name, type of perturbation, frequencies (Ω_K) at r_c obtained from simulations and modes corresponding to solid lines in PSDs, respectively.

References

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Thinner Tori

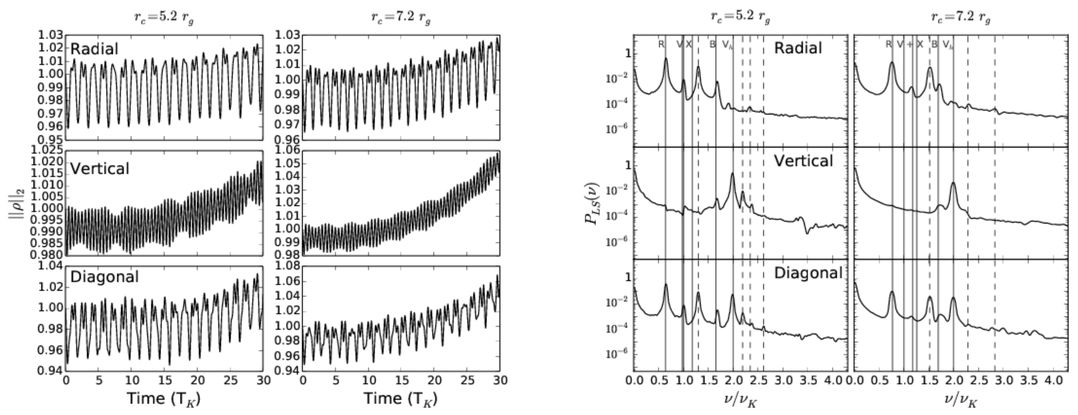

Fig. 1: *Left:* $\|\rho\|_2$ as a function of Keplerian time (T_K at r_c) for models T1a and T2a. *Right:* PSDs of $\|\rho\|_2$. Solid lines correspond to the theoretical values of fundamental eigenfrequencies and dashed lines to additional frequencies in the simulations.

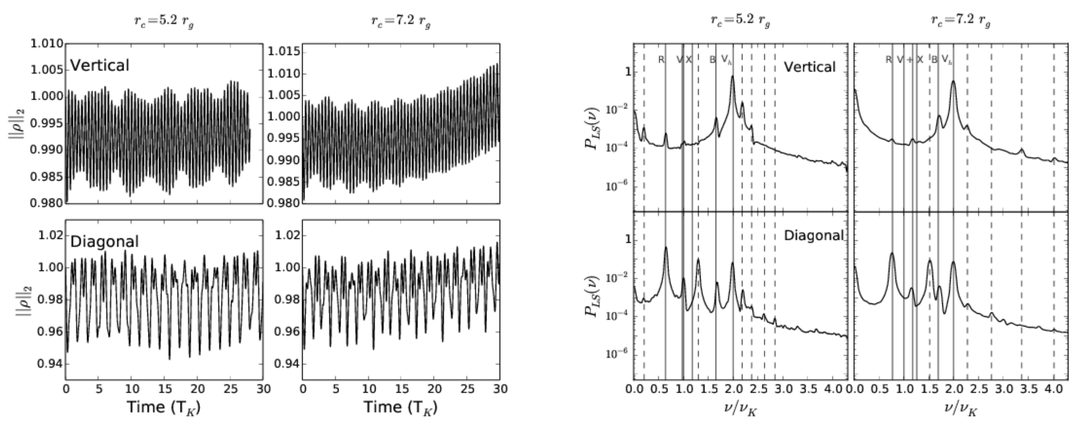

Fig. 2: Same as Fig. 1 for models T1b and T2b, respectively.

Thicker Torus

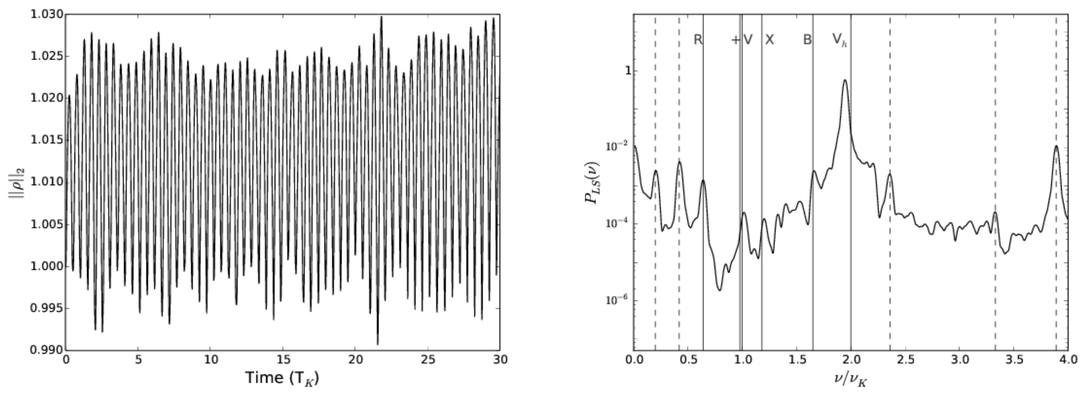

Fig. 3: Same as Fig. 1 for model T3. $r_c = 5.2\ r_g$

Conclusions

✓ The thinner tori (T1a-T2b) manifests radial mode (R)/harmonic, plus-mode (+), breathing mode (B)/harmonic and vertical mode (V_h)/harmonic. The plus-mode and radial epicyclic mode appear in an approximate 3:2 ratio. Vertical epicyclic motion was not excited by radial perturbation.

✓ Vertical oscillation of thicker torus (T3) exhibits radial mode (R), plus-mode (+), breathing mode (B)/harmonic, x-mode/harmonic and vertical mode (V_h)/harmonic.

✓ Presence of radial mode and plus-mode in vertical oscillations of thinner tori (T1b & T2b) and thicker torus (T3) are numerical in origin and not a result of coupling between radial and vertical epicyclic modes, since simulations of unperturbed tori (T1b, T2b & T3) shows the presence of radial mode (R), plus-mode (+) and breathing mode (B).

✓ Results from our simulations are relevant in the context of high-frequency quasi-periodic oscillations (HF QPOs) observed in stellar-mass black hole binaries.

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