Mechanism of the Changing Look phenomenon in Active Galactic Nuclei

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ABSTRACT

Changing-look phenomenon observed now in a growing number of active galaxies challenges our understanding of the accretion process close to a black hole. We propose a simple explanation for periodic outbursts in sources operating at a few per cent of the Eddington limit. The mechanism is based on two relatively well understood phenomena: radiation pressure instability and formation of the inner optically thin Advection-Dominated Accretion Flow. The limit cycle behaviour takes place in a relatively narrow transition zone between the standard disk and optically thin flow. Large changes in the cold disk are due to the irradiation by the hot flow with accretion rate strongly varying during the cycle. The model gives quantitative predictions and works well for multiple outbursts of NGC 1566.

Keywords: galaxies: active – galaxies: Seyfert – quasars: emission lines – accretion, accretion disks

1. INTRODUCTION

Active Galactic Nuclei have been always known as strongly variable sources in most of their broad band spectra (e.g. IR: Edelson & Malkan 1987; Kozłowski et al. 2016; optical: Ulrich et al. 1997; Kawaguchi et al. 1998; Sesar et al. 2007; X-ray: Ulrich et al. 1997; Lawrence & Papadakis 1993). Most of the variability can be attributed to variations of the red noise character, both in the optical and in the X-ray band (McHardy & Czerny 1987; Lehto et al. 1993; Czerny et al. 1999; Czerny et al. 1999; Gaskell & Klimek 2003). However, some of the observed changes lead to more dramatic flux change which is then reflected in the temporary change of the source classification, and these sources started to be known as Changing-Look AGN (CL AGN; Matt et al. 2003).

CL AGN phenomenon was once considered as rather rare, and they corresponded either to a drastic change in X-ray spectrum, or in the optical/UB emission lines and continuum, depending on the studies wavelength, which forced a change in source formal classification (Bianchi et al. 2005; Denney et al. 2014; Shappee et al. 2014). On the other hand, historical lightcurves of nearby sources, including well studies AGN (e.g. Cohen et al. 1986; Iijima et al. 1992; Storchi-Bergmann et al. 1993; Bon et al. 2016; Oknyanskij et al. 2016; Shapovalova et al. 2019) indicated that such episodes happen. With more and more optical and X-ray surveys the number of CL AGN is rapidly growing (Ruan et al. 2016; Ross et al. 2018; Yang et al. 2018; Stern et al. 2018; Trakhtenbrot et al. 2019; MacLeod et al. 2019), and the question about the mechanism of the phenomenon must be addressed.

There is still an on-going discussion whether the phenomenon is intrinsic to the central engine of the active galaxy, or just is a result of a temporary obscuration or disappearance of such obscuration. While for some CL AGN phenomenon the obscuration mechanism can work, for most of the sources there are strong arguments in favor of the intrinsic changes:

- complex multi-band recovery, inconsistent with obscuration (e.g. Mathur et al. 2018)
- strong changes are also seen in the IR, where the obscuration should not play a role (Sheng et al. 2017; Stern et al. 2018)
- low level of polarization in CL AGN argues against the scattering (and abscuration) scenario (Hutsemékers et al. 2019)
- different variability behaviours of the observed emission lines in spectra of CL AGN (e.g. Kynoch et al. 2019).

Thus in most sources the change in the bolometric luminosity affect the BLR and X-ray appearance, which leads a spectral type of an AGN.

These intrinsic changes can again be either related to Tidal Disruption Event (TDE), or be a result of the spontaneous un-
forced behavior of the accretion flow close to a black hole. In some cases perhaps TDE provides the answer but in sources with repeated events the TDE is statistically unlikely.

