VARIABILITY OF THE Hβ LINE PROFILES AS AN INDICATOR OF ORBITING BRIGHT SPOTS IN ACCRETION DISKS OF QUASARS: A CASE STUDY OF 3C 390.3

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ABSTRACT

Here we show that in the case when double-peaked emission lines originate from outer parts of the accretion disk, their variability could be caused by perturbations in the disk emissivity. In order to test this hypothesis, we introduced a model of the disk perturbing region in the form of a single bright spot (or flare) by a modification of the power-law disk emissivity in an appropriate way. The disk emission was then analyzed using numerical simulations based on the ray-tracing method in the Kerr metric and the corresponding simulated line profiles were obtained. We applied this model to the observed Hβ line profiles of 3C 390.3 (observed in the period 1995–1999) and estimated the parameters of both the accretion disk and the perturbing region. Our results show that two large amplitude outbursts of the Hβ line observed in 3C 390.3 could be explained by successive occurrences of two bright spots on the approaching side of the disk. These bright spots are either moving, originating in the inner regions of the disk and spiralling outward by crossing small distances during the period of several years, or stationary. In both cases, their widths increase with time, indicating that they most likely decay.

Key words: galaxies: active – line: profiles – quasars: emission lines – quasars: individual (3C 390.3)

Online-only material: color figures

1. INTRODUCTION

The huge amount of active galactic nucleus (AGN) energy is released through accretion onto a super-massive black hole (BH), which is supposed to exist in the center of AGN. The emission of the accretion disk is not only in the continuum, but also in the emission lines (e.g., in Fe Kα line) and in low ionization lines, as, e.g., in broad Balmer emission lines which are seen as double peaked (DP). DP Balmer lines are found in 20% of radio loud AGNs at z < 0.4 (Eracleous & Halpern 1994, 2003) and 4% of the Sloan Digital Sky Survey quasars at z < 0.33 (Strateva et al. 2003).

Broad DP emission lines of AGNs provide dynamical evidence for the presence of an accretion disk feeding a supermassive BH in the center of AGNs. But in some cases, the variability of these lines shows certain irregularities which could not be explained just by the standard model of the accretion disk.

The DP line profiles are often used to extract the disk parameters (see, e.g., Chen et al. 1989; Chen & Halpern 1990; Eracleous & Halpern 1994, 2003; Strateva et al. 2008; Eracleous et al. 2009). In a series of papers, Dumont & Collin-Souffrin (see Collin-Souffrin 1987; Collin-Souffrin & Dumont 1990; Dumont & Collin-Souffrin 1999a, 1999b, 1990c, and references therein) investigated the radial structure and emission of the outer regions of the optically thin accretion disks in AGNs and calculated a detailed grid of photonionization models in order to predict the relative strengths of low–ionization lines emitted from the disk. They obtained integrated line intensities and line profiles emitted at each radius of the disk for its different physical parameters. They also studied the influence of the external illumination on the structure of the disk, considering the point source model, where a compact source of non-thermal radiation located at a given height illuminates the disk, and the diffusion model, where the radiation of a central source is scattered back toward the disk by a hot diffusing medium. One of the first methods for calculating the profiles of optical emission lines from a relativistic accretion disk was proposed by Chen et al. (1989). The limitation to this method is that the accretion disk structure required to explain the variability of the line profiles cannot be axi-symmetric, i.e., very often the red peak is higher than the blue one and that cannot be explained by this model. It is not possible in a circular disk, in which the blue peak is always Doppler boosted to be stronger than the red peak. Therefore, Eracleous et al. (1995) adapted the circular accretion disk model to elliptical disks in order to fit the profiles of DP emitters with a red peak stronger than the blue one. This model introduced eccentricity and phase angle parameters to the circular model described above, and the pericenter distance of the elliptical orbits (see Eracleous et al. 1995).

Spectroscopic monitoring of DP emitters (see, e.g., Shapovalova et al. 2001, 2009; Gezari et al. 2007) has revealed that a ubiquitous property of the DP broad emission lines is the variability of their profile shapes on timescales of months to years, i.e., on timescales on the order of the dynamical time or longer (e.g., Veilleux & Zheng 1991; Zheng et al. 1991; Marziani et al. 1993; Romano et al. 1998; Sergeyev et al. 2000; Shapovalova et al. 2001; Storchi-Bergmann et al. 2003; Gezari et al. 2007).

