On different types of instabilities in black hole accretion discs. Implications for X-ray binaries and AGN

Agnieszka Janiuk¹*, Bożena Czerny²
¹ Center for Theoretical Physics, Al. Lotnikow 32/46, 02-680 Warsaw, Poland
² N. Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland

ABSTRACT

We discuss two important instability mechanisms that may lead to the limit-cycle oscillations of the luminosity of the accretion disks around compact objects: ionization instability and radiation-pressure instability. Ionization instability is well established as a mechanism of X-ray novae eruptions in black hole binary systems but its applicability to AGN is still problematic. Radiation pressure theory has still very weak observational background in any of these sources. In the present paper we attempt to confront the parameter space of these instabilities with the observational data. At the basis of this simple survey of sources properties we argue that the radiation pressure instability is likely to be present in several Galactic sources with the Eddington ratios above 0.15, and in AGN with the Eddington ratio above 0.025. Our results favor the parameterization of the viscosity through the geometrical mean of the radiation and gas pressure both in Galactic sources and AGN. More examples of the quasi-regular outbursts in the timescales of 100 seconds in Galactic sources, and hundreds of years in AGN are needed to formulate firm conclusions. We also show that the disk sizes in the X-ray novae are consistent with the ionization instability. This instability may also considerably influence the lifetime cycle and overall complexity in the supermassive black hole environment.

Key words: physical processes:accretion; X-rays:binaries; galaxies: active – galaxies: evolution – galaxies

1 INTRODUCTION

The description of the viscous torque through the α-parameter by Shakura & Sunyaev (1973) boosted the modeling of the disk accretion onto the central object, with application in various fields, from young stellar objects through stellar close binary systems to active galactic nuclei. The parameterization was justified, but not based on a specific well developed theory. However, the properties of the stationary disk flow weakly depend on this assumption. The spectra models were totally unaffected by the viscosity unless either departure from the Keplerian motion or departure of the emission from a local black body were taken into account.

However, the stability of disk models does depend significantly on the adopted description of the viscosity. First, it was noticed that the assumption of the proportionality of the viscous troque to the total (i.e. gas plus radiation) pressure leads to the viscous Pringle et al. (1974) and thermal Lightman & Eardley (1974) instabilities. Later, the instability of the outer gas-pressure dominated parts of the disk was discovered, in the region of partially ionized hydrogen and helium (Meyer & Meyer-Hofmeister 1981, Smak 1984). Such instabilities should lead to semi-regular periodic outbursts. Therefore, observations of objects containing accretion disks can be used to test the assumptions about the viscosity law.

Such confrontation of the models and theory is being done in case of the ionization instability. The early model development was actually motivated by the need to explain the dwarf novae outbursts (Cannizzo et al. 1982; for a review see Lasota 2001). It may also apply to active galaxies (Lin & Shields 1980, Mineshige & Shields 1990) although observational tests are at the early stage of development.

The presence of the radiation pressure instability is not proved yet (see e.g. Done et al. 2007). The understanding of the true nature of the viscosity as being due to the
magnetorotational instability [Balbus & Hawley 1991] did not simply set the issue. The limit cycle cannot be seen in 3-D simulations of this instability since the authors cannot follow the global evolution of the disc in a viscous timescale and the radial propagation of heating and cooling fronts is here neglected. However, recent computations indicate that radiation pressure contributes to the viscous torque and the instability may be there [Hirose et al. 2009b]. The comparison of the predictions of this instability with observational data was done only in a few papers so far.

In this work we propose to study further the models of the accretion disc instabilities in a global picture, as well as to better support them observationally. In case of the radiation pressure instability, we use two models: one is based on the assumption of the viscouscous torque proportional to the total pressure and the other is based on the assumption of the viscouscous torque proportional to geometrical mean of the gas and radiation pressure. We also include the cooling term due to the outflow. We mark the instability strips in the disk radius - accretion rate plane and we compare them with the observed properties of the X-ray lightcurves of accreting black holes in binary systems, taken from the literature. We claim that the observational constraints for the thermal disc instability and the limit-cycle behaviour is much more than the one famous example of the microquasar GRS 1915+105. We give some examples of other sources and discuss further need for the detailed observational studies for both Galactic individual X-ray sources and AGNs.

This article is organized as follows. In Section 2 we discuss the theoretical background for the radiation pressure and partial hydrogen ionization instabilities. We also present the results for the extension and overlapping of the unstable regions in the accretion discs. In particular, we focus on the constraints for the accretion rate and jet efficiency which would be adequate for the astrophysical black hole discs to become unstable for one or both types of instabilities. These results are based on the numerical codes developed by ourselves and discussed in detail in a series of previous works. In section 3 we present the observational constraints for the disc instabilities found for a number of Galactic black hole binaries. We also discuss the supermassive black hole AGNs and some observational constraints found in the literature. In Section 4 we give a summary and conclusions.