In this case the source behaviour should be related to some instabilities in the accretion flow. However, the radiation pressure instability expected to be operational in the innermost part of an AGN accretion disk does not provide the proper timescales (e.g. Gezari et al. 2017). Convenient formulae for the duration of such outbursts given in (Grzędzioński et al. 2017) give timescales of hundreds of years for a black hole mass of $10^7 M_\odot$. (Dexter & Begelman 2019) suggested that strong magnetization can shorten the estimated timescales. On the other hand, we can look for another mechanism related to the complexity of the innermost part of the flow, and Noda & Done (2018) proposed that the CL behaviour in the source Mrk 1018 is related to the temporary disappearance of the warm corona. However, the source NGC 1566 notable for numerous CL outbursts (e.g. Alloin et al. 1986; Baribaud et al. 1992; Oknyansky et al. 2019) does not show the presence of the warm corona component before the outburst (Parker et al. 2019). The present observations cannot resolve directly any of these issues since they show at best the presence of the gas reservoir at a distance of 60 pc from the black hole (Mkn 590; Raimundo et al. 2019). They only show that the phenomenon is complex, for example the reappearance of broad lines in Mkn 590 is not accompanied by the full recovery of the continuum (Raimundo et al. 2019).

In this paper we propose a new mechanism which is suitable for explaining CL phenomenon in sources which are not very close to the Eddington ratio, like NGC 1566.

2. ANALYTICAL ESTIMATES AND THE MODEL GEOMETRY

We will concentrate here on the specific properties of the outbursts observed in the CL galaxy NGC 1566(z=0.005017), and we will use its parameters as discussed in Parker et al. (2019). We adopt the black hole mass value, $M_{BH}$ as $10^7 M_\odot$, the mean Eddington ratio, $\lambda_{high}$, of the source during outburst 0.05, and the mean Eddington ratio, $\lambda_{low}$ of the source between outbursts as 0.002. We will express the corresponding values for more general case in these units, as $M_\tau$, $\lambda_{high,0.05}$, and $\lambda_{low,0.002}$. For the rise time, duration and the decay timescale, we adopt the values from Alloin et al. (1986) ($\tau_{rise} = 20$ days, $\tau_{peak} = 60$ days, $\tau_{decay} = 400$ days, $\tau_{total} = 5$ years) since they observed four such episodes during the period 1970 - 1985 and thus have better statistics. Outbursts are not identical, but the orders of magnitudes are well preserved.

Optical/UV continuum in AGN comes from an optically thick geometrically thin accretion disk, and the study of optical/UV variability is in general consistent with variations in the local thermal timescale. This interpretation allowed to determine the effective viscosity parameter $\alpha$ (Shakura & Sunyaev 1973a) from observations at a chosen wavelength, i.e. at the radius where most of the emission seen at that wavelength originates (Siemiginowska & Czerny 1989; Sterling et al. 2004). The most recent studies using the Damped Random Walk (DRW) approach are also consistent with $\alpha = 0.02$ (see Grzędzioński et al. 2017) which we use in further considerations.

If the rise time corresponds to the thermal timescale of the source, then using the definition of the thermal timescale

$$\tau_{thermal} = \frac{1}{\alpha} \tau_{dyn} = \frac{R^{3/2}}{\alpha G M}$$

(1)

(see e.g. a review by Czerny 2006) we can obtain the value of the disk radius which is responsible for the rise of the source luminosity

$$R_{tr} = 30 \left( \frac{\alpha^{0.02} \tau_{rise,20}^{2/3}}{M_\tau} \right)$$

(2)

Since NGC 1566 is not a high Eddington ratio source, we identify this radius with the transition radius between the outer cold disk and the inner hot flow in the source in quiescence. This value of the transition radius is well within the expected transition (Abramowicz et al. 1995, see also Czerny et al. 2019)

$$R_{ADAF} = 800 \lambda_{low,0.002}^{-2} \alpha_{0.02}^{4} [R_{Schw}]$$

$$R_{ADAF} = 1 \lambda_{high,0.05}^{-2} \alpha_{0.02}^{4} [R_{Schw}],$$

(3)

but this quantity is very sensitive both to adopted value of viscosity as well as the Eddington ratio, and it is appropriate for a stationary solutions. The behaviour of CL AGN is clearly non-stationary, and an intermediate value of the transition radius seems plausible. The position of the transition radius at 30$R_{Schw}$ would imply the mean Eddington ratio $\lambda_{mean} = 0.009$.