This slow, systematic variability of the line profile is on the timescale of dynamical changes in an accretion disk and has been shown to be unrelated to the shorter timescale variability seen in the overall flux in the line, due to reverberation of the variable ionizing continuum. Patterns in the variability of the broad Balmer lines are often a gradual change and reversal of the relative strengths of the blueshifted and redshifted peaks (see, e.g., Newman et al. 1997).

Periodic variability of the red and blue peak strengths has also been attributed to a precessing elliptical disk, a precessing single-armed spiral (as e.g., 3C 332, 3C 390.3: Gilbert et al. 1999; NGC 1097: Storchi-Bergmann et al. 2003), and a precess-
ing warp in the disk. For instance, Wu et al. (2008) computed the profiles of Balmer emission lines from a relativistic, warped accretion disk in order to explore certain asymmetries in the DP emission line profiles which cannot be explained by a circular Keplerian disk. Elliptical disks and spiral waves have been detected in cataclysmic variables (Steeghs et al. 1997; Baptista & Catalán 2000), and a radiation-induced warp has been detected in the large-scale disk of the AGN NGC 4258 (Maloney et al. 1996).

Spiral waves are a physically desirable model since they can be produced by instability in the vicinity of a BH. They can play an important role in accretion disks because they provide a mechanism for transporting angular momentum outward in the disk, allowing the gas to flow inward, toward the central BH. Long-term profile variability is thus a useful tool for extracting information about the structure and dynamics of the accretion disk, most likely producing the DP emission lines.

In this paper, we present an investigation of the disk line variations due to instability in the accretion disk. First, we developed a model, assuming that instability in the accretion disk affects disk emissivity. This model and some simulations of expected line profile variability are presented in Section 2. In Section 3, we compare the model with observations taken from long-term monitoring of 3C 390.3 (Shapovalova et al. 2001) in order to obtain parameters of perturbations. In Section 4, we discuss our results in light of possible physical mechanisms which could cause such perturbations, and finally, in Section 5, we outline our conclusions.

2. THE MODEL OF PERTURBATION IN THE ACCRETION DISK

Here, we introduce the model and some approximations used in the simulations of accretion disk perturbation.

2.1. Long-term Variation of DP Line Profiles: Some Assumptions and Problems

As we mentioned above, the DP line profile variability does not appear to correlate with changes in the line and/or continuum flux, and consequently one can assume that changes in the line profile are likely caused by changes in the accretion disk structure. There are several examples of the long-term variability (on timescales of several years) of the DP line profile of some objects which has been successfully modeled by the precession of a non-axisymmetric accretion disk, such as an elliptical disk or a disk with a spiral arm (Gezari et al. 2007; Storchi-Bergmann et al. 2003; Shapovalova et al. 2001; Gilbert et al. 1999, and references therein). These models, however, fail to explain the long-term variability of some objects and the short-term variability (on timescales from several months to a year) of all objects (Lewis 2005; Lewis et al. 2010). For instance, Lewis et al. (2010) found that the two simple models, an elliptical accretion disk and a circular disk with a spiral arm, are unable to reproduce all aspects of the observed variability, although both account for some of the observed behaviors. Therefore, these authors suggest that many of the observed variability patterns could be reproduced assuming a disk with one or more fragmented spiral arms.

Other attempts to explain the DP line profile variability through perturbations of the disk structure introduced bright spots over an axisymmetric accretion disk. As an example, Newman et al. (1997) successfully modeled the variation of the Hα peak intensity ratio of Arp 102B with a single spot rotating within the disk, but Gezari et al. (2007) were not able to apply the same model to the same object at a different time period.

In the case of Fe Kα variability, Turner et al. (2006) used the spot model to explain the variability of the iron line profile of Mrk 766 in the X-ray band. Also, Dovčiak et al. (2008) studied variations of the iron line due to an orbiting spot which arises by reflection on the surface of an accretion disk, following its illumination by an X-ray flare in the form of an off-axis point-like source just above the accretion disk. Besides the spots on the accretion disk, the Fe Kα line of some AGNs could also be significantly affected by highly ionized fast accretion disk outflows. For instance, Sim et al. (2010) found that the major features in the observed 2–10 keV spectrum of the bright quasar PG1211+143 can be well reproduced by their Monte Carlo radiative transfer simulations which include a variety of disk wind (outflow) models.