2 DISC INSTABILITIES

2.1 Radiation pressure

The black hole accretion disc with the classical heating term proportional to the pressure with the $\alpha$ coefficient (Shakura & Sunyaev 1973) is subject to the thermal and viscous instability when the radiation pressure dominates over the gas pressure. This occurs in the innermost radii of the accretion disc around a compact object (in case of a white dwarf such a region cannot be present). Radiation pressure instability of classical alpha models of Shakura & Sunyaev (1973) was noticed very early (Lightman & Eardley 1974, Pringle et al. 1974) and it was fully analyzed by Shakura & Sunyaev (1976).

The time evolution of the system and its stability is governed by the accretion rate outside the unstable region (i.e., the mean accretion rate). If the accretion rate is low, then the disc remains cold and stable, with a constant low luminosity. If the accretion rate is large, then the whole disc becomes hot and is stabilized by advection, i.e. enters a slim disc solution (Abramowicz et al. 1988). However, for the intermittent accretion rates, larger than some critical value, the unstable mode activates. In this case the source enters a cycle of bright, hot states, separated by the cold, low luminosity states. The outburst amplitudes and durations are sensitive to black hole mass, viscosity parameter and the mean accretion rate. Also, the heating prescription is important here. If the viscous heating is proportional to the total pressure, the outburst amplitudes are very large, however, they can be reduced if the heating is proportional to the square root of the gas times the total pressure. If we assume the heating proportional only to the gas pressure, the instability disappears. In case of the geometrical mean of the two components the parameter space of the instability is greatly reduced.

Preliminary shearing-box 3D simulations replacing the alpha viscosity with a physical (magnetic) viscosity mechanism indicated that there is no thermal runaway even when the radiation pressure is 10 times larger than the gas pressure [Hirose et al. 2009a]. However, the same authors [Hirose et al. 2009b] in their follow-up work already suggested the possibility of radiation pressure instability in some of their calculations, as the unstable solutions may be seen on the surface density - effective temperature plot. The limit cycle cannot be seen in those simulations since they do not follow the global evolution of the disc in a viscous timescale and the radial propagation of heating and cooling fronts is here neglected. Full time-dependent computations of the global evolution can be only performed with a simple viscosity parameterization, and in such computations a limit-cycle behaviour is seen, with disc alternating between the hot and cold states (e.g. Nayakshin et al. 2000, Janiuk et al. 2002, Janiuk & Czerny 2007, Czerny et al. 2009).

Observationally, the situation is far from clear (see e.g. the review by Done et al. 2007). Several authors suggested that the radiation pressure instability is an attractive explanation of the regular outbursts lasting a few hundreds of seconds observed in the microquasar GRS 1915+105 (e.g. Taam et al. 1997, Deegan et al. 2009). The radiation pressure instability is the only model which explains the absence of the direct transitions from the state C to the state B in this source. The lightcurves of some other objects also show the fluctuations in a form of a limit cycle on the appropriate timescales. An interesting example is X-ray pulsar GRO J1744-28 (Cannizzo 1996, Cannizzo 1998) with periods of very high accretion rate and low magnetic field which allows for the presence of the inner radiation-pressure dominated part of the disk. This instability operates when the radiation pressure is important, so it is expected only in high Eddington ratio Galactic sources and AGN. However, for many sources accreting at very high rates the limit cycle oscillations have not been reported. Comparison of the Eddington ratios of the stable sources and those showing fast (100 - 1000 s) regular outbursts is a key test of the correct viscosity parameterization.
2.2 Partial Hydrogen ionization

Another type of the thermal - viscous instability occurs due to the partial ionization of hydrogen and helium. The unstable zone is typically present in the outer part of the disc, where the effective temperature is of order of 6000 K. The ionization instability is thus an example of a firm agreement between the observations and theory. A recent example is SU UMa-type dwarf nova V344 Lyr observed by Kepler satellite, for which its outbursts and superoutbursts have been modeled with this instability (Cannizzo et al. 2010).

This instability also likely applies to active galaxies (Lin & Shields 1986, Mineshige & Shields 1990) although this is still uncertain. The models of the outbursts were further developed by Siemiginowska et al. (1996), Janiuk et al. (2004), and they were applied to statistics of AGN by Siemiginowska & Elvis (1997). Menou & Quataert (2001) and Hameury et al. (2009) argued that the amplitude of such outbursts will be small but the evaporation of the inner disk enhances the amplitude considerably (Janiuk et al. 2004) and prolongs the quiescent state (Hameury et al. 2009).

In this case the situation is much similar to the above, as the disc cycles between two states. The hot and mostly ionized state of a small local accretion rate is intermittent with a cold, neutral state of a small local accretion rate. Again, the quantitative outcome of the model is governed by the assumed external (mean) accretion rate, viscosity and mass of the central object.