During the outburst, the material from the cold disk close to the transition radius is being removed. We can connect the timescale of the outburst, represented by $\tau_{decay}$, the Keplerian disk surface density, $\Sigma$, the accretion rate during the outburst with the radial extension of the cold disk $\Delta R$ which is removed during the outburst

$$\tau_{decay} = \frac{\Sigma \Delta R 2 \pi R}{M}. \quad (4)$$

We assume that the accretion efficiency $\eta$ of the flow is high during the outburst ($\eta = 0.1$), so the accretion rate can be estimated from the bolometric luminosity during outburst ($L_{bol} = \eta_{high} \eta^2$), the disk surface density at the radius $\sim 30 R_{Schw}$ for viscosity parameter $\alpha = 0.02$ is of the order of $10^5$ g cm$^{-2}$ (radiation pressure dominated zone, Equation 2.8 of Shakura & Sunyaev 1973), so assuming $r = R_{tr}$
we can obtain the radial extension of the cold disk removed during the enhanced accretion episode

\[
\frac{\Delta R}{R_{\text{tr}}} = 0.003 \frac{\tau_{\text{decay}, \text{400}} \lambda_{\text{high}, 0.05} M_{\odot}^{1/3}}{\eta_{\odot}^{4/3} \nu_{\text{rise}, 0.2}^{4/3} \Delta R_{\text{trans}}}. \tag{5}
\]

The reconstruction of the cold disk after the enhanced accretion episode should usually happen in the viscous timescale of the cold disk flow

\[
\tau_{\text{visc}, SS} = \tau_{\text{th}} \left( \frac{R}{H} \right)^2, \tag{6}
\]

where \(H\) is the disk thickness. The disk thickness for radiation pressure dominated disk is independent from the disc radius, but linearly depends on the dimensionless accretion rate. For the cold state accretion rate this ratio calculated at 30 \(R_{\text{Schw}}\), for the mean Eddington ratio would be \(\sim 80\), and the corresponding timescale would become by a factor 6 000 longer than the thermal timescale, i.e. instead of 20 days it would become 330 years. However, this value is reduced by the factor

\[
\tau_{\text{recovery}} = \tau_{\text{visc}} \frac{\Delta R}{R}, \tag{7}
\]

since we only have to refill a narrow belt, and such a timescale of about 1.6 years is roughly consistent with the observed total duration of the outburst episode, \(\tau_{\text{total}}\). The radial range of the disk affected during the outburst is tiny, \(\Delta R \ll R_{\text{tr}}\), and the radial extension of the affected disk is actually of a similar order than the disk thickness.

### 2.1. Instability mechanism

Looking for an actual instability mechanism we plot the position of the radiation pressure instability as a function of the Eddington ratio, using the criterion \(\beta = P_{\text{gas}}/P_{\text{tot}} = 0.4\) from Shakura & Sunyaev (1976) in the disk equatorial plane. We also mark the position of the transition radius to ADAF solution as functions of the Eddington ratio (Abramowicz et al. 1995; Czerny et al. 2004). Computations were done with the use of the code describing the vertical structure of the stationary Keplerian disk for any radiation to gas pressure ratio and opacity, calculated self-consistently in the code (Różańska et al. 1999; Czerny et al. 2016). The plot (see Figure 1) shows that for small values of the Eddington ratio as in NGC 1566 the two curves cross at the radius \(\sim 2 \times 10^{14}\) cm, i.e. about 30 \(R_{\text{Schw}}\). Thus, for a low Eddington ratio source the radiation pressure instability strip is narrow, and may correspond to the observationally required narrow belt.

### 2.2. One-zone time-dependent model

In order to check whether the mechanism may indeed give repeated outbursts of the observationally required properties, we construct a very simple model of the full time evolution of the zone under the radiation pressure instability. We basically follow the 1-D model of Janiuk et al. (2002) but we do not consider the evolution of the whole disk but we concentrate on a single radial zone.

