Non-linear variability in microquasars in relation with the winds from their accretion disks

Agnieszka Janiuk
Center for Theoretical Physics, PAS

Collaboration: Petra Sukova, Mikołaj Grzędzielski (Warsaw)
Fiamma Capitanio, Stefano Bianchi (Roma)

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Instabilities in accretion flows

Instabilities in the disks

- In accretion disks we can have two main types of thermal-viscous instabilities:
  - Radiation pressure instability
  - Partial hydrogen ionization instability

- They can lead to:
  - Short term limit cycle oscillations in black hole x-ray binaries (tens-hundreds seconds scales)
  - Cyclic activity of quasars (scales of tens-thousands of years)
  - X-ray novae eruptions (scales of months-years)
  - Long-term activity cycles in AGN (scales of millions of years)
- The disk can be stabilized by:
  - Very strong jet/wind
  - Heating prescription
  - Companion star
  - Viscous fluctuations

$$H \frac{3}{2} \Omega \alpha P = \frac{1}{H} \frac{a c T^4}{3 \kappa \rho} - \frac{1}{2 \pi r} \dot{M} T \frac{dS}{dr}$$

Viscous dissipation of energy

Radiative losses

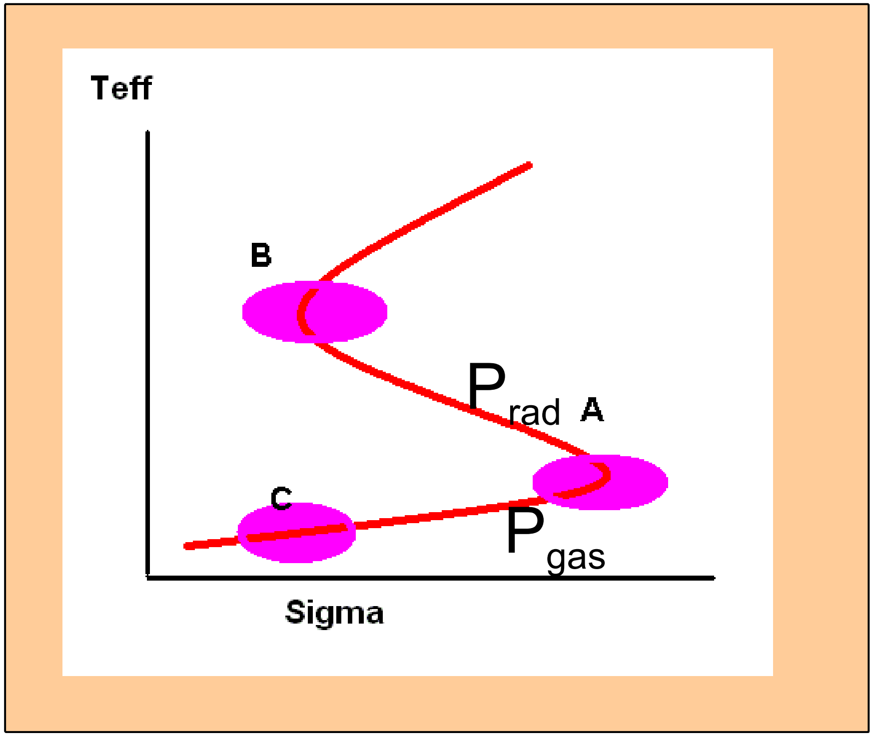
Advection of energy

$$\frac{P}{\rho} = \Omega^2 H^2$$

Hydrostatic equilibrium

$$F_{tot} = \frac{3 G M \dot{M}}{8 \pi^3} f(r)$$

Total fux emitted at radius r



Stationary black hole disk

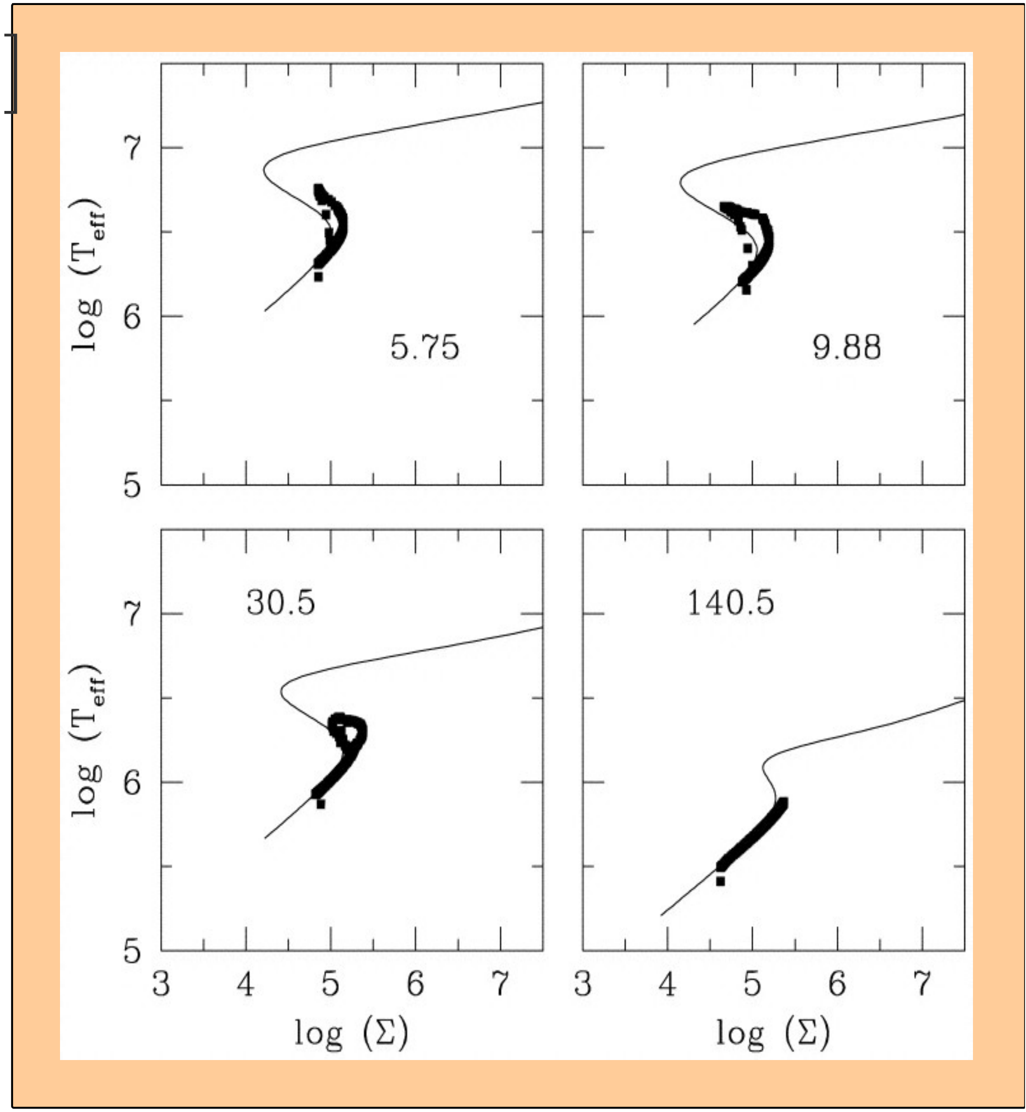
$$\frac{\partial \Sigma}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[3 r^{1/2} \frac{\partial}{\partial r}\left(r^{1/2} \nu \Sigma\right)\right]$$

Conservation of mass and angular momentum

$$\Sigma T \frac{dS}{dt} = Q_{visc} - Q_{rad}$$

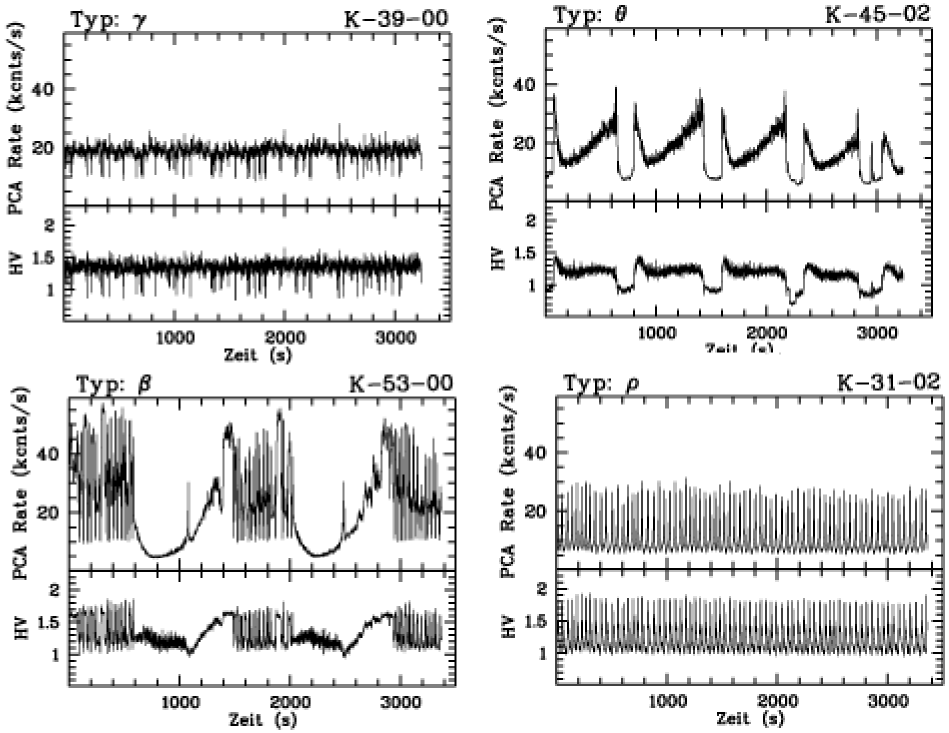
Energy equation

Janiuk et al. (2002)