2.3 Location of the unstable zones

We calculated the steady-state models of the accretion disc structure, for two exemplary values of the black hole mass, characteristic for Galactic sources ($10 M_\odot$) and AGN ($10^7 M_\odot$). The models are based on the vertically averaged equations for the energy balance between the viscous heating and radiative as well as advective cooling and hydrostatic equilibrium. The heating term, governed by the viscosity parameter $\alpha$, is in the radiation pressure dominated region assumed proportional to either the total pressure, or to the square root of the total times the gas pressure. In the gas pressure dominated region, located at larger distances, the heating is assumed proportional only to the gas pressure. We calculate here the vertical profiles of temperature, density and pressure, using the opacity tables that cover the temperature range relevant for partial hydrogen ionization, including the presence of dust and molecules (see details in Rożanska et al. 1999).

The basic parameter of each stationary model is the global (external) accretion rate, through which we determine the total energy flux dissipated in the disc at every radius $r$. Once the effective temperature and surface density are determined at every disc radius, we find the stable solutions, i.e. the accretion rates for which the slope of $T - \Sigma$ (or $M - \Sigma$) relation is positive, and the unstable solutions, with the negative slopes. In other words, the “S-curve” is plotted locally at a number of disk radii, and we search for the critical $m$ points at which the curve is bending. These points limit the minimum and maximum values of accretion rates for which the disk will be unstable. In turn, we determine the range of radii, for which at a given global accretion rate the disc is unstable first due to the radiation pressure and then to the ionization instability.

For the latter, the unstable strip is located at the outskirts of the disk. Obviously, if the instability arises at the outer disk, the front will then propagate inwards to much smaller radii. However, if the disk size is smaller than the inner edge of the unstable strip plotted in Figure 1 no ionization instability outbursts should take place. Our results, based on the detailed vertical structure calculations, are consistent with the simplified formulae given in the Appendix of Hameury et al. (2001), with respect to the inner boundary of the ionisation instability strip. The outer edge we determined is somewhat larger, due to a different opacity tables in our model which include absorption on molecules, e.g. molecular hydrogen, as described in Rożanska et al. (1999).

In Figure 1 we show the maps of the disc instabilities for the two chosen black hole masses, on the plane radius vs. global accretion rate (in dimensionless units). In addition, we distinguish the two possible stabilizing mechanisms for the radiation pressure instability: the heating prescription and the possibility of energy outflow to the jet. The latter is parameterized by the following function:

$$\eta_{\text{jet}} = 1 - \frac{1}{1 + A \alpha n^2}$$

and the jet outflow acts as a source of additional cooling (Nayakshin et al. 2004, Janiuk et al. 2002).

The jet outflow reduces the size of the unstable zone for large accretion rates, as well as limits the instability to operate below some threshold maximum $m$. This rate is of course sensitive to our adopted parameter for the jet strength. The Figure 1 shows the case of a very strong jet, with $A = 25$ and in this case the limiting accretion rate is about 20% of the Eddington rate. For a 10 times weaker jet the limiting accretion rate is about 3 times larger.

The viscosity parameter, $\alpha$, only moderately affects the results for the radiation pressure instability, apart from the timescales of the limit cycle. The Figure 1 presents the conservative case of a very small viscosity, $\alpha = 0.01$, for which the extension of the unstable zone is small. If the viscosity is larger, the unstable zone size is also increased, for instance for $\alpha = 0.1$ the outer radius of the instability is larger by a factor of $\sim 1.25$. This also means that the minimum accretion rate for which the disc is unstable, is slightly smaller. However, in this smallest accretion rates the unstable zone is very narrow. For a very narrow width of the zone, the instability does not work, because the front does not propagate, and we have only marginally stable solutions (Suszczewicz & Miller 1997). For instance, Hameury et al. (2009) find that the heating and cooling fronts of the ionization instability do not propagate strongly.
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Figure 1. The extension of the radiation pressure (solid and dotted lines) and hydrogen ionization (green; dashed lines) unstable zones, depending on mean accretion rates (Eddington units). The results are for two heating prescriptions: $\alpha P_{\text{tot}}$ (blue; solid lines) and $\alpha \sqrt{P_{\text{gas}} P_{\text{tot}}}$ (red; dotted lines). The crossed regions mark the results for a non-zero fraction of jet power, described by Eq. (1) with $A = 25$. The black hole mass is $M = 10^8 M_\odot$ (bottom) and $M = 10^9 M_\odot$ (top). The viscosity is $\alpha = 0.01$.

Thus the fast radiation pressure instability is expected to operate for an average accretion rate higher than a certain lower limit, mostly dependent on the adopted viscous scaling. There is an upper limit as well if the outflow is strongly increasing function of the Eddington ratio. The ionization instability should operate if the disc is large enough to show a partially ionized hydrogen zone for a given average accretion rate. Confronting the observational constraints with model predictions will in turn allow us to find the constraints for the viscosity parameterization and the role of the outflow. In the next sections we make a preliminary step in this direction.