To explain the short-timescale variability of the DP line profiles, Flohic & Eracleous (2008) constructed stochastically perturbed accretion disk models and calculated Hα line profile series as the bright spots rotated, sheared, and decayed. They ruled out spot production by star/disk collisions and favored a scenario where the radius of marginal self-gravity is within the line emitting region, creating a sharp increase in the radial spot distribution in the outer parts.

2.2. The Model of the Bright Spot-like Perturbing Region

We model the emission from the accretion disk using numerical simulations based on the ray-tracing method in the Kerr metric (see, e.g., Jovanović & Popović 2009a, and references therein). Although this method was developed for studying the X-ray radiation which originates from the inner parts of the disk close to the central BH (see, e.g., Jovanović & Popović 2008a), it can also be successfully applied to modeling the UV/optical emission which originates from the outer regions of the disk.5

Surface emissivity of the disk is usually assumed to vary with radius as a power law (e.g., Popović et al. 2003): \( \varepsilon(r) = \varepsilon_0 \cdot r^q \), where \( \varepsilon_0 \) is an emissivity constant and \( q \) is an emissivity index. Total observed flux is then given by

\[
F_{\text{obs}}(E_{\text{obs}}) = \int_{\text{image}} \varepsilon(r) \cdot g^4 \cdot e^{-\frac{E_{\text{obs}} - E_0}{\sigma}} \, d\Omega,
\]

where \( g \) is the energy shift due to relativistic effects: \( g = \frac{\nu_{\text{em}}}{\nu_{\text{obs}}} \); \( E_0 \) is the rest energy of the line, \( \sigma \) is the local turbulent broadening, and \( d\Omega \) is the solid angle subtended by the disk in the observer’s sky.

In this paper, we adopt the following modification of the power-law disk emissivity in order to introduce a bright spot-like perturbing region in the disk (Jovanović & Popović 2008b, 2009a, 2009b; Stalevski et al. 2008):

\[
\epsilon_1(x, y) = \epsilon(r(x, y)) \cdot \left(1 + \epsilon_p \cdot e^{-\left(\frac{(x-x_p)^2 + (y-y_p)^2}{\sigma^2}\right)}\right),
\]

where \( \epsilon_1(x, y) \) is the modified disk emissivity at the given position \((x, y)\) expressed in gravitational radii \( R_g \), \( \epsilon(r(x, y)) \)

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5 As shown in Jovanović & Popović (2008a), the effects of the strong gravitational field and angular momentum of rotating BH are significant only in the innermost parts of the accretion disk, in the vicinity of the central supermassive BH, up to several dozens of gravitational radii. In the outer parts of the disk, such as those where the Hα line originates, these effects are negligible and Kerr metric with zero angular momentum, i.e., Schwarzschild metric, is a very good approximation.
is the ordinary power-law disk emissivity at the same position, \( e_p \) is emissivity of the perturbing region (i.e., amplitude of the bright spot), \((x_p, y_p)\) is the position of the perturbing region with respect to the disk center \((R_g)\) and \((w_x, w_y)\) are its widths (also in \(R_g\)). A three-dimensional plot of the above expression for modified emissivity law is given in Figure 1.

This simple model is suitable for our purpose because it allows us to change amplitude, width, and location of a bright spot with respect to the disk center. In that way, we are able to simulate displacement of a bright spot along the disk; its widening and amplitude decrease with time (decay). Moreover, the above bright spot model can be successfully applied to studying the variations of accretion disk emission in different spectral bands, from X-rays to the optical band (see, e.g., Jovanović & Popović 2008b, 2009b; Stalevski et al. 2008).