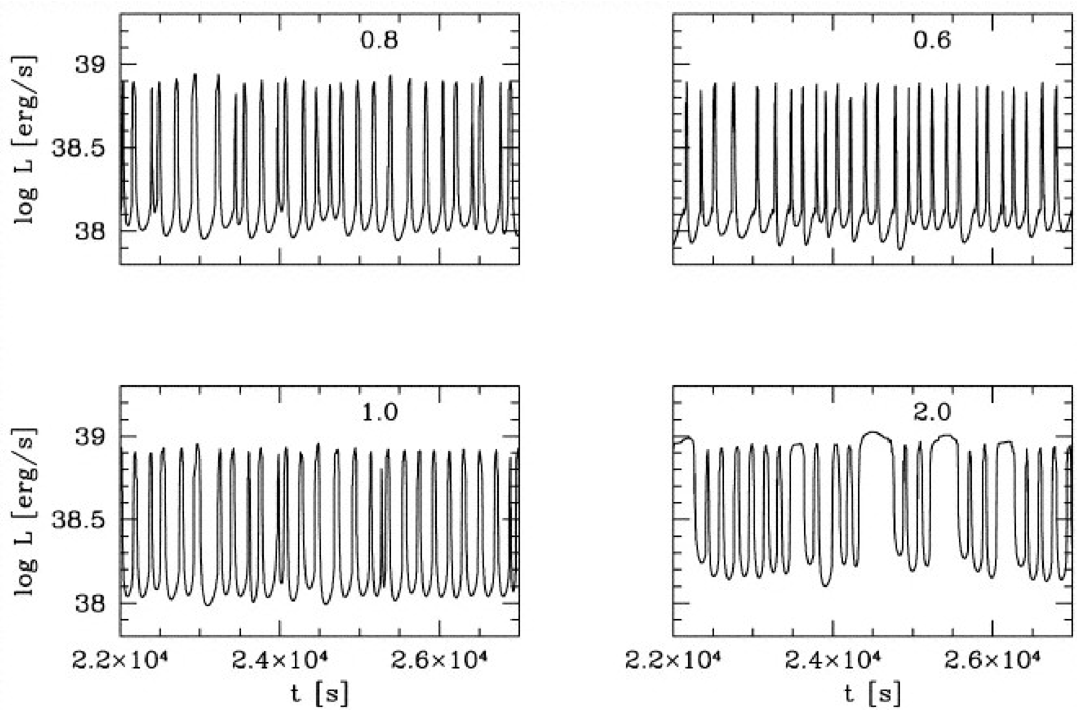


Time dependent disk

GRS 1915+105



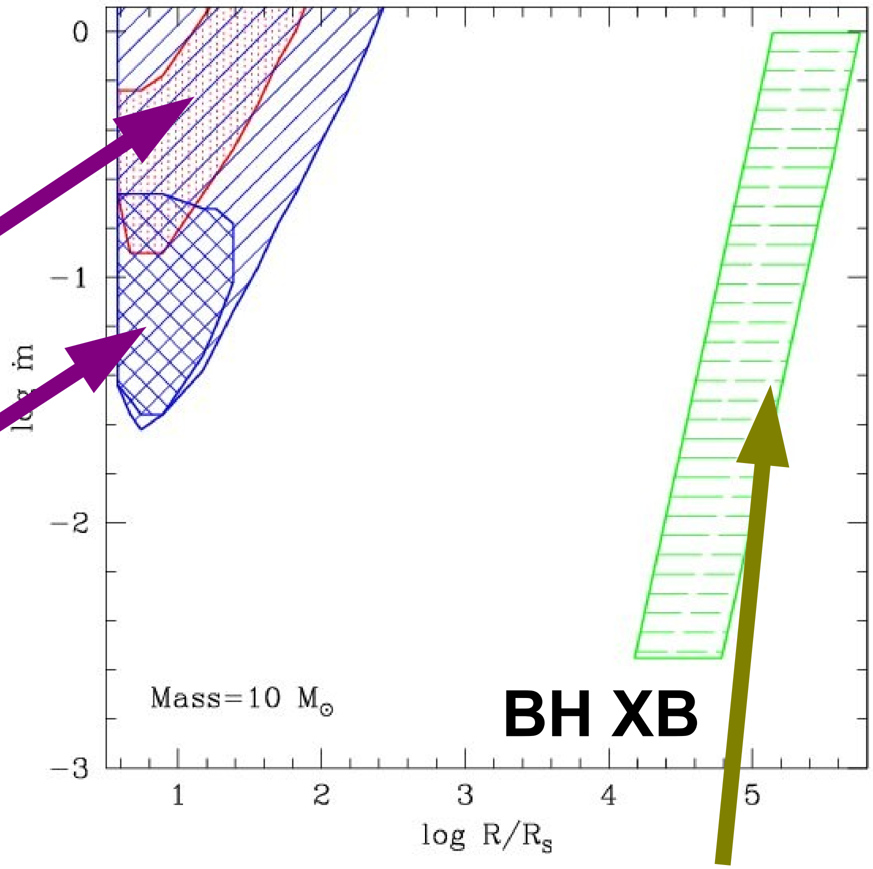
Belloni et al. (2000)



Janiuk, Czerny & Siemiginowska (2000)

In some states, the microquasar shows limit-cycle oscillations of its X-ray luminosity

Instability range in the disk depends on mass accretion rate



Radiation pressure instability

$Q_{visc} \sim P_{tot}$

$Q_{visc} \sim \mathrm{sqrt}(P_{gas} * P_{tot})$

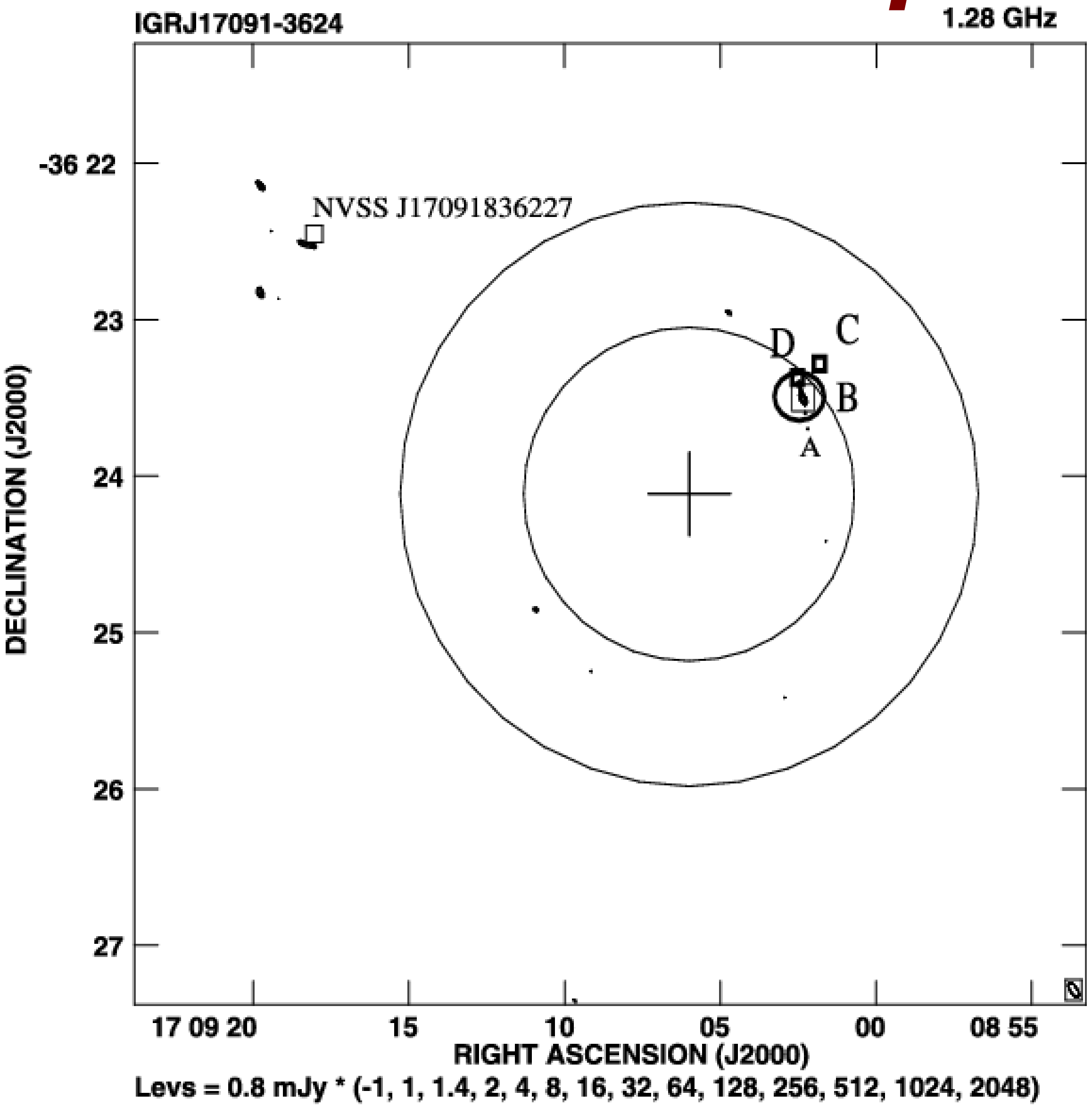
Partial stabilisation by mass/energy outflow

Hydrogen ionisation (dwarf-nova type) instability

$$f_{out} = \frac{1}{1 + A\dot{m}(r,t)^2}$$

$$\dot{m}_z = \frac{F_{tot}\, m_p}{B\, k\, T_{vir}}\left(1 - f_{out}\right)$$

Discovery of the new microquasar



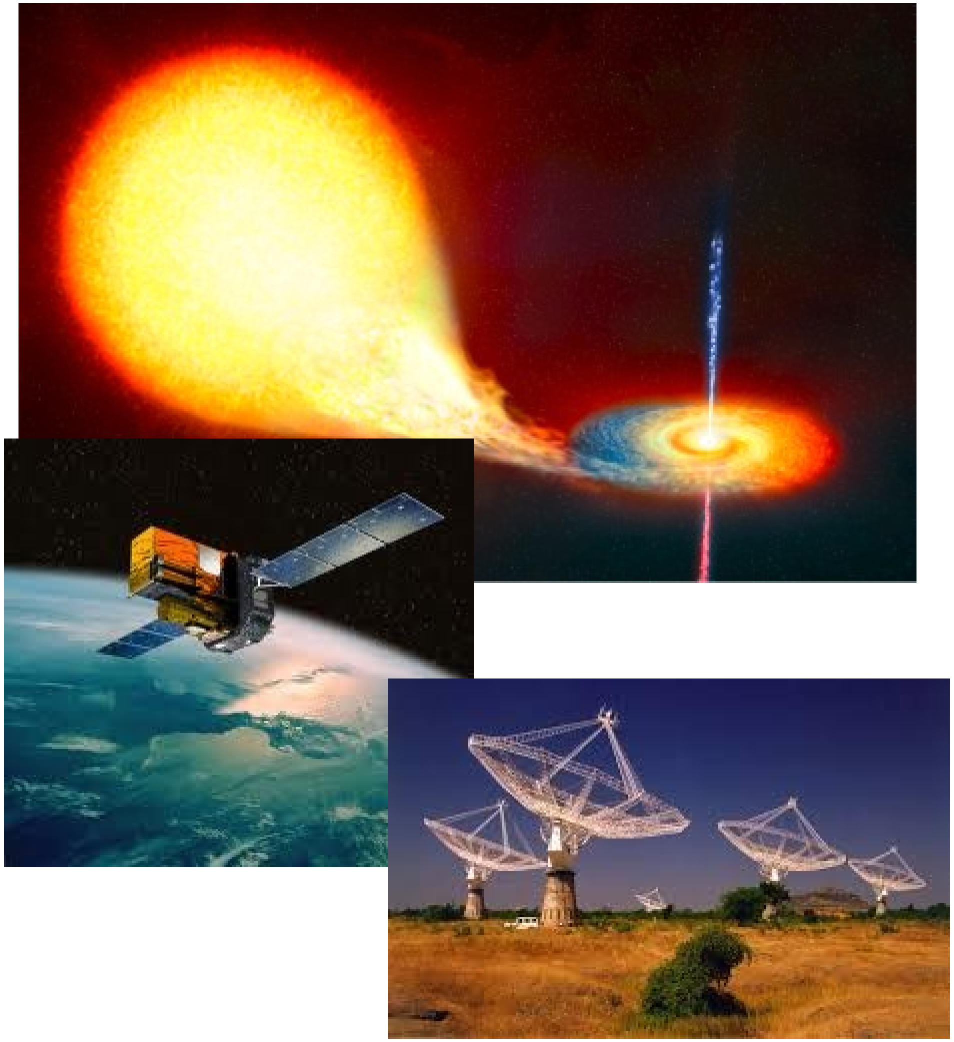
X-ray source in Scorpius constellation
Discovered by INTEGRAL
in 2003 (Kuulkers et al.),
It brightened to 40 mCrab and 25 mCrab for 15-40 and 40-100 keV

The radio observations at 1.28 GHz in Pune

X-ray data from Chandra (2011) showed the presence of a fast wind in this object, v~ 0.03 c.