3 OBSERVATIONAL CONSTRAINTS

The Galactic X-ray binary systems are variable in wide range of timescales. First, the transient X-ray sources undergo their X-ray active states on timescales of years. Second, some sources exhibit X-ray periodic variability on timescales of months. Third, some of the most luminous sources are variable in timescales of tens-thousands of seconds. Finally, many of X-ray binaries undergo quasi-periodic oscillations. Direct comparison of these data and the models is not simple: even the identification of the type of the variability with the mechanism is not unique.

In Table 1 we summarize the properties of the exemplary, best studied X-ray binary sources found in the literature, which in our opinion may display radiation pressure or ionization instability. We list their characteristic variability timescales and amplitudes, estimated Eddington ratios and disc sizes, as well as we indicate a possible instability mechanism responsible for the variability, whenever it is in agreement with our computations presented in Sec. 2. The maximum disc radius is estimated based on the 60% of the Roche lobe size, from the simplified formula given by Paczyński (1971), whenever we had the data for the system orbital parameters.

The estimates given in Table 1 should be treated only as indications. The information comes mostly from the literature and frequently relies on quantitative description. All objects in Table 1 display ionization instability since we selected objects classified as X-ray novae and there is very little uncertainty in the establishment of their nature. Most of them show large amplitude outbursts lasting days. The ratio of the maximum to minimum flux was estimated from the peak and the emission level at the end of the outburst so it represents the lower limit - only some of the X-ray novae have clear detection in the quiescence. Clearly, more careful observational analysis is needed to better study the amplitude pattern during the ionization instabilities in these sources.

However, from the comparison of the accretion rates and disc sizes with our map presented in Figure 1 one can already infer some information about the individual sources. All but one among the sources are well within the instability strip, so the instability operates as expected. Only one source, SWIFT J1753.5-0127, is at the inner border of the instability strip. However our disc size estimation is based on the black hole mass. If this mass is larger than current value inferred from the mass function, the unstable strip will be broader in its accretion disc. The amplitude of the outbursts

enough in their model to account for the large luminosity oscillations in AGN.

The outburst cycles caused by the ionization instability are very sensitive to the viscosity parameter. As was shown already for dwarf novae, the amplitudes consistent with observations can be obtained only in the models with non-constant viscosity, i.e. $\alpha$ in the hot state must be larger than in the cold state. This may also be the case in the X-ray binaries, however in AGN the situation may be different (see Janiuk et al. (2004)).
Table 1. Sample of the black hole X-ray binary sources. $\Delta T$ is the estimated duration of an outburst, and $F_{\text{max}}/F_{\text{min}}$ is its amplitude. $R_d/R_*$ is the estimated disc size in Schwarzschild units. The observations were found in the literature and taken from http://xte.mit.edu/.

| Source            | $\Delta T$  | $F_{\text{max}}/F_{\text{min}}$ | $M/M_{\text{Edd}}$ | $R_d/R_*$ | Instability | Ref. |
|-------------------|-------------|---------------------------------|---------------------|-----------|-------------|------|
| A0620-00          | 150 days    | 300                             | $10^{-2} - 3$       | 4.8 x 10^5 | Ioniz.      | 14   |
| GRS 1915+105      | 20-100 yrs  | > 100                           | 0.25-0.7            | 6.3 x 10^5 | Ioniz.      | 2    |
| GRS 1915+105      | 100-2000 s  | 3-20                            | as above            | as above   | $P_{\text{rad}}$ | 1,3,19 |
| GS 1354-64        | $\sim 30$ d | > 20                            | 0.1-1.8             | 1.8 x 10^5 | Ioniz.      | 33   |
| GS 1354-64        | $\sim 20$ s | 1.5-2                           | as above            | as above   | $P_{\text{rad}}$ | 4,20,21,35 |
| XTE J1550-564     | 200 d       | 300                             | $\sim 0.15$        | 1.3 x 10^5 | Ioniz.      | 36   |
| XTE J1550-564     | $\sim 2000$ s | 1.5                          | $\sim 0.15$        | as above   | $P_{\text{rad}}$ | 5, 22 |
| GX 339-4          | 100-400 days | 75                             | < 0.05              | 1.6 x 10^3 | Ioniz.      | 6, 23, 24 |
| GRO J0422+32      | 200 days    | > 30                            | 0.002 - 0.02        | 4.8 x 10^4 | Ioniz.      | 7, 25 |
| GRO J1655-40      | 20-100 days | 16                             | 5 x $10^{-4} - 0.45$ | 1.0 x 10^3 | Ioniz.      | 8, 26, 27 |
| GRO J1655-40      | 0.1-1000 s  | 7.5                             | as above            | as above   | $P_{\text{rad}}$ | 8, 32 |
| 4U 1543-47        | 50 days     | 300                             | 4.5 x $10^{-4} - 0.04$ | 9.6 x 10^4 | Ioniz.      | 9    |
| GS 1124-684       | 200 days    | 24                             | $\sim 10^{-4} - 1.0$ | 5.2 x 10^4 | Ioniz.      | 6, 14 |
| GS 2023+338       | 150 days    | > 100                           | 0.01 - 1.0          | 3.8 x 10^3 | Ioniz.      | 10, 29, 30 |
| GS 2023+338       | 60 s ?      | 500                             | as above            | as above   | $P_{\text{rad}}$ | 10   |
| SWIFT J1753.5-0127 | 150 days   | 10                             | 0.03                | 2.0 x 10^4 | Ioniz.      | 17, 31 |
| 4U 1630-47        | 50-300 days | 60                             | as above            | as above   | $P_{\text{rad}}$ | 15   |
| GRS 1739-312      | 6 days      | 200                             | as above            | as above   | $P_{\text{rad}}$ | 11   |
| H 1743-322        | 60-200 days | 100                             | as above            | as above   | $P_{\text{rad}}$ | 12   |
| GS 2000+251       | 200 days    | 240                             | as above            | as above   | $P_{\text{rad}}$ | 6    |
| MAXI J1659-152    | 20 days     | 15                             | as above            | as above   | $P_{\text{rad}}$ | 6    |
| CXOM31 J004253.1+411422 | > 30 days | > 300                          | as above            | as above   | $P_{\text{rad}}$ | 13   |
| XTE J1818-245     | 100 days    | 40                             | as above            | as above   | $P_{\text{rad}}$ | 15   |
| XTE J1650-500     | 80 days     | 120                            | as above            | as above   | $P_{\text{rad}}$ | 16   |
| XTE J1650-500     | 100 s       | 24                             | as above            | as above   | $P_{\text{rad}}$ | 18   |