The geometry of the problem can be schematically illustrated in the following way (see Fig. 2). The inner edge of the disk cannot be considered as very geometrically thin structure but rather as a wall, facing the inner hot flow and exposed to the intense X-ray irradiation by the hot inner flow. Thus time-dependent partial differential equations (26) and (33) from Janiuk et al. (2002) reduce to time evolution of a surface density and temperature in the equatorial plane of a single zone. As in Janiuk et al. (2002), we assume the disk is in the hydrostatic equilibrium, and the pressure consists of the gas and radiation pressure. However, we change the description of the advection term (radial derivative terms in Janiuk et al. 2002). The evolution of the surface density in...
the zone is given as

\[ \frac{d\Sigma}{dt} = \frac{\dot{M}_0 - \dot{M}}{2\pi R \Delta R} \]

where \( \dot{M}_0 \) is a constant inflow rate into the zone, and \( \dot{M} \) is a variable outflow rate from the zone to ADAF flow. This flow is caused by the cold material evaporation through the electron conduction, thus it depends on the interaction surface (i.e. zone height) and amount of available material (i.e. surface density). We specifically parametrize it as

\[ \dot{M} = \frac{\dot{M}_0}{R_0} \frac{\Sigma}{\Sigma_0}, \]

where the quantities \( R_0 \) and \( \Sigma_0 \) describe the height and surface density of the stationary disk model at the considered radius, for assumed accretion rate \( \dot{M}_0 \).

The evolution of the temperature is given by the energy balance equation

\[ \frac{d\log T}{dt} = \frac{(Q^+ - Q^- - Q_{adv})(1 + \beta)}{PH [(12 - 10.5\beta)(1 + \beta) + (4 - 3\beta)^2]} + 2 \frac{d\log \Sigma}{dt} \frac{4 - 3\beta}{12 - 10.5\beta}(1 + \beta) + (4 - 3\beta)^2 \]

Here the calculation of the derivatives of the disk thickness \( h \) are already included in the expression. The values of the disk thickness, total pressure \( P \), gas to the total pressure ratio, \( \beta \), viscous heating \( Q^+ \), radiative cooling \( Q^- \) are determined from the standard equations of the vertically averaged disk structure in hydrostatic equilibrium as in Janiuk et al. (2002), but here we do not introduce any additional correction coefficients related to the disk vertical structure (like \( C_1, C_2 \)) since the current model is very simple. The advection cooling term \( Q_{adv} \) is determined as

\[ Q_{adv} = \frac{\dot{M} PH}{2\pi R \Delta R \Sigma}, \]

so we include only advection term related to the inflow from the zone to inner ADAF, and we neglect the energy carried into the zone from the outer disk, which should be negligible.

3. RESULTS

We first perform a simple check whether our model of the radiation pressure instability in a narrow zone between the outer cold disk and an inner hot ADAF flow is likely to give a limit cycle behaviour for the adopted parameters. With this aim we calculate the surface density corresponding to viscous and thermal equilibrium for a given accretion rate \( \dot{M} \).

The result is shown in Figure 3.

The plot (blue line) shows two branches of solutions with positive slope which is a signature of the zone stability, and an intermediate branch with negative slope which is an indication that the zone will be unstable if the outer accretion rate corresponds to that parameter range.

We then select the value of the accretion rate corresponding to the unstable branch, \( 4.57 \times 10^{23} \) g s\(^{-1}\) and performed computations for the period of about 100 years. When we skipped the first outburst which did not start perfectly from the equilibrium, we saw that the system settled on a very regular limit cycle. It is marked as a loop in Figure 3 (red line), and it shows periodic increase and decrease of the accretion rate and the surface density.

The change in the accretion rate is by one order of magnitude. This, by itself, does not modify the luminosity of the disk plus zone system since the zone is very narrow, so the rough estimate of the change of the system luminosity gives about 0.003 \( \times 10 = 0.03 \), i.e. only an increase of 3%. However, the change in the accretion rate (factor 10) is large, and it can be reflected in the variable X-ray emission from the ADAF flow.

ADAF flow was frequently considered as inefficient, but most estimates of the ion-electron coupling and of the Ohmic heating imply that actually ADAF flow in energetically quite efficient, at least when the accretion rate is not many orders of magnitude below the Eddington accretion rate. Therefore, the inner part of the flow generates more energy than the outer part of the disk and the transition zone (the exact number would depend on the black hole spin). This energy is emitted in X-rays but part of the produced X-ray radiation will illuminate the disk and enhance the disk emission.