Data from GMRT (Pandey et al. 2006)

IGR J17091-3624



Active again in 2007 (Capitanio et al. 2009) and back in 1994, 1996, 2001

New outburst in February 2011

Most probably a black hole

The accretion rate may be close to Eddington

In some states, clearly exhibits limit-cycle oscillations of X-ray luminosity

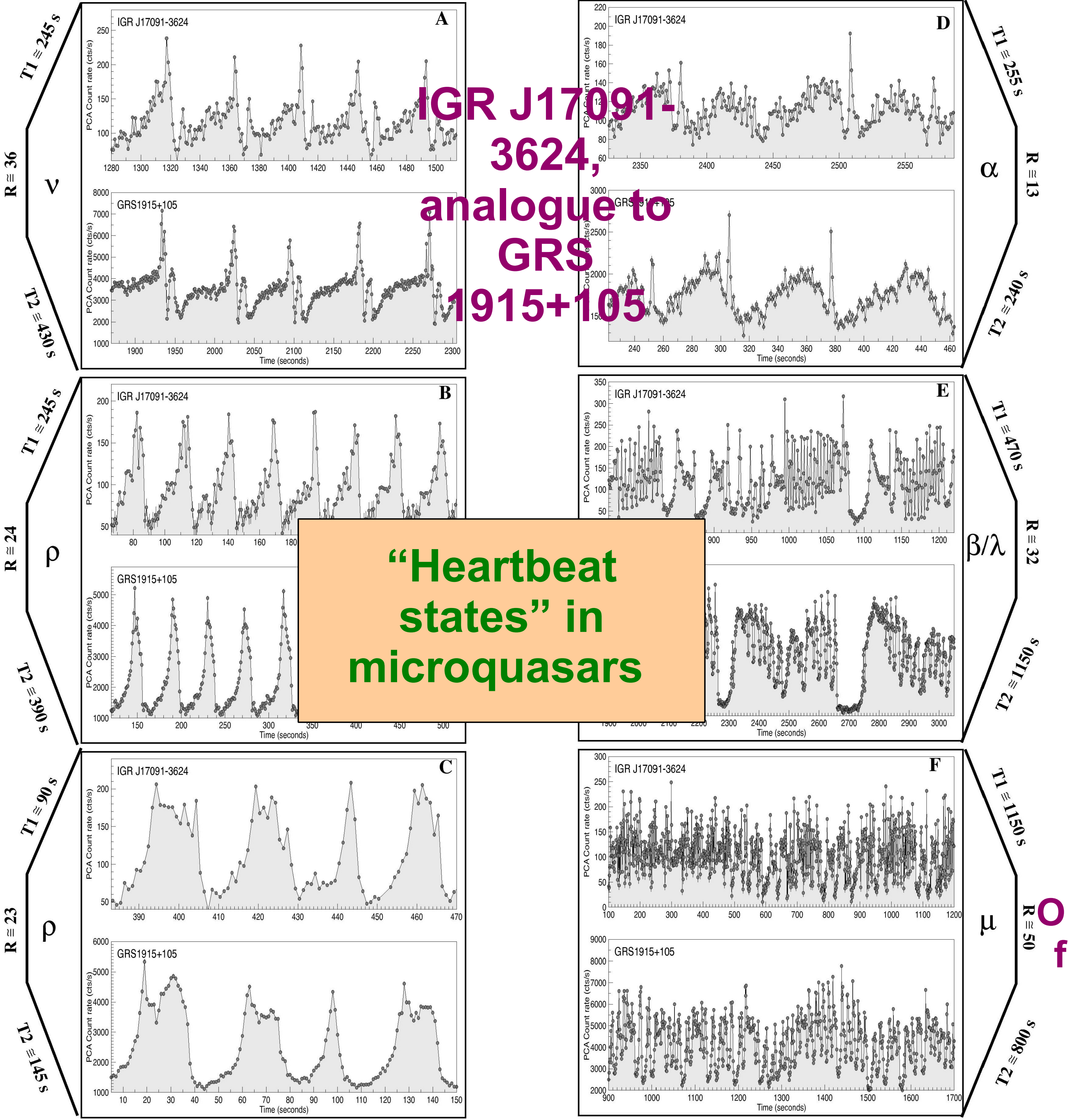
Comparison to GRS 1915+105

Two clear differences:

- (i) the time scales can be different (IGR J17091–3624 tends to be faster), and
- (ii) the average count rate (or flux) of the source can be much higher (factor 10-50) in GRS 1915+105.

If one assumes that the period of a quasi-periodic feature is proportional to some power of the mass of the compact object (see, e.g., Belloni et al. 1997; Frank et al. 2002), then the **black hole in IGR J17091–3624 could be a factor of a few less massive** than the 14 ± 4. 4 $M_\odot$ of GRS 1915+105.

IGR J17091-3624, analogue to GRS 1915+105

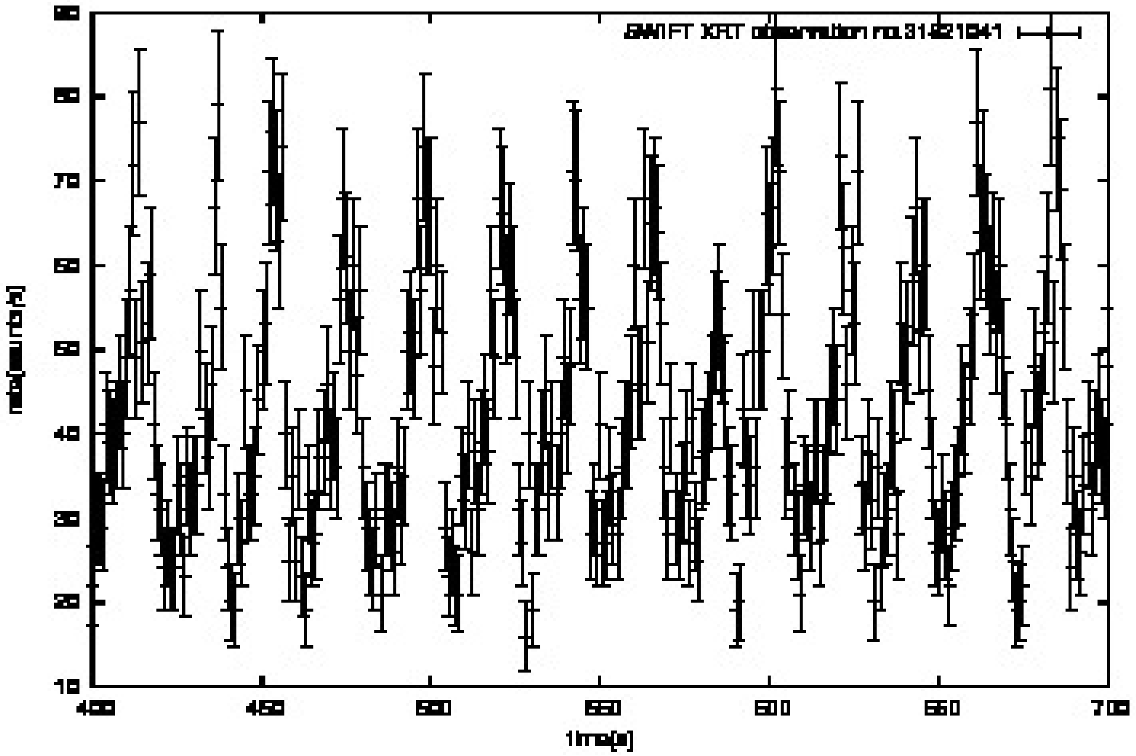


“Heartbeat states” in microquasars

Observations: figure from Altamirano et al. 2011;

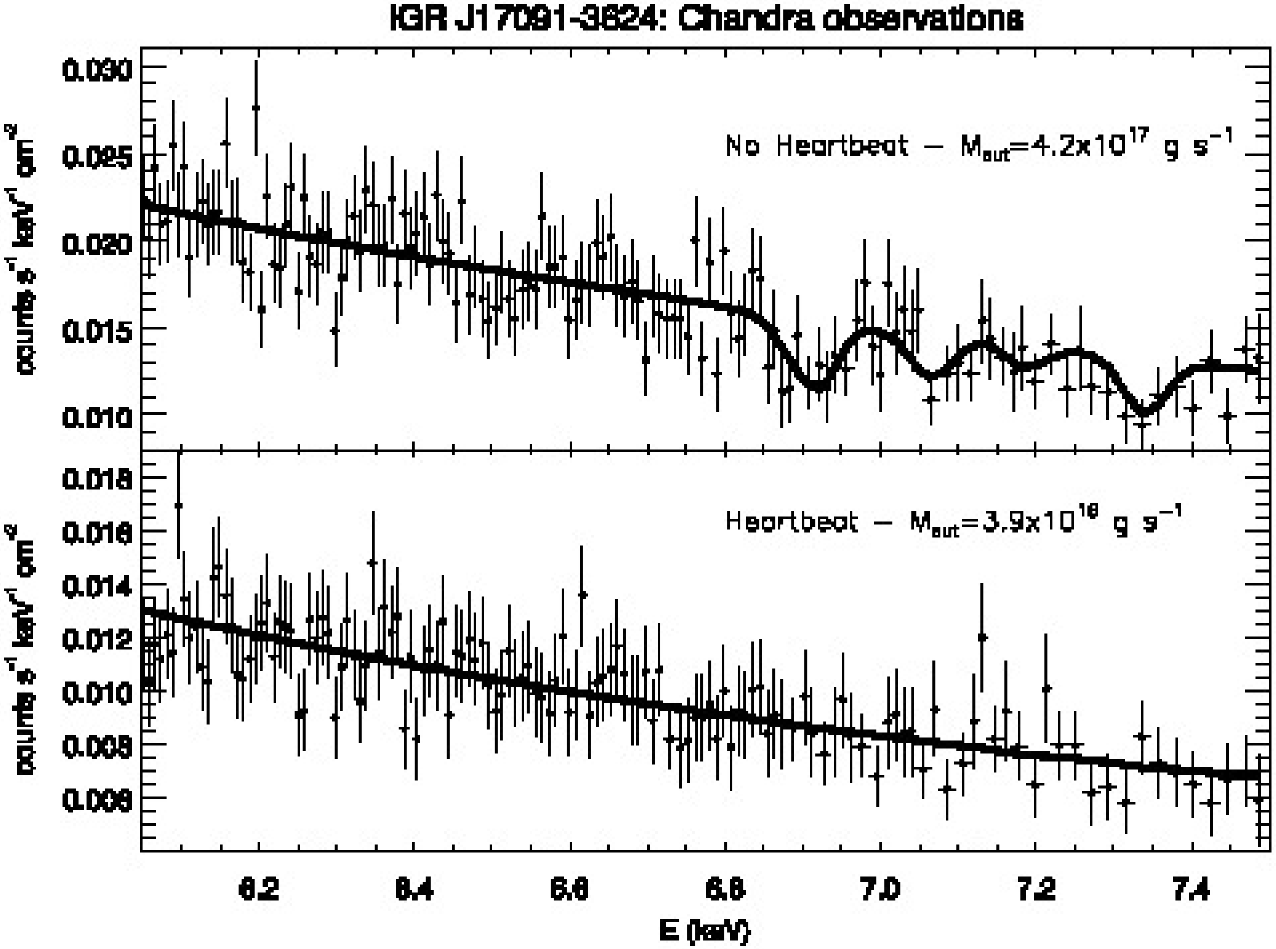
Oscillations and wind in IGR J17091

IGR J17091 flares



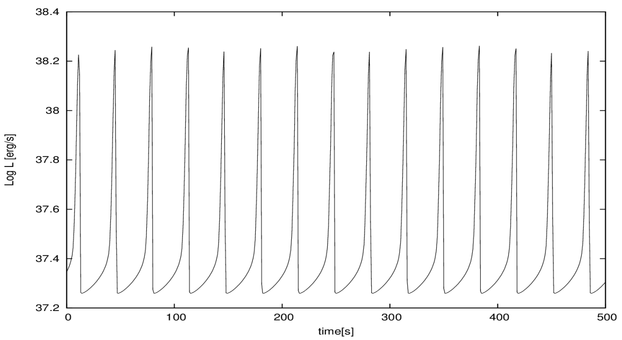
X-ray lightcurve of IGR J17091;
Data from Swift XRT;
(Janiuk, Grzędzielski, Capitanio & Bianchi, 2015)