1 Wu et al. 2010; 2Deegan et al. 2009; 3Taam 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 Tomsett 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 al. (1997); 26 van Paradijs 1996; 27 Kolb et al. 1997; 28 Buxton & Bailyn 2004; 29 Zycki et al. 1997; 30 Zycki et al. 1999; 31 Zhang et al. 2007; 32 Greiner 1994; 33 Brockepp et al. 2001; 34 Osterbrock et al. 1997; 35 Cui et al. 1996; 36 Sobczak et al. 1999

in this source is rather small compared to the other X-ray novae in Table 1 which would be consistent with the narrow instability strip due to too small disk radius. Further studies of this exceptional source can provide key tests of the exact location of the instability zone.

We also indicated in Table 1 which sources are promising candidates for the presence of the radiation pressure instability. In selecting them we paid attention to the possible detection of exceptionally low frequency QPO or just reports of outbursts or variability in timescales longer than 10 s. Any faster variability than 10 s in unlikely related to radiation pressure instability and for such fast QPO there are other mechanisms under consideration.

GRS 1915+105 is the most obvious candidate, with its semi-regular outbursts in timescales of 100 - 2000 s present in several among the brighter characteristic states (Belloni et al. 2000). Those outbursts were already modeled by several authors as caused by the radiation pressure instability.

However, fast outbursts are apparently present in several other sources. We show a specific example. In Figure 2 we show an exemplary lightcurve of GS 1354-64, which we extracted from RXTE data archive. Clearly, a periodicity of the $\sim 20$ s outbursts is visible in the data. The profiles with a slow rise and fast decay are characteristic for the limit cycle oscillations in the radiation pressure instability.

For comparison, the lightcurve of Cyg X-1 in its hard state is plotted in the bottom panel of the Figure 2. We see here a very stable X-ray emission and no signatures of the cyclic outbursts. Other sources were selected at the basis of their description in the literature. The selection is thus not completely objective or uniform but may serve as a guide of the viability of the approach.

Having devised the Galactic sources into those which possibly show radiation pressure instability and those which seem stable we can compare the Eddington ratios within the two groups.

Sources with the Eddington ratio below 0.03 are stable. Examples are GRO J0422+32, GX 339-4, as well as Cyg X-1. Among the unstable sources, the object XTE J1550-564 has the smallest Eddington ratio, 0.15. The instability seen in this source, however, is likely marginal. [Cui et al. (1999) reported 82 mHz oscillations, with the frequency later increasing to a few Hz. Low frequency oscillations in this source were recently studied by [Rao et al. (2010), and they report periods varying between 2 and 10 Hz which is far too high for the radiation pressure instability. The interesting transition hinting for an instability was reported by [Homan et al. (2001). In the MJD 51,254 observation, when the source was still very bright, the luminosity suddenly increased without a change in the color. Whether indeed this single transition hints for the radiation pressure instability...
or not, the source likely defines the lower limit for the radiation pressure instability to operate.

In Table  we do not see sources which have very large Eddington ratio and are stable against the radiation pressure instability. As we mentioned above, GRS 1915+105 is a good example of showing outbursts even at Eddington ratio close to 1 so it seems we have no upper limit for the Eddington ratio in the case of radiation pressure instability.

Thus, observationally, the radiation pressure instability should operate between the Eddington ratio 0.15 up to 1 or more. Comparing this with the several theoretical possibilities plotted in Fig.  we can draw certain conclusions.