We thus assume the typical flow efficiency of 10% in ADAF and calculate the result of the disk irradiation. ADAF is an extended medium so in principle this is a complex 2-D issue but in our simple model we represent the ADAF emission by emission localized along the symmetry axes since that allows us to calculate the effect in a simple way (we used the method and the code developed in Loska et al. (2004). This irradiation is very important.

In Figure 4 we show two extreme examples of the spectra from an illuminated disk: between the outburst and at the peak of the outburst. The flux at V band has changed by an order of magnitude, and the spectrum became much bluer in the far UV. The actual amplitude of the outburst in the data from Alloin et al. (1986) is lower since the starlight provides a significant contribution to the measured flux at V band.

Using the irradiation effect we calculated the disk plus transition zone flux at B band for all the time steps of the produced outburst, using always the current value of \( \dot{M} \) to calculate the disk illumination. We plot the fragment of the lightcurve in Figure 5. We compare this time-dependent pattern with the observational points representing the H\( \beta \) line flux (Alloin et al. 1986). Unfortunately, we do not have the continuum lightcurve, so we do not include any dilution ef-
Figure 3. Accretion rate vs. surface density in the transition zone between the cold SS outer disk and the inner ADAF: blue line shows the solution in thermal equilibrium, red points show the time evolution of the zone. Parameters: log \( M = 6.92 \), \( r = 30R_{Schw} \), \( \Delta r = 0.003r \), \( \alpha = 0.02 \).

Figure 4. Two extreme states of the accretion disk in the source: between outbursts (blue line) and during outburst (red line). Here we neglect the contribution from the starlight.

Figure 5. The model prediction for the nuclear flux at V band from the time evolution of the transition zone between the inner ADAF and a standard irradiated outer accretion disk (continuous line) confronted with the H\( \beta \) line flux evolution from Alloin et al. (1986) (points).

4. DISCUSSION

We propose that the radiation pressure instability operating in the narrow zone between the outer gas-dominated stable accretion disk and an inner hot ADAF flow may be responsible for repeating outbursts in some CL AGN, as NGC 1566. We show that the proposed mechanism can lead to outbursts in a timescale much shorter than the usual viscous timescale in a cold disk.

The mechanism to operate requires that the mean accretion rate in the source is relatively low so the inner ADAF flow extends to a radius which is not much smaller than the radius where the radiation pressure in a standard Keplerian disk dominates. The amplitudes of the outbursts in the optical band are large due to the irradiation of the outer disk by the enhanced inner hot flow.

The generic prediction of the model is that the spectrum of the nucleus should become much bluer during outburst, and the outbursts in X-ray band should have comparable or larger amplitude. The current model gives the timescale of the luminosity rise somewhat longer than the delay timescale but this may depend on the modelling details.

The current model is very simple, describes just a single zone in a vertically averaged approximation. Future modelling should be 2-D since the height of the zone is compa-
rable to its radial extension, and it should include full time-
dependence of the outer disk since the irradiation would cou-
ple to the stability properties. However, such a model is far
beyond the aim of the current project.

Ross et al. (2018) considered a possibility that the be-
haviour of the quasar J1100-0053 is related to instability in
a cold disk/ADAF transition zone but argues against it since
in other objects (e.g. NGC 1097) the transition zone is sta-
ble. Indeed, the position of the transition radius determined
by balancing the cold disk evaporation rate and the inner hot
flow depends on the global accretion rate (e.g. Różańska &
Czerny 2000; Spruit & Deufel 2002; Taam et al. 2012) and
seems rather stable. Our solution to the problem comes from
introducing the radiation pressure instability. It also implies
that for lower Eddington ratio objects the instability would
not operate while for higher Eddington objects this mech-
nism would lead to outbursts of much larger part of the disk
and it will operate in a timescale of thousands of years, as
typically predicted for the radiation pressure instability im-
ply (Janiuk et al. 2002; Czerny et al. 2009; Wu et al. 2016;
Grzędzielski et al. 2017).

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