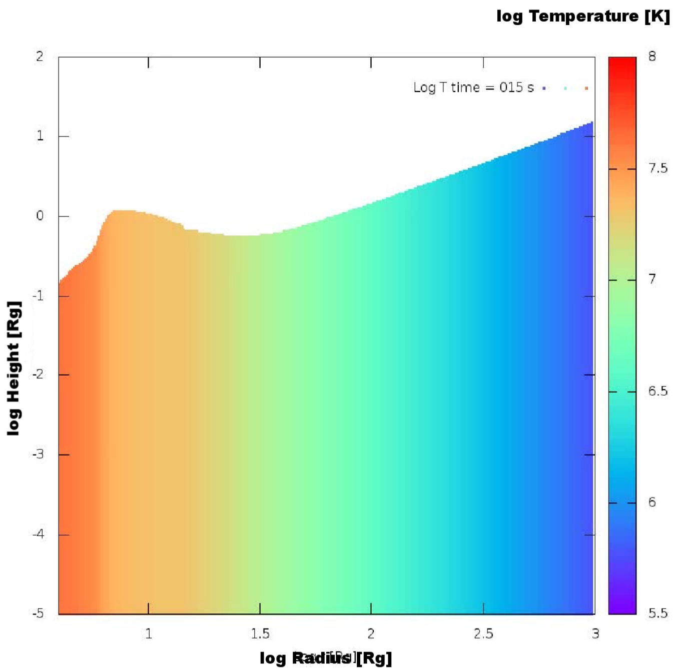
IGR J17091. Wind diagnostics

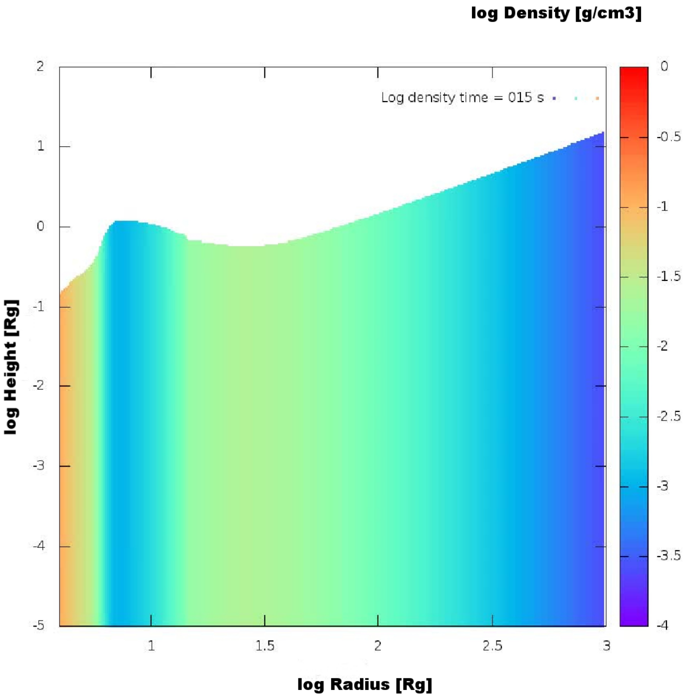


Spectra from Chandra ACIS-S HETG (obID 12406 – top panel, and 12405 - bottom panel), in 6-7.5 keV. Wind components seen in 12406 are below detection treshold in w 12405, when we assume that wind density is by factor 10 lower.

Changes of the luminosity, temperature and density of the disk during outbursts







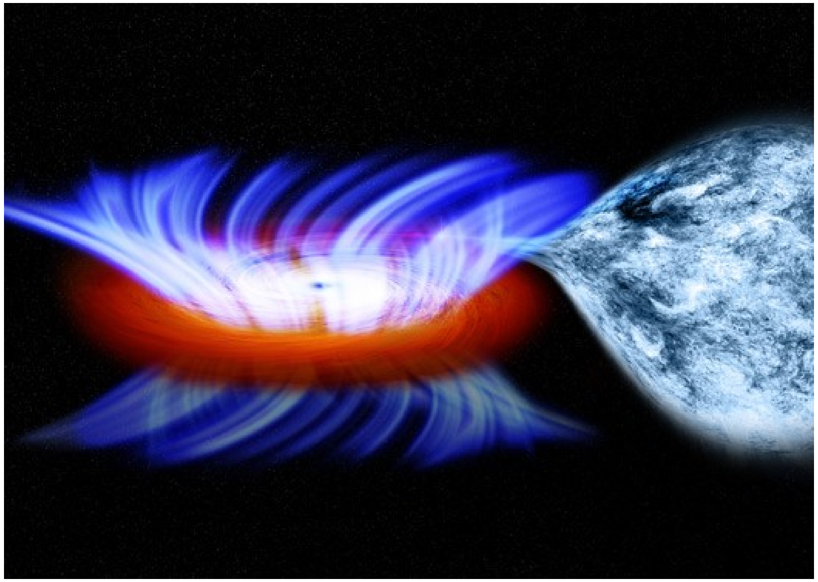
Parameters: mass of black hole 6 M_{Sun}, accretion rate 0.1 Eddington, viscosity parameter alpha 0.1. Also, a wind, with dimensionless strength coefficient A=15, was assumed, it takes away a part of energy flux dissipated locally in the disk.

* our own hydrodynamical code GLADIS **(GLobal Accretion Disk InStability)** we created a model which simulates the behaviour of an accretion disk around IGR-J17091.

* 1,5 – dimensional hydrodynamical code, which models a geometrically thin, Keplerian alpha-disk

* energy dissipation rate scales with the total (including radiation) pressure *(Janiuk et al. 2000; 2002)*

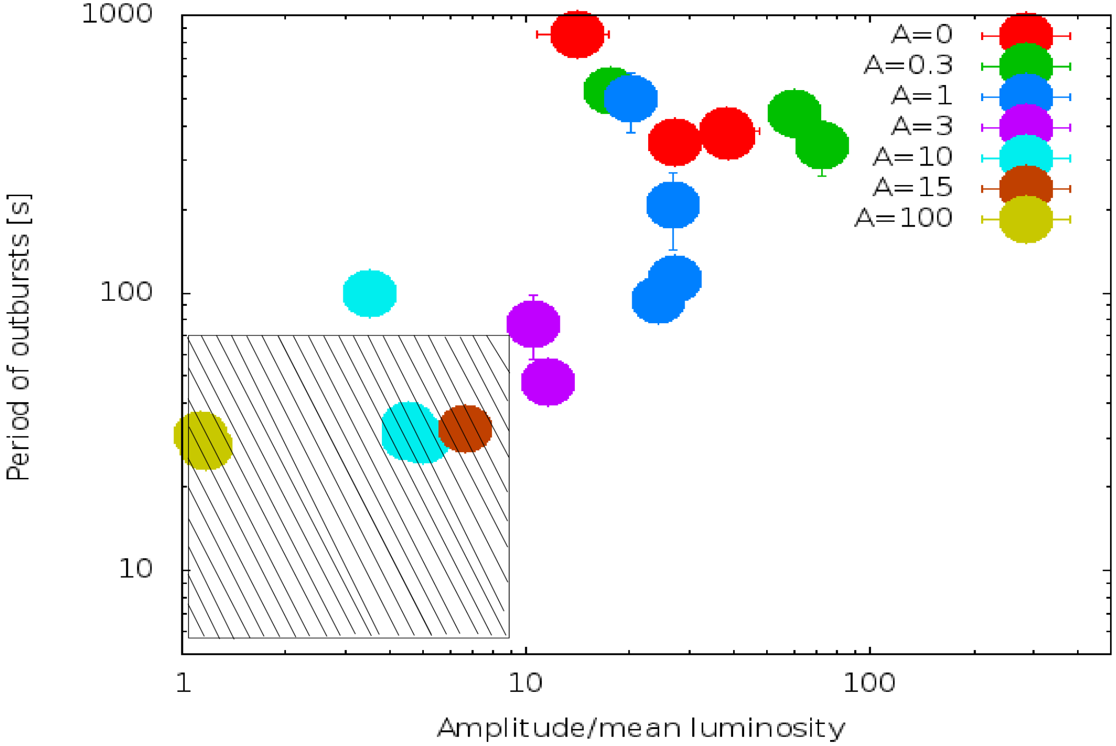
* pseudo-newtonian Paczyński-Wiita potential.



* The presence of wind is important to regulate the amplitudes of disk oscillations, to the level that reproduce the observed X-ray variability.

* Is has been also confirmed by the spectroscopic observations of the microquasar IGR J17091

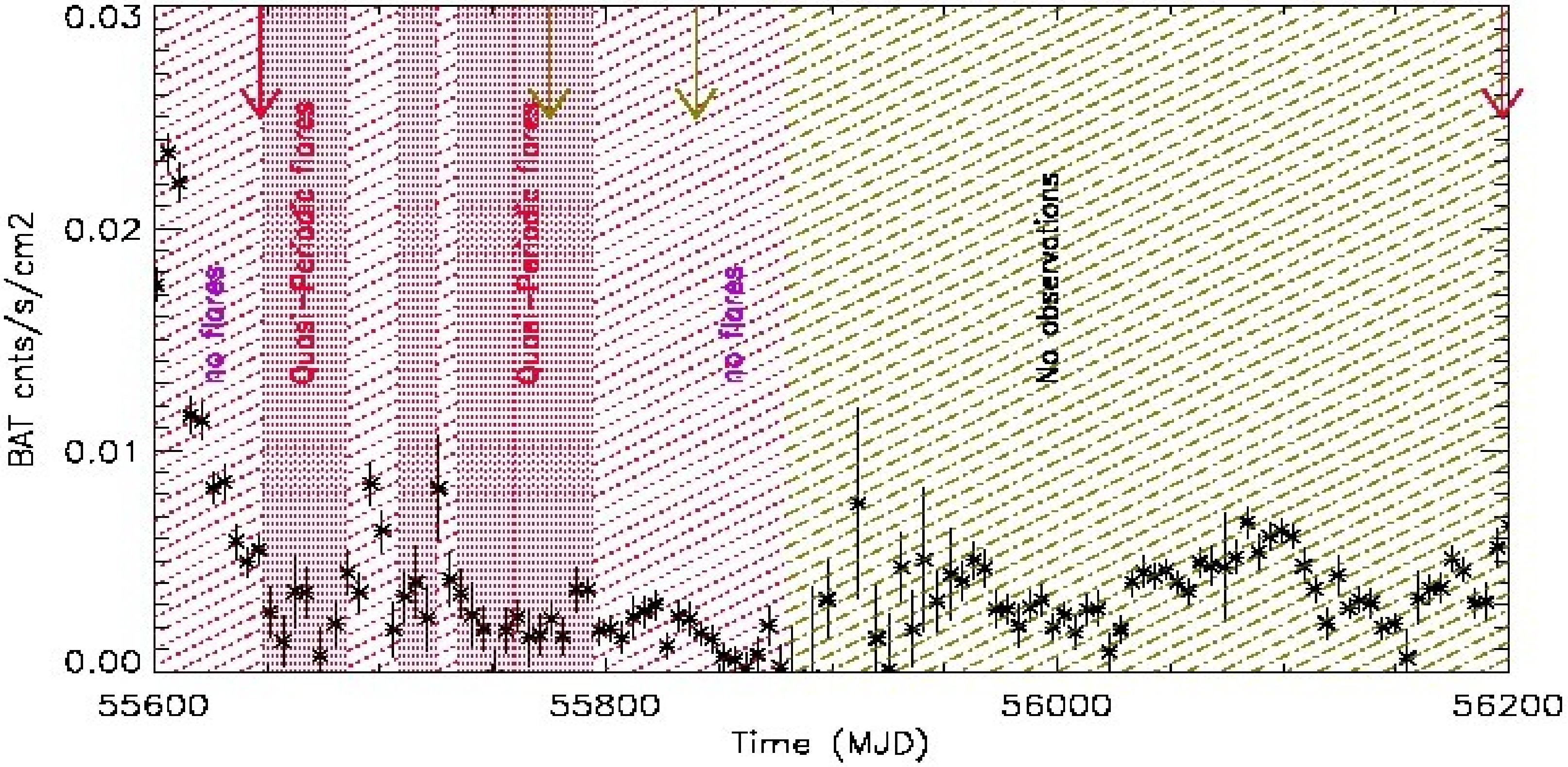
Modeling and analysis



Amplitudes and timescales of outbursts in the accretion disk instability model.

The wind strength parameter *A* governs the mass loss rate in the wind, which is dependent n time and distance from the black hole

IGR J17091



Long term evolution of the source, studied with the data from Swift/XRT and RXTE/PCA.
Correlation between the X-ray flares and wind in IGR J17091.

Data from Swift/BAT (15-50 keV) are marked with points.