First, only the viscosity prescription $\alpha\sqrt{P_{\text{gas}}P_{\text{tot}}}$ is consistent with the lower limit for the radiation pressure instability, as the unstable region then extends from the Eddington 0.16 up. The prescription $\alpha P_{\text{tot}}$ would allow instability to operate at too low luminosity.

Second, too efficient cooling by the jet is also ruled out. The cooling operates similarly in both cases of viscosity parameterization and stabilize the disc. For the adopted values of the jet efficiency parameter, the disc is stable for Eddington ratio above 0.22, which is clearly inconsistent with observations. Therefore, the parameter $A$ is Eq (1) of the disk-jet coupling must be significantly lower than this exemplary value of $A = 25$. However the jet is by no means excluded and still can carry a substantial energy, because in the case of equipartition between the disk and jet radiation, for the Eddington accretion rate $\dot{m} = 1$ the jet coupling constant equal to $A = 1$ would be enough.

The parameterization $\alpha\sqrt{P_{\text{gas}}P_{\text{tot}}}$ has an additional advantage of reducing the outburst amplitude in comparison to $\alpha P_{\text{tot}}$. Most of the candidate sources for radiation pressure instability show rather low to moderate amplitudes, from factor 2 to 20. Only one source - GS 2033+338 - shows huge outbursts, with the factor of 500 brightenings in timescales of 60 seconds. m't Zand et al. (1992) interpreted this short timescale variability as caused by variable absorption. The behaviour of this source is exceptional and puzzling.

When studying the instabilities in the supermassive black hole environment, we usually cannot directly observe a duty cycle of a single object, since the black hole masses are large and the expected timescales are very long. Instead, the statistical studies are useful here and we can find an evidence for the source episodic activity (e.g. Czerny et al. (2009)). However, the exceptional object is NGC 4395, with the black hole mass of $3.6 \times 10^8 M_\odot$ (Peterson et al. (2005)). In this source, in principle, we could observe the variability due to radiation pressure instability. As was shown by Czerny et al. (2009), the outbursts for the central black hole of the mass $10^8 M_\odot$ should last below 100 years, so for a mass 30 times smaller, the outbursts should last ~3 years! No such outbursts are observed. However, this fact is actually consistent with our expectations, since the Eddington ratio in this source is only $1.2 \times 10^{-3}$. The source is thus stable with both $\alpha P_{\text{tot}}$ and $\alpha\sqrt{P_{\text{gas}}P_{\text{tot}}}$ mechanisms and provides no useful constraints for the parameterization of the viscous torque.

Significant constraints can be obtained from radio galaxies. In case of the accretion discs in radio galaxies, the Eddington ratios can be estimated e.g. through the correlation with the broad line luminosities (Dai et al. (2007)). The FR I and FR II sources in this sample have low Eddington ratios, of 0.00975 and 0.0096, for FR I and FR II sources, respectively. Observations clearly show that these sources are stable against the radiation pressure instability since they form very large scale radio structures. In particular, the central engine of FR II galaxies must be operating in a continuous way for millions of years. Fig. shows that their stability is consistent with theory if the heating is given by $\alpha\sqrt{P_{\text{gas}}P_{\text{tot}}}$. On the other hand, the FSRQ sources with compact radio structures tend to have larger Eddington ratios. These sources may in fact exhibit episodic activity and the small size of the structure is indicating a new episode, as proposed by Czerny et al. (2009). Therefore, it seems that the assumption of the $\alpha\sqrt{P_{\text{gas}}P_{\text{tot}}}$ can accomodate the observational constraints both for Galactic sources and AGN.

A typical value of the Eddington ratio found in the SDSS sample of quasars by Kelly et al. (2010) is 0.05 with a scatter of 0.4 dex. This is also large enough for the episodic activity caused by the radiation pressure instability. Possibly, the selection effect is in fact the reason why we detect only the sources in the active state: most of the sources in the quiescent state are too dim to be detectable. There is also a possibility that active galaxies at high Eddington ratios, close to 1, are actually stable due to the stabilizing power of jet/outflow. This mechanism seems not to work efficiently in Galactic sources but the relative jet power in accreting sources rises with the black hole mass:

$$\log L_R = 0.6 \log L_X + 0.8 \log M$$

as was discussed in the context of the so called 'fundamental plane' of the black hole activity (Merloni et al. (2003), Falcke et al. (2004)). Therefore, this effect in AGN can be much stronger than in the Galactic sources.

Figure 2. Top panel: an RXTE lightcurve of GS 1354-64, observed on 05/12/1997. Bottom panel: a lightcurve of Cyg X-1, observed by RXTE in the hard state, rescaled to the mean countrate of GS 1354-64. The time bin is 0.1 s in both data.

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4 DISCUSSION

The theory of accretion disks suggests the presence of two instabilities: ionization instability and radiation pressure instability. In the present paper we made a step towards confronting the theoretical expectations with the observations of Galactic sources and AGN.