3. RESULTS: MODEL VERSUS OBSERVATIONS

3.1. Perturbation in the Accretion Disk: Modeled Profiles

In order to test how this bright spot model affects the H\(\beta\) line profile, we performed several numerical simulations of perturbed emission of an accretion disk in the Kerr metric for different positions of a bright spot along the \(x\)- and \(y\)-axes in both, positive and negative directions. For these simulations we adopted the following parameters for the disk: inclination \(i = 30^\circ\), inner and outer radii \(R_{in} = 200 R_g\) and \(R_{out} = 1200 R_g\), power-law emissivity with index \(q = -1\), local turbulent broadening \(\sigma = 2000 \text{ km s}^{-1}\), and normalized angular momentum of BH, \(a = 0.5\). The corresponding results are presented in Figure 2. As can be seen from this figure, when the bright spot moves along the positive direction of the \(x\)-axis (receding side of the disk) it affects only the “red” wing of the line (Figure 2, top right), but when it moves along the negative direction of the \(x\)-axis (approaching side of the disk) it affects only the “blue” wing of the line (Figure 2, top left). In both cases, the other wing and the line core stay nearly constant, and therefore almost unaffected by the bright spot. The situation is quite opposite when the bright spot moves in both directions along the \(y\)-axis because then it affects only the line core, while both of its wings stay almost intact (see the bottom panels of Figure 2).

We also performed the corresponding simulations for different positions of a bright spot which moves from the inner radius of the accretion disk toward its outer parts along the \(y = x\) direction, and found similar behavior in the simulated line profiles (see Figure 3). As one can see from Figure 3, for certain positions of the perturbing region along the \(y = x\) direction we obtained the line profile with almost symmetrical wings, while in other cases either the “blue” peak is brighter than the “red” one, or the “red” peak is stronger than the “blue” one.
The next step in our analysis was to use our numerical simulations for fitting the observed spectra of 3C 390.3 in order to study the variability of its Hβ spectral line due to emissivity perturbations in its accretion disk.

3.2. Observations of 3C 390.3

To test the model, we used 22 spectra of 3C 390.3 observed from 1995 November until 1999 June (see Figure 8 in Shapovalova et al. 2001).

Spectra of 3C 390.3 were taken with the 6 m and 1 m telescopes of the SAO RAS (Russia, 1995–2001) and INAOE’s 2.1 m telescope of the “Guillermo Haro Observatory” at Cananea, Sonora, Mexico (1998–1999) in the monitoring regime in 1995–1999. They were obtained with long slit spectrographs, equipped with CCD detector arrays. The typical wavelength interval covered was from 4000 Å to 7500 Å, the spectral resolution varied between 5 and 15 Å, and the signal-to-noise ratio was >50 in the continuum near Hα and Hβ. Spectrophotometric standard stars were observed every night. The spectrophotometric data reduction was carried out either with software developed at SAO RAS or with the IRAF package for the spectra obtained in Mexico. The image reduction process included bias, flat-field corrections, cosmic-ray subtraction, addition of the spectra for every night, and relative flux calibration based on standard star observations. Spectra were scaled by the [O III] λλ4959,5007 integrated line flux under the assumption that the latter did not change during the time interval covered by our observations (1995–2001). A value of $1.7 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ (Veilleux & Zheng 1991) for the integrated [O III] line flux was adopted. In order to calculate a normalization coefficient, the continuum was determined in two 30 Å wide clean—line free—windows centered at 4800 Å and 5420 Å. After continuum subtraction, blend separation of the Hβ and [O III] components was carried out by means of a Gaussian fitting procedure, applied to the following: Hβ, broad blue, broad red and central narrow; [O III] λλ4959,5007, broad and narrow components. The forbidden lines are represented by two Gaussian curves with an intensity ratio $I(5007)/I(4959) = 2.96$.

Comparisons between mean and rms spectra of the Hα and Hβ broad line profiles of 3C 390.3 during 1995–2007 (including the Hβ spectra from this paper) are given in Figure 12 of Shapovalova et al. (2010). It can be seen that these profiles are similar, and moreover, the corresponding Hα profiles of 3C 390.3 from Shapovalova et al. (2010) and Gezari et al. (2007) are also similar. These comparisons indicate that the [O III] λλ4959,5007 narrow lines subtraction in the Hβ region was performed correctly.

The flux of Hβ and the broad component profile was obtained from scaled spectra after continuum subtraction and removal of the [O III] doublet and narrow Hβ component. Then the observed continuum fluxes were corrected for the aperture effects using a scheme by Peterson et al. (1995). The mean error (uncertainty) in our flux determinations for the continuum and Hβ flux is <3%. More details can be found in Shapovalova et al. (2001).