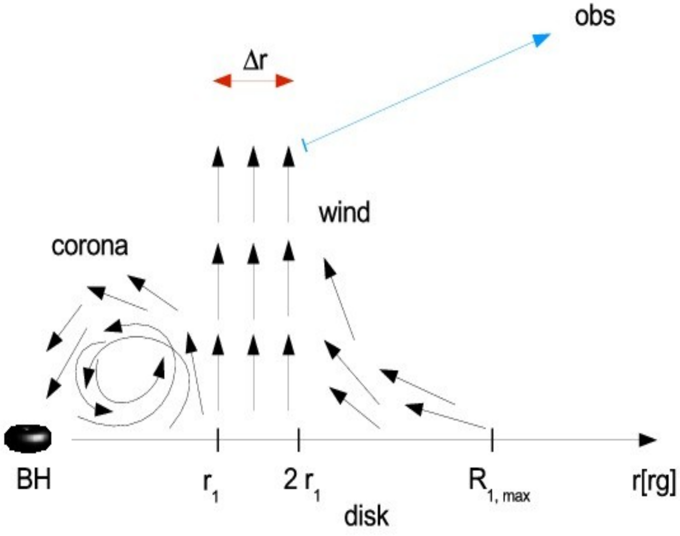
Second Chandra observation (second green arrow) shows presence of fast ionized wind.

Observation from XMM-Newton (first red arrow) and first Chandra observation (first green arrow), are in the heartbeat state of the source, but the wind is weak (below detection treshold)

Observed wind properties vs. model

$$\dot{M}_{wind} = 2\pi f m_p v n r^2$$

$$\xi = \frac{L_{ion}}{n r^2}$$



Observed mass loss rate in wind. Ionisation parameter from the spectrum (fit with the code Cloudy; G. Ferland et al. 2013).

$$\dot{M}_{wind} = Const * \left(R_{max}^{0.2} - r^{0.2}\right) [g/s]$$

Theoretical fit from model. The *Const depends on the wind* "strength", which is able to partially stabilize the disk

Observed wind parameters wiatru vs. model

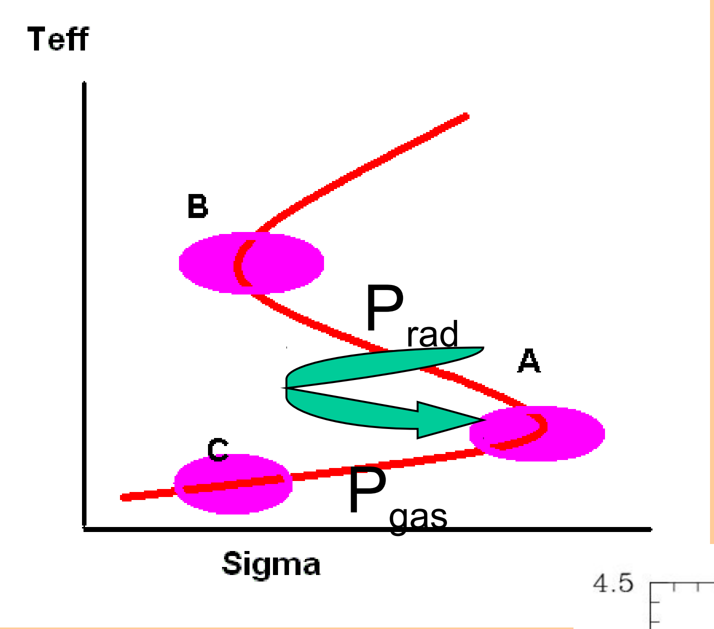
		Observations				Model			
State	Wind comp.	v [km/s]	log ξ	n [cm^{-3}]	f	Mdot [g/s]	R_{min} [R_{Schw}]	R_{max} [R_{Schw}]	A
No “Heartbeat”	w1	9700 ± 800	3.4 ± 0.3	$5.1\ 10^{15}$	0.0015	$2.7\ 10^{17}$	950	4200	300
	w2	15700 ± 600	3.8 ± 0.2	$1.3\ 10^{16}$	0.0037	$4.2\ 10^{17}$	380	4700	300
“Heartbeat”	w1			$< 5\ 10^{14}$		$2.5\ 10^{16}$	950	4900	15
	w2			$< 10^{15}$		$3.9\ 10^{16}$	380	5900	15

Non-linear variability in other BH X-ray sources

Internal instabilities in accretion disk

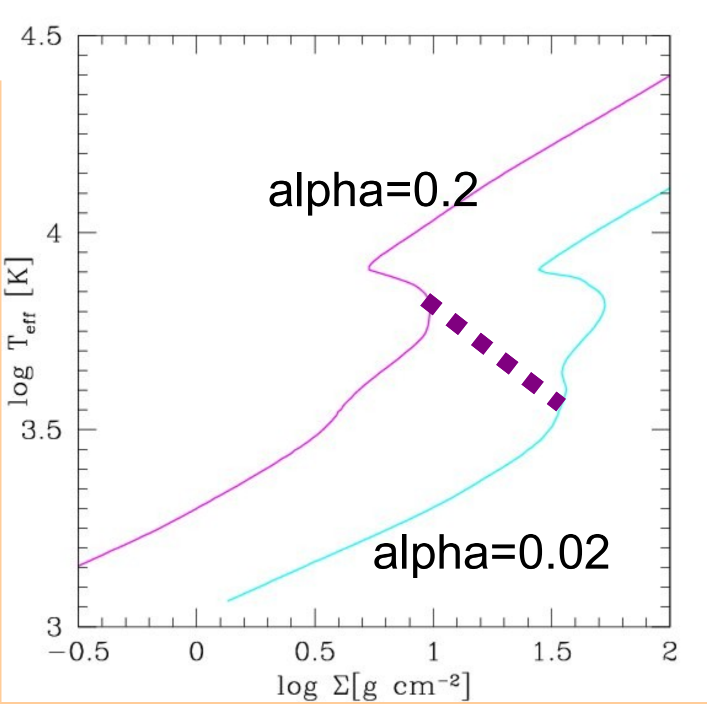
Radiation pressure:

- Radiatively cooled phase unstable if $P_{rad}>P_{gas}$
- Advection stabilizes the hot phase

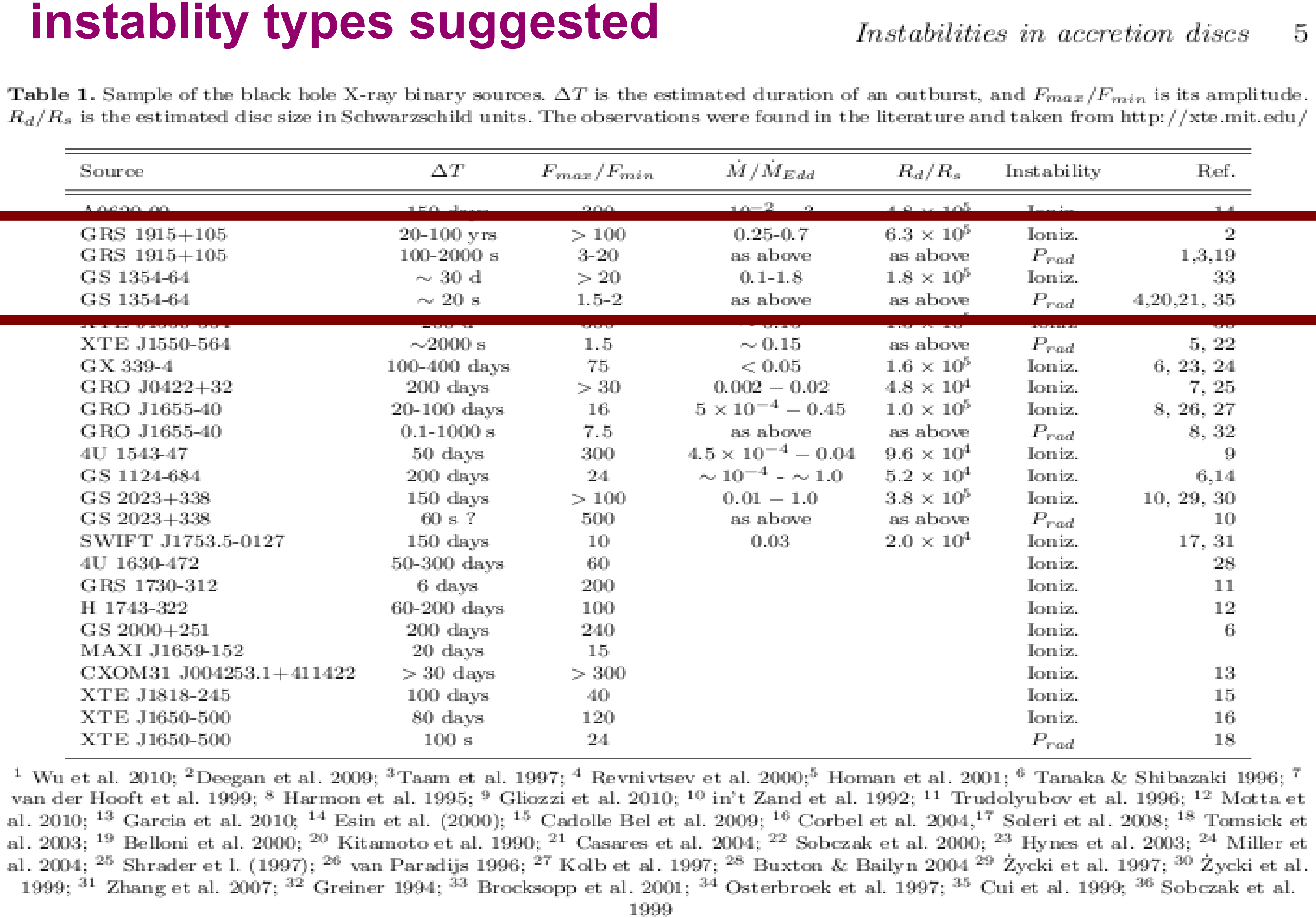


Partial hydrogen ionization:

- Unstable if 3.5<log T<4
- Opacities depend on temperature and density inversely in that region
- Cycle enhanced if $alpha_{hot}>alpha_{cold}$



Sample of X-ray novae: 2 instablity types suggested



Instabilities in accretion discs 5

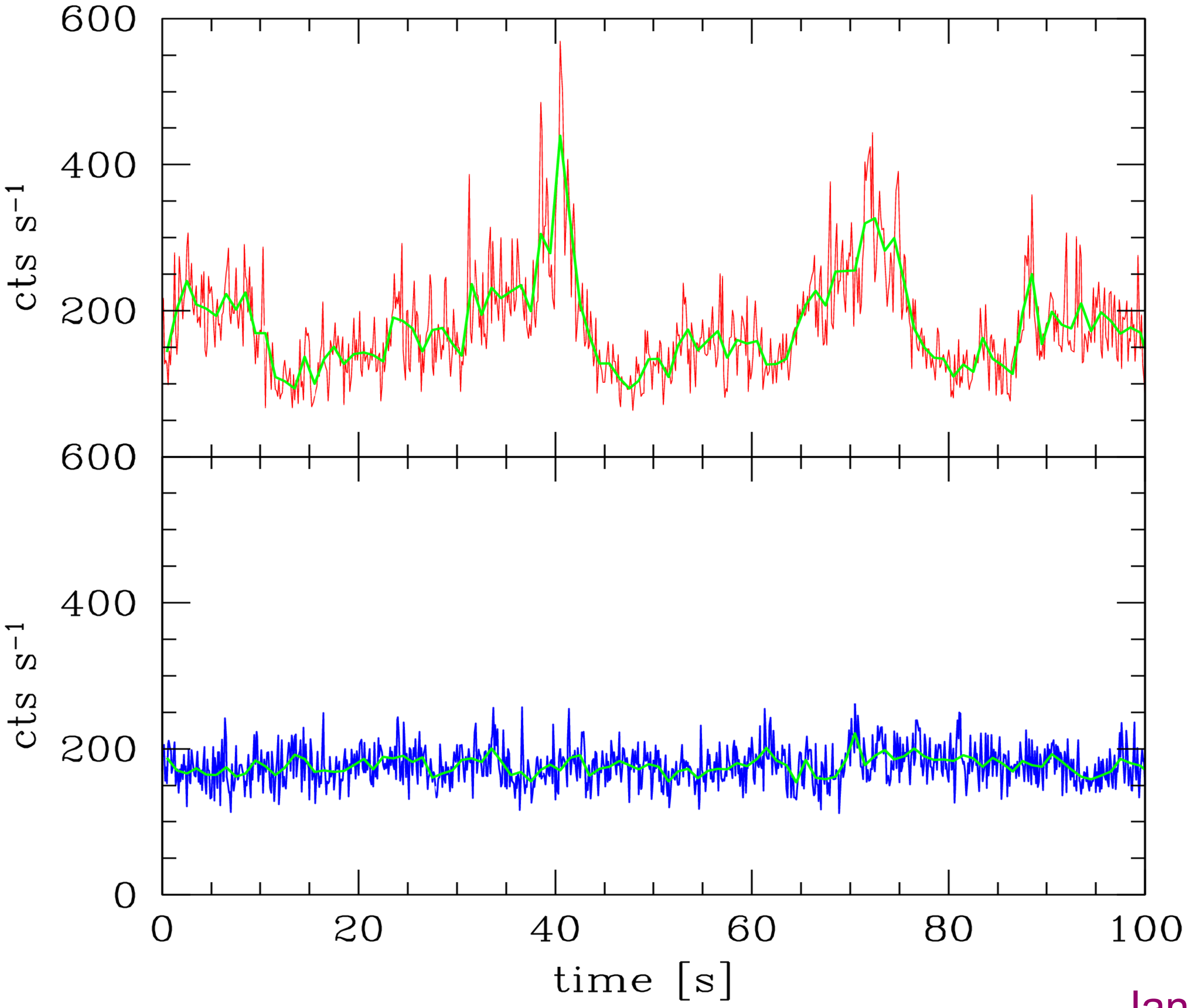
Table 1. Sample of the black hole X-ray binary sources. ΔT is the estimated duration of an outburst, and F_{max}/F_{min} is its amplitude. R_d/R_s is the estimated disc size in Schwarzschild units. The observations were found in the literature and taken from http://xte.mit.edu/