The ionization instability is broadly accepted as an explanation of the X-ray novae phenomenon and it was compared to the data for galactic sources by several authors. In this paper we tested whether the size of the disk in the X-ray novae systems is consistent with the conditions of the ionization instability. The source SWIFT J1753.3-0127 is at the border of the instability strip, which may explain the low outburst amplitude in this source. All other sources are located well within the instability strip supporting this outburst mechanism.

The details of the outbursts, however, are not well understood yet. We note here that the interpretation of the time profiles of X-ray novae is somewhat complex. Some of the outbursts have well understood FRED profile (i.e. fast rise and exponential decay), with the sharp luminosity rise due to the ionization instability and an extended wing due to the X-ray irradiation of the outer disc. However, in many cases an additional ‘superoutburst’ follows the first outburst (see Figure 3). The possible interpretation of this secondary, extended maximum may be that the accretion rate from the companion star increases due to some modulation effect (see e.g. Smak (2010) for the analysis of the dwarf novae superoutbursts, very much similar to the X-ray novae presented here). Therefore the classification and quantitative analysis of the outburst durations due to the ionization instability is not very straightforward.

Interestingly, the famous microquasar GRS1915+105, observed in the very high state since its discovery in 1992, may in fact still be in such a ‘superoutburst’ phase. On the other hand, the FRED profile is not always seen possibly also due to the lack of irradiation of the disc due to unknown reasons. In this case, the ionization instability results in a short, symmetric profile. An example of such a source can be GRS1730-312, with a timescale of 6 days (see Table 1).

In the case of AGN the applicability of the ionization instability is still under discussion. Fortunately, radio observations can give direct insight into the activity history. The radio maps of several sources show multiple activity periods, mostly in the form of double-double structures (Schoenmakers et al. (2001), Saripalli & Subrahmanyan (2009), Marecki & Szablewski (2009)). Some of those events may be due to mergers and significant change of the jet direction suggests such a mechanism. However, if the jet axis does not change, either a minor merger or ionization instability are the likely cause. The timescales can be studied by analyzing the ages of the structures.

Some other sources in turn show a decay phase (Marecki & Swochoda (2014)). It is quite likely that the microquasar, which has been recently discovered to possess the outflow highly dominated by the kinetic power (Pakull et al. (2014)) actually also represents such a fading source. The analysis of such a complex behaviour requires the radio maps with large dynamical range. Nevertheless, multiple radio surveys are under way and more observational constraints should be soon available.

The radiation pressure instability model has been proposed first to model the microquasar time variability (Taam et al. (1997), Nayakshin et al. (2000)). In case of the regular periodic outbursts of GRS 1915+105 (see e.g. Fender & Belloni (2004), lasting from ~100 to ~2000 s, (depending on the source mean luminosity), this approach is successful (Janiuk et al. (2002)). No other quantitative mechanism has been put forward to explain the observed behavior of this object, and only the limit cycle mechanism (likely driven by the radiation pressure instability) explains the absence of the direct transitions from its spectral state C to the state B.

Still, the question arises, why the microquasar seems to remain an exceptional case where the radiation pressure instability gives an observational signature. In the present paper we suggest that several other black hole binaries can also be promising objects for the radiation pressure instability. All the candidate sources have the Eddington ratio above ~0.15. Such a condition is consistent with theory if the viscous torque parameterization as $\alpha \sqrt{P_{\text{gas}} P_{\text{tot}}}$ is adopted, instead of $\alpha P_{\text{tot}}$. Small outburst amplitudes in all candidate sources (with one exception) also support $\alpha \sqrt{P_{\text{gas}} P_{\text{tot}}}$ prescription. The recent 3-D MHD simulations show the contribution to the stress from radiation pressure, but likely weaker than $\alpha P_{\text{tot}}$ (Hirose et al. (2009)). Further numerical work and observational constraints aimed at finding the proper description of the viscous torque should be treated as complementary.

We argue that the radiation pressure instability also likely applies to active galaxies. The derived separations between outbursts are on order of $10^6$ yrs for a $10^8 M_\odot$ black hole, while the outburst duration is an order of magnitude shorter.

Again the parameterization of the viscosity through

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**Figure 3.** RXTE/ASM lightcurves of two X-ray novae. The bottom panel shows 4U 1543-475 which is the example of classical FRED behaviour. The top panel shows a much more complex behaviour of GRO 1655-40: almost symmetric short outburst, followed by extended phase of activity. This is possibly an analog of superoutbursts seen in many CV systems.
\[ \alpha \sqrt{P_{\text{gas}} P_{\text{tot}}} \] seems to be working better than \( \alpha P_{\text{tot}} \). Such parameterization is consistent with the lack of instability in FR II radio galaxies as their Eddington ratio is below 0.025 - the lower limit for the instability in active galaxies if the \( \alpha \sqrt{P_{\text{gas}} P_{\text{tot}}} \) is adopted. This lower limit here is much lower than in case of stellar mass objects (see also, \cite{Sadowski2009}) due to the direct dependence on the black hole mass. This model has been applied recently also to explain the apparent young ages of the Giga-Hertz Peak Spectrum radio sources \cite{Czerny2009}. We speculate that in the hot state, the luminous core will power a radio jet, while during the cold state the radio activity ceases. Scaling the timescale with the black hole mass by a factor \( 10^8 \) gives the outbursts durations of \( 10^2 - 10^4 \) yrs, and amplitudes are sensitive to the energy fraction deposited in the jet. This gives an additional, model-independent argument that the intermittency in quasars on the timescales of hundreds/thousands of years is likely of a similar origin as in the microquasars.