Source	ΔT	F_{max}/F_{min}	$\dot{M}/\dot{M}_{Edd}$	R_d/R_s	Instability	Ref.
A0620-00	150 days	200	$10^{-2} - 2$	4.8×10^5	Ioniz.	14
GRS 1915+105	20-100 yrs	> 100	0.25-0.7	6.3×10^5	Ioniz.	2
GRS 1915+105	100-2000 s	3-20	as above	as above	P_{rad}	1,3,19
GS 1354-64	~ 30 d	> 20	0.1-1.8	1.8×10^5	Ioniz.	33
GS 1354-64	~ 20 s	1.5-2	as above	as above	P_{rad}	4,20,21, 35
XTE J1550-564	200 d	[illegible]	~ 0.15	[illegible]	Ioniz.	[illegible]
XTE J1550-564	$\sim$2000 s	1.5	~ 0.15	as above	P_{rad}	5, 22
GX 339-4	100-400 days	75	< 0.05	1.6×10^5	Ioniz.	6, 23, 24
GRO J0422+32	200 days	> 30	$0.002 - 0.02$	4.8×10^4	Ioniz.	7, 25
GRO J1655-40	20-100 days	16	$5 \times 10^{-4} - 0.45$	1.0×10^5	Ioniz.	8, 26, 27
GRO J1655-40	0.1-1000 s	7.5	as above	as above	P_{rad}	8, 32
4U 1543-47	50 days	300	$4.5 \times 10^{-4} - 0.04$	9.6×10^4	Ioniz.	9
GS 1124-684	200 days	24	$\sim 10^{-4}$ - ~ 1.0	5.2×10^4	Ioniz.	6,14
GS 2023+338	150 days	> 100	$0.01 - 1.0$	3.8×10^5	Ioniz.	10, 29, 30
GS 2023+338	60 s ?	500	as above	as above	P_{rad}	10
SWIFT J1753.5-0127	150 days	10	0.03	2.0×10^4	Ioniz.	17, 31
4U 1630-472	50-300 days	60			Ioniz.	28
GRS 1730-312	6 days	200			Ioniz.	11
H 1743-322	60-200 days	100			Ioniz.	12
GS 2000+251	200 days	240			Ioniz.	6
MAXI J1659-152	20 days	15			Ioniz.	
CXOM31 J004253.1+411422	> 30 days	> 300			Ioniz.	13
XTE J1818-245	100 days	40			Ioniz.	15
XTE J1650-500	80 days	120			Ioniz.	16
XTE J1650-500	100 s	24			P_{rad}	18

[1] Wu et al. 2010; [2]Deegan et al. 2009; [3]Taam et al. 1997; [4] Revnivtsev et al. 2000;[5] Homan et al. 2001; [6] Tanaka & Shibazaki 1996; [7] van der Hooft et al. 1999; [8] Harmon et al. 1995; [9] Gliozzi et al. 2010; [10] in't Zand et al. 1992; [11] Trudolyubov et al. 1996; [12] Motta et al. 2010; [13] Garcia et al. 2010; [14] Esin et al. (2000); [15] Cadolle Bel et al. 2009; [16] Corbel et al. 2004,[17] Soleri et al. 2008; [18] Tomsick et al. 2003; [19] Belloni et al. 2000; [20] Kitamoto et al. 1990; [21] Casares et al. 2004; [22] Sobczak et al. 2000; [23] Hynes et al. 2003; [24] Miller et al. 2004; [25] Shrader et l. (1997); [26] van Paradijs 1996; [27] Kolb et al. 1997; [28] Buxton & Bailyn 2004 [29] Życki et al. 1997; [30] Życki et al. 1999; [31] Zhang et al. 2007; [32] Greiner 1994; [33] Brocksopp et al. 2001; [34] Osterbroek et al. 1997; [35] Cui et al. 1999; [36] Sobczak et al. 1999

Janiuk A. & Czerny B.; MNRAS, 2011, 414, 2186

Short times cycles: stable and unstable source

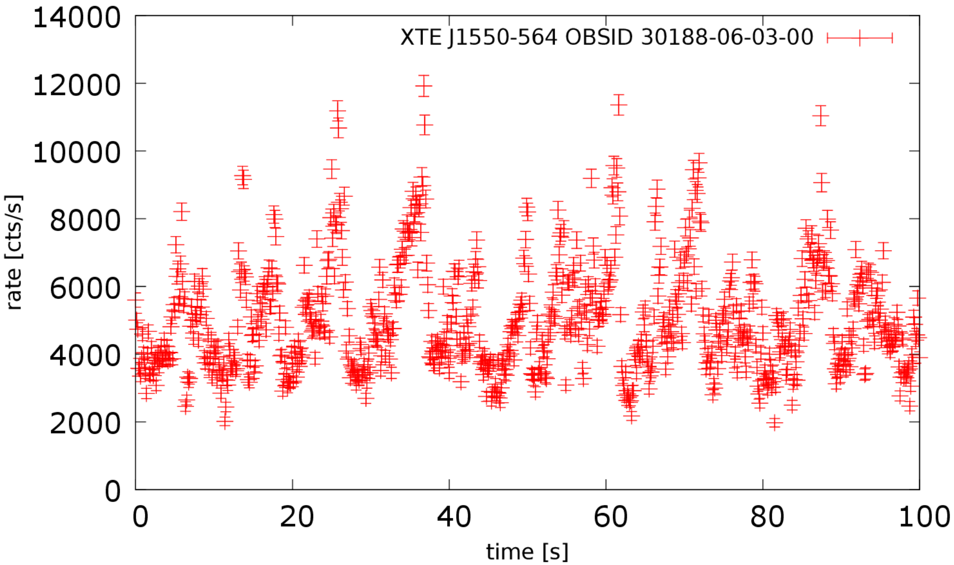


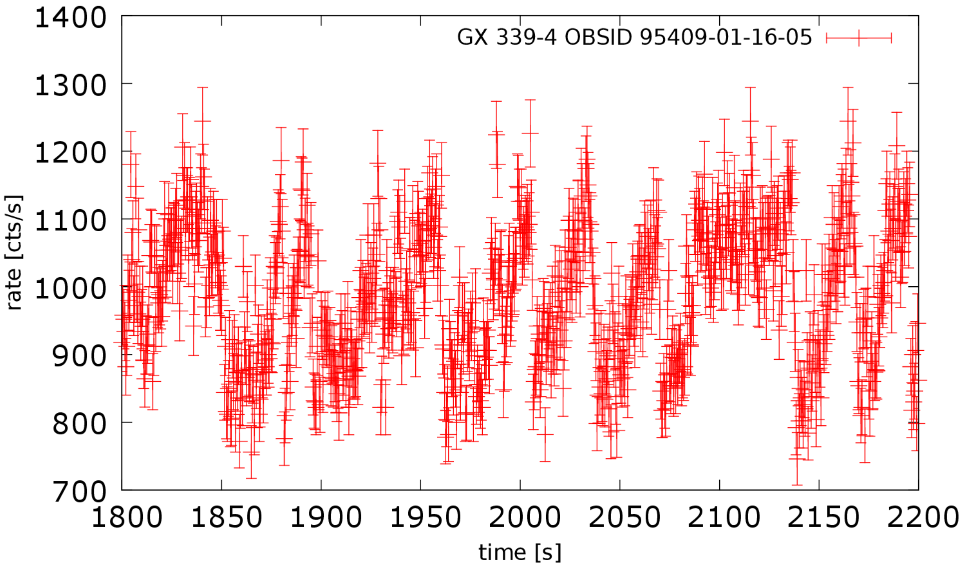
GS 1354-64

Cyg X-1

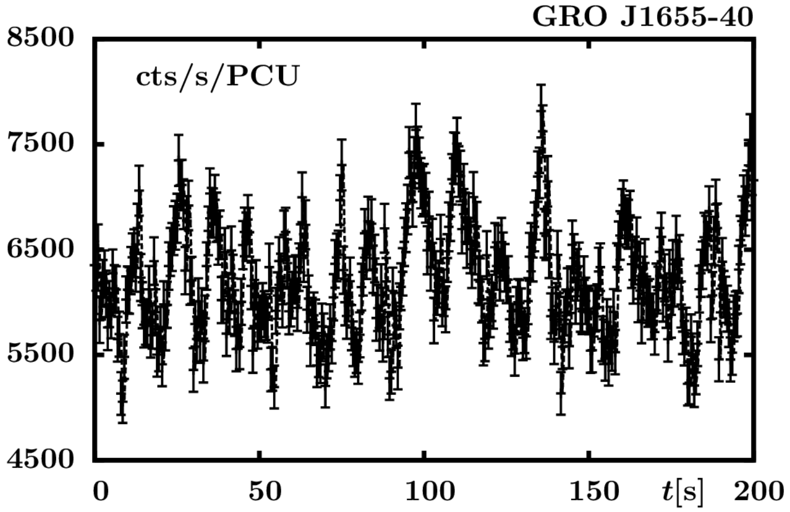
Janiuk & Czerny, 2011

Revealing the non-linear variability in X-ray sources





P. Sukova, M. Grzędzielski, A. Janiuk (2015, submitted to A&A, arXiv:1506.02526);
see also the poster by Petra Sukova



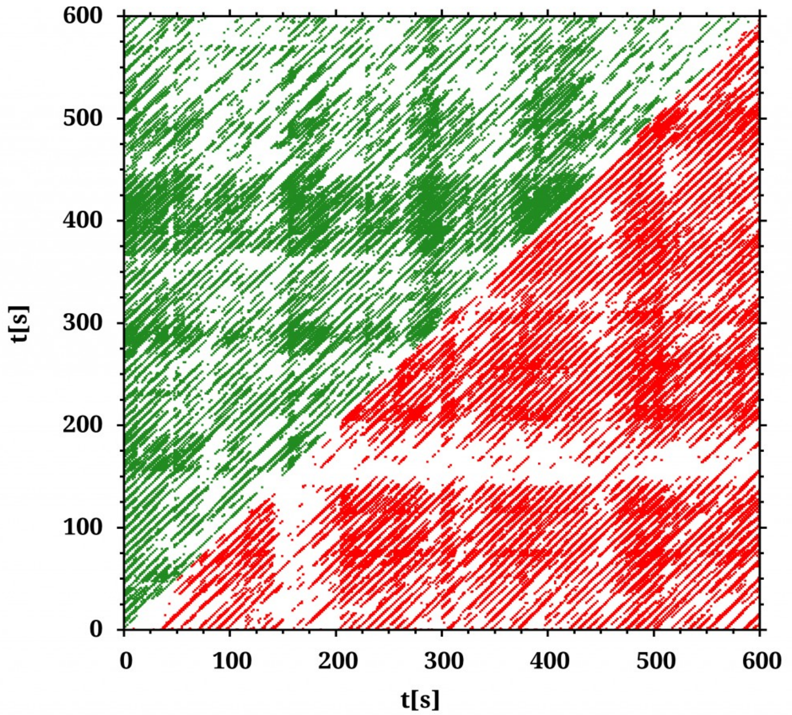
Recurrence analysis method

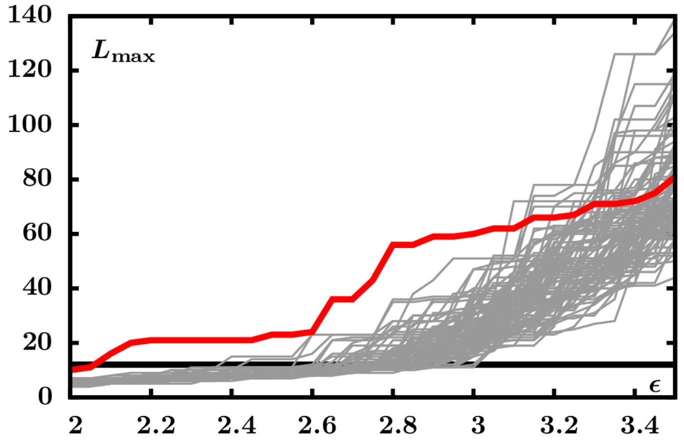
- The method works with simulated trajectories of complicated non-linear systems, e.g. motion of the test particle in the field of a black hole, given by Einstein equations. The chaotic orbit shows high significance of non-linear dynamics.

- Recurrence plot is a visualisation of the recurrence matrix. The long diagonal lines represent the situation, when the trajectory (reconstructed from the time-series by time delay technique) returns close to itself in two different times

- We compare the results between real and surrogate data, the latter have the same power spectra, but variability is stochastic.

- The significance of chaos is defined as a weighted difference between the Renyi entropy K_2 of the data and its surrogates sample.





see the poster by Petra Sukova...

Application to X-ray binaries

- We applied the recurrence analysis on observations of six black hole X-ray binaries measured by RXTE satellite.

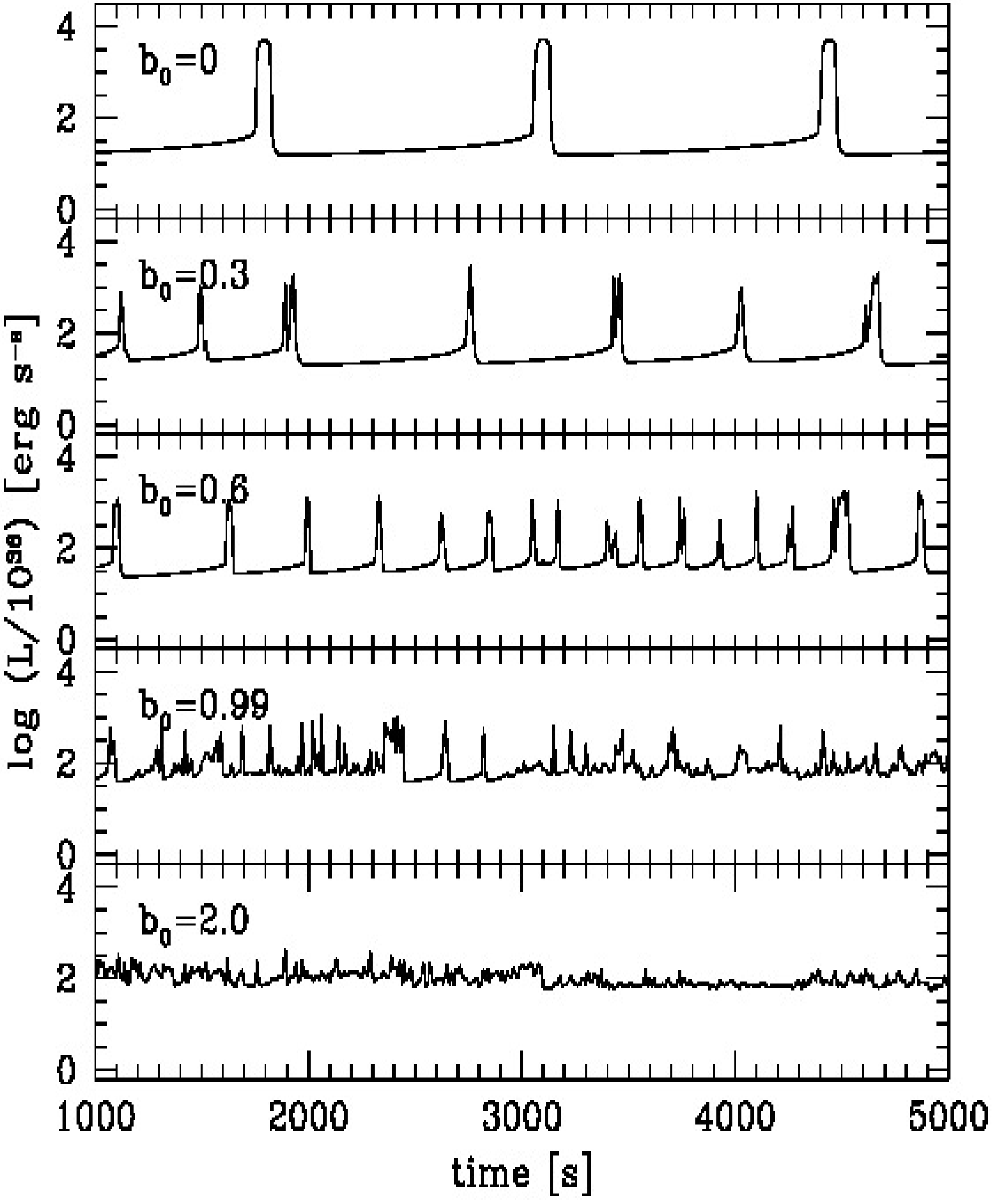
- We developed a method for distinguishing between stochastic, non-stochastic linear and non-linear processes using the comparison of the quantification of recurrence plots with the surrogate data.

- We tested our method on the sample of observations of the microquasar **IGR J17091-3624**, which spectral states were provided by Pahari et al. (2014). Significant results for the ``heartbeat'' state were obtained.

- We examined several observations of the other five microquasars. Aside from the well-studied binary **GRS 1915+105**, we found significant traces of non-linear dynamics also in three other sources (**GX 339-4, XTE J1550-564 and GRO J1655-40**).

- The non-linear behavior of the lightcurve during some of the observations gives the evidence, that the accretion flow in the binaries is governed by low number of non-linear equations. Possible explanation is that the accretion disc is in the state prone to the thermal-viscous instability and is undergoing the induced limit cycle oscillations.

Stabilizing the disk: viscosity fluctuations due to a Markov chain process



$$\alpha(r,t)=\alpha_0[1+\beta(r,t)]$$

viscosity with a constant; α_0 ~ 0.1, and fluctuating part

$$\beta(r,t)=b_0 u_n$$

$$u_n=-0.5u_{n-1}+\epsilon_n$$

$$\tau_{visc}=\frac{1}{\alpha}\Omega\left(\frac{r}{H}\right)^2$$

Timescale of a fluctuation

$$H=\frac{c_s}{\Omega}$$

Spatial scale of a fluctuation

See: Lyubarskii 1997; King et al. 2004

Janiuk A. & Misra R.; 2012, A&A, 540, A114

Summary

- **IGR J17091** is another microquasar, after **GRS 1915+105**, that in some states exhibits the limit-cycle oscillations of its X-ray luminosity
- These oscillations are plausibly explained by the intrinsic thermal-viscous instability of the accretion disk, induced by the radiation pressure
- The fast, ionized wind ejected from the accretion disk on the cost of a fraction of dissipated energy is a viable mechanism to completely stabilize the disk in other states, or to govern the moderate amplitude of the disk oscillations
- In other Black Hole X-ray binaries, i.e. **GX 339-4, XTE J1550** and **GRO J1655**, the hints of a non-linear variability were also found, using the novel method adopted for the analysis of a deterministic chaos process
- Possible further mechanism stabilizing the oscillations in other sources or different spectral states is a stochastic fluctuation of the viscosity (modeled as a Markov chain process)

Thank you

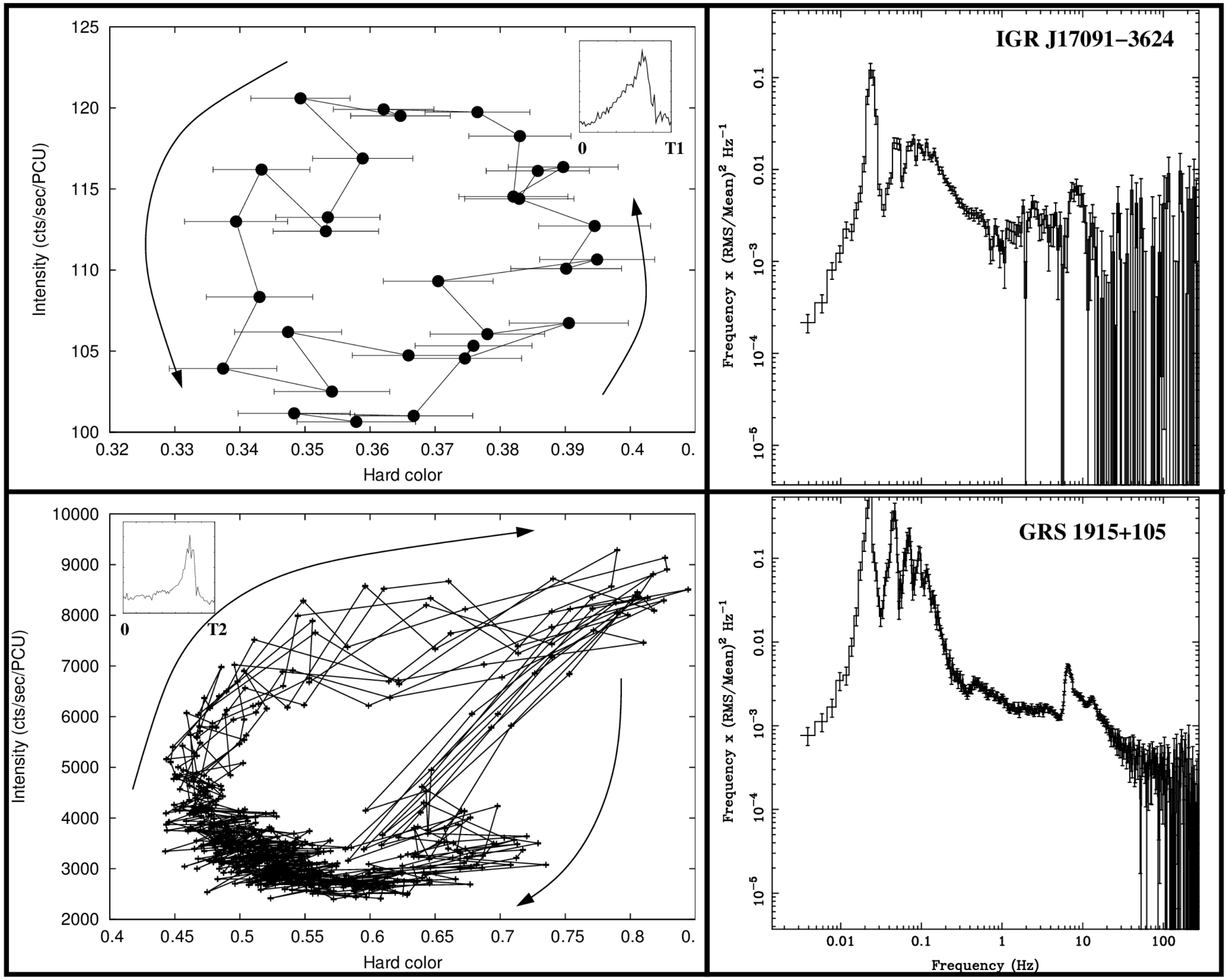


Fig. 4.— Left panels show the hardness-intensity diagram for flares observed during the variability class in IGR J17091–3624 (top; ObsID 96420-01-04-03) and GRS 1915+105 (bottom; ObsID 96378-01-01-00) occurring at an average period of T1=70.96 seconds and T2=63.72 seconds, respectively. Arrows mark the time evolution. Inset shows representative flares. Light curves and colors are estimated from 1 sec averages. Intensity is the count rate in the 2-60 keV range (absolute channels 0-240) and hard color is the 6.5–15.0 keV / 2–6.5 keV count rate ratio (channels 15-35 and 0-14, respectively). Right panels show representative power spectra from averages of 512 sec segments during the variability class for IGR J17091–364 (top, ObsID:96420-01-05-000, MJD 55647.9) and for GRS 1915+105 (bottom, ObsID:40703-01-07-00, MJD 51235.3).