An important, unstudied aspect is a possible interplay between the two instabilities. The location of the unstable zone is sensitive to the black hole mass (see Fig. 1). The two zones are located much closer to each other in the case of the active galaxies than in the case of Galactic systems. In Galactic binaries only one - ionization instability - is frequently operating. For small accretion rates, which allow for systematically lower disc temperatures and the ionization instability fits well in the disc size, the radiation pressure instability will not develop. If both instabilities are present, they are separated in the disc by over 1000 \( R_S \) which implies that they are well separated in time, acting on timescales of seconds and tens of days, respectively, so they can be modeled independently, as the radiation pressure instability oscillations of a short timescale will be just superimposed on the high luminosity state.

In AGN, the situation is different. The partly ionized zone is much closer to the black hole. If the two unstable zones are very close to each other, the rate of supply of material to the radiation pressure dominated region may be modulated on slightly longer timescales, independently of the environment changes in the host galaxy. This poses an observational challenge to deconvolve the interplay between the two instability timescales, as well as the environmental effects. Additional modeling effort should thus be undertaken to better formulate the theoretical expectations of these instabilities.

Our research has a very preliminary character, and further work is clearly needed. On the observational side, careful search for excess variability in Galactic sources at timescales of a few tens of seconds to a few hundreds of seconds should be done. The main difficulty will concern inventing a proper mathematical description of this excess, because the outbursts due to radiation pressure instability are not likely to be strictly periodic and appear clearly in periodograms. In the case of the disks around supermassive black holes, more constraints should come from detailed radio maps of compact sources showing reactivation events in short timescales of hundreds - thousands of years. Further development of the models, particularly in the case of the radiation pressure instability is also needed, and this should be done in two ways. First, if the 3-D MHD computations as those done by Hirose et al. (2009) with realistic boundary conditions can be prolonged to viscous timescales, we would see whether the instability develops a limit cycle without an ad-hoc parametric description of the viscosity. This approach is computationally challenging and may not happen soon. Second, the sources which in our opinion are promising candidates for the radiation pressure instability do not exhibit regular outbursts which implies that strong non-linear/non-local phenomena are important. Several such phenomena can be implemented into the current parametric codes. Irradiation is certainly important, and actually some models for ionization instability incorporate them. The disk irradiation may also be important for the radiation pressure instability. The parameter \( \alpha \) may depend locally on the disk thickness, and in addition the dissipation may be coupled to the magnetic pressure with a radius-dependent significant time delay (Kluzniak, private communication). The theoretical lightcurves can be distorted by a stochastic process, such as magnetic dynamo, operating on the local dynamical timescale \cite{Mayer2006}; see also \cite{Janiuk2007} for the additional discussion of this problem in the context of the magnetically coupled hard X-ray corona). That process can evolve e.g. according to the Markov chain model. The timescale and possibly also the magnetic cell size are governed by the \( H/R \) ratio. As a result, the outbursts in the limit cycle can be affected by the flickering, as the fluctuations propagate to the inner disc. On the other hand, in between the outbursts the fluctuations are more likely to be smeared out. The resulting lightcurve and PDS spectrum will depend on the adopted magnitude of the poloidal magnetic field and other parameters. Comparison of such better models with observational constraints will help in the future to better understand the disk dynamical behaviour.

5 CONCLUSIONS

Our preliminary survey of model predictions in confrontation with observational data suggests that the parametric description of accretion disk viscosity through \( \alpha \sqrt{P_{\text{gas}} P_{\text{tot}}} \) is a promising representation in the radiation pressure dominated disk part. We selected several Galactic sources as the candidates which may show the radiation pressure instability, but further research is clearly needed. The same law likely applies to AGN, and the support comes from the stability of dwarf Seyfert galaxy NGC 4395 and FR I and FR II sources. Ionization instability criterion in Galactic sources is consistent with the disk sizes. There are only very limited constraints for this instability in AGN.

Acknowledgments We thank Rob Fender, Ranjeev Misra, Marek Abramowicz, Wlodek Kluzniak and Olek Sadowski for helpful discussions. We are very grateful to the anonymous referee for his comments which helped us to improve the presentation of the results. This work was supported in part by grant NN 203 512638 from the Polish Ministry of Science. The ASM lightcurves were taken from [http://xte.mit.edu/](http://xte.mit.edu/)

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\[ \sqrt{P_{\text{gas}} P_{\text{tot}}} \]