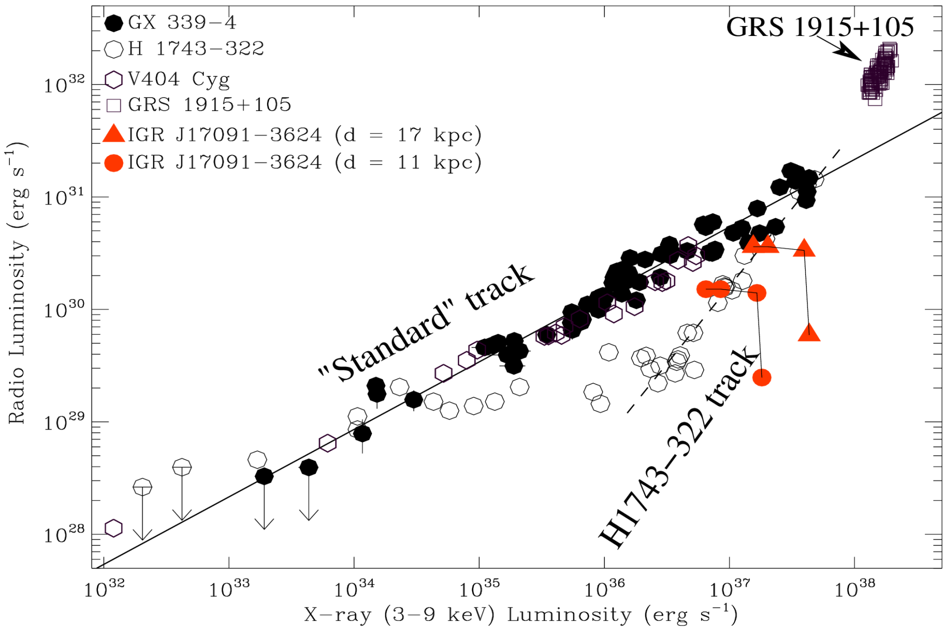
Eddington ratio and distance to IGR J17091

Large distance (> 17 kpc) suggested by the value of N_H absorption ($6x10^{21}$ cm^{-2})

At spectral transition, the flux $F=4x10^{-9}$ erg/s/cm^2 implies the distance of 11-17 kpc, if the transition occurs at 4-10% of L_{Edd} and black hole mass of 10 M_{sun}

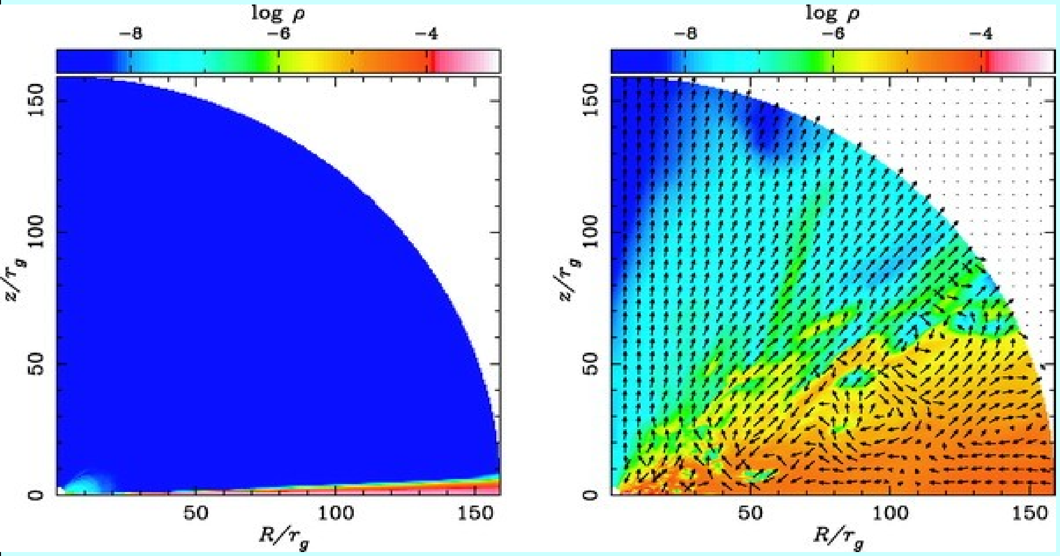
Discrete jet ejections are observed in radio during the state transitions

The source does not follow the radio-X-ray 'fundamental plane' track, standard for low Eddington ratio accreting black holes



Rodriguez et al. 2011

Numerical work to test the radiation pressure instability



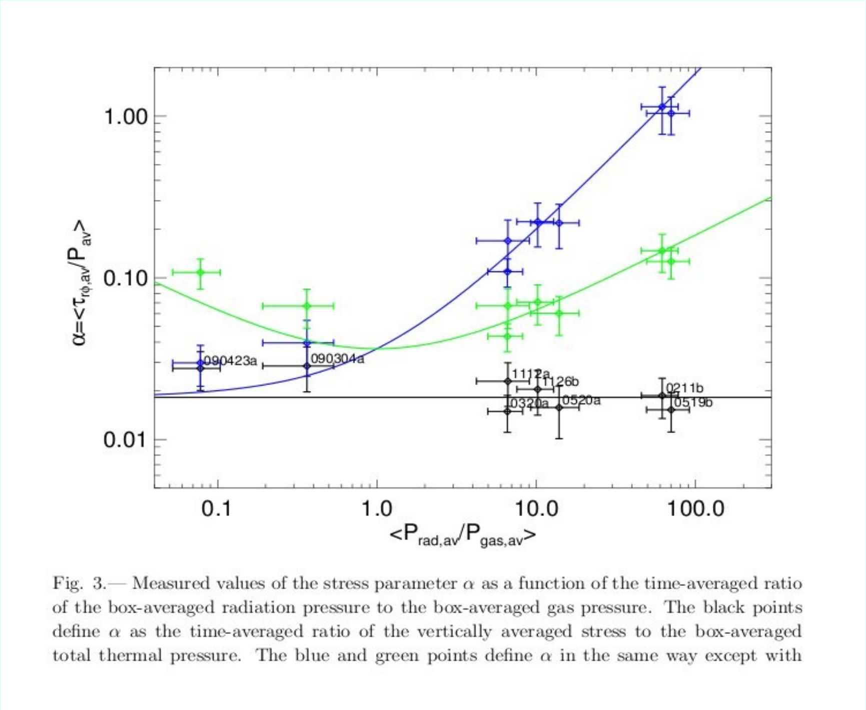
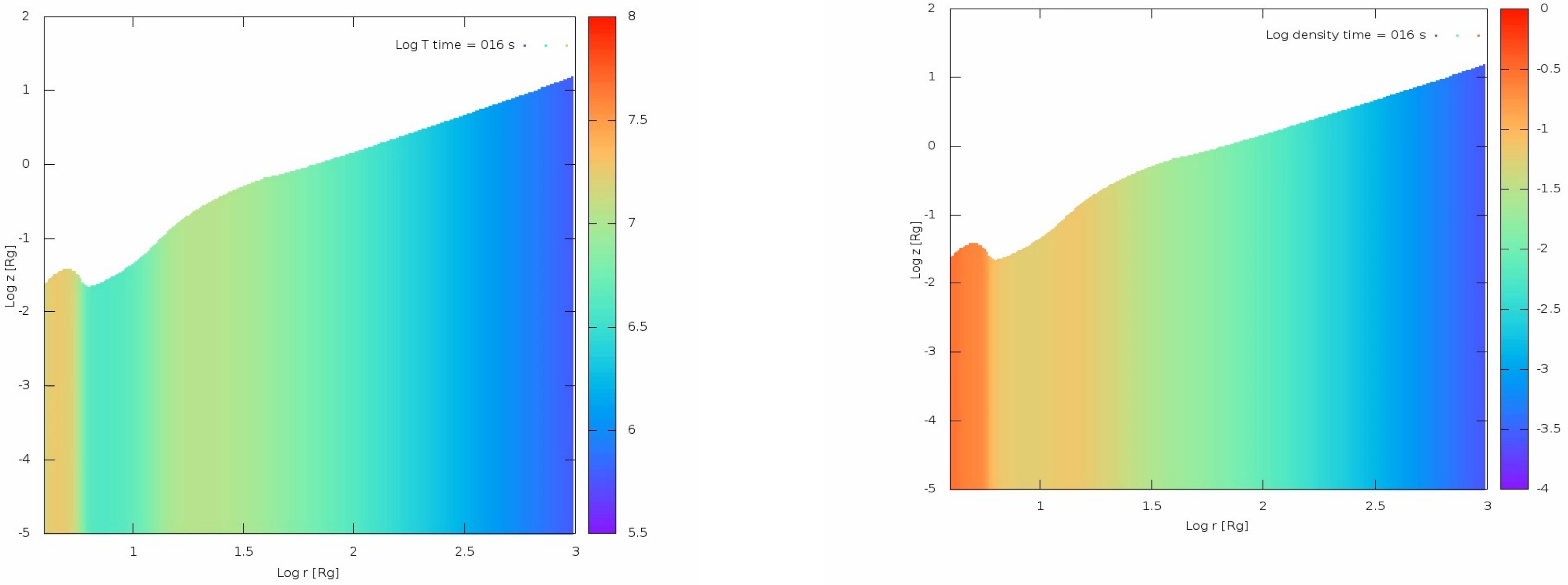


Fig. 3.— Measured values of the stress parameter α as a function of the time-averaged ratio of the box-averaged radiation pressure to the box-averaged gas pressure. The black points define α as the time-averaged ratio of the vertically averaged stress to the box-averaged total thermal pressure. The blue and green points define α in the same way except with

2D global hydro-simulations show the limit cycles (Ohsuga 2006)

MHD “shearing-box” simulations (Hirose, Blaes i Krolik, 2009a; 2009b)



Changes of the temperature and density of the disk during its outbursts.

Colors present the profile of the disk in a log-scale, in the r-z plane.

Parameters: mass of black hole 6 M_{Sun}, accretion rate 0.1 Eddington, viscosity parameter alpha 0.1. Also, a wind, with dimensionless strength coefficient A=15, was assumed, it takes away a part of energy flux dissipated locally in the disk.

Abstract:

The microquasar IGR J17091, as the recently discovered analogue of the well known source GRS 1915+105, exhibits quasi-periodic outbursts, of the period 5-70 seconds, and regular amplitudes, frequently referred to as a 'heartbeat state'. We argue that these states are plausibly explained by the accretion disk instability, driven by the dominant radiation pressure. Using our GLobal Accretion DIsk Simulation hydrodynamical code, we model these outbursts quantitatively. We also find a correlation between the presence of massive outflows launched from the accretion disk and stabilization of the oscillations. We verify the theoretical predictions with the available timing and spectral observations.

Furthermore, we postulate that the underlying non-linear differential equations that govern the evolution of an accretion disk, are responsible for the variability pattern of several other microquasars, including XTE J1550-564 and GX 339-4, observed in some states. This study is based on the signatures of deterministic chaos in the observed lightcurves of these sources, which we found using the recurrence analysis method and comparison to the surrogate data. We discuss these results in the frame of the accretion disk instability model.