3.3. Perturbation in the Accretion Disk of 3C 390.3

Radial velocities of the blue and red peaks of the Hβ and Hα broad lines of 3C 390.3 vary with time (see, e.g., Gaskell 1996; Eracleous et al. 1997; Shapovalova et al. 2010). Shapovalova et al. (2001) obtained the Hβ difference profiles by subtracting the average spectrum corresponding to the minimum activity state (1997 September 9) from the individual spectra (see their Figure 11). These authors found (see their Table 7) that the radial velocity of the blue peak increased from $-3200$ km s$^{-1}$ in 1995–1996 to $-5200$ km s$^{-1}$ in 1999. At the same time the radial velocity of the red peak increased from $+4900$ km s$^{-1}$ in 1995–1996 to $+7000$ km s$^{-1}$ in 1999. Here, we analyze the possibility that the velocities, corresponding to the peak shifts in the Hβ integral and difference profiles, vary with time due to perturbations in disk emissivity.

In order to fit the spectral Hβ line shapes of 3C 390.3, we first estimated the disk parameters from several profiles. We found the following parameters of the disk: inclination $i = 20^\circ$, inner and outer radii $R_{in} = 100$ and $R_{out} = 1300 R_g$, broken power-law emissivity with index $q = -1$ for $R_{in} < r < R_{br}$ and $q = -3$ for $R_{br} < r < R_{out}$, radius at which slope of emissivity changes $R_{br} = 500 R_g$, emissivity of the perturbing region $\varepsilon_p = 1$, local turbulent broadening $\sigma = 2000$ km s$^{-1}$, and normalized angular momentum of BH $a = 0.5$. These values are in accordance with the corresponding parameters for 3C 390.3 obtained by Flohic & Eracleous (2008), who found the following values: $i = 27^\circ$, $R_{in} = 450$, $R_{out} = 1400 R_g$, and
Figure 4. Comparisons between the observed Hβ line profiles of quasar 3C 390.3 (black solid line) and the corresponding simulated profiles due to two successive bright spots. The red solid line represents the simulated profiles due to the moving bright spots whose estimated positions are presented in Figure 5 and widths in Table 1. The blue dashed line corresponds to the simulated profiles due to the stationary bright spots, positioned at $x = -220 R_g$, $y = 125 R_g$ during the first outburst and at $x = -220 R_g$, $y = 125 R_g$ during the second outburst.

(A color version of this figure is available in the online journal.)
direction as they get further away from the center of the disk. Table 1 contains the obtained values of the fitted parameters, as well as the corresponding RMSD in the case of both moving and stationary perturbing regions. We first studied the moving perturbations, but after examining the obtained results we found that, during a period of a few years, such perturbations move only by small distances which are comparable to their widths (see Table 1). Therefore, in order to test whether the obtained displacements are reliable, we repeated the fitting, but this time assuming the stationary perturbing regions with variable widths. In this case, we obtained the best fits for two perturbations positioned at $x = -100 \ R_g$, $y = 220 \ R_g$ and at $x = -220 \ R_g$, $y = 125 \ R_g$, respectively (denoted by crosses in Figure 5).

As one can see from Figure 4 and Table 1, regardless of the significant variations of the H\beta line profile during the analyzed period, both models of the perturbing region resulted in similar fits for most of these spectra, except for the spectra observed during 1999, where the moving perturbing region achieved better fits. The latter result should be taken with caution because the observations from 1999 were performed after a large gap of $\approx 1 \ yr$. Therefore, the displacements of the perturbing regions cannot be considered as indisputably confirmed, but on the contrary, their widths almost certainly vary with time. The last conclusion is valid for both moving and stationary perturbing regions, since neither of them can provide satisfactory fits with fixed widths.

The obtained best-fit positions of both moving and stationary perturbations are located on the approaching side of the accretion disk (see Figure 5) and these perturbations can most likely be attributed to successive occurrences of two different bright spots. This assumption is in good agreement with observations since two large amplitude outbursts of the H\beta line are
Figure 5. Positions of moving perturbing region along the accretion disk corresponding to two observed amplitude outbursts: 1994 October–1997 July outburst (squares) and 1997 July–1999 June outburst (triangles). In both cases, the moving perturbation originates in the inner regions of the disk and spirals away toward its outer parts. For the average speed of the first perturbation we obtained a value of 7298 km s\(^{-1}\) and for the second one a value of 6575 km s\(^{-1}\). Positions of the stationary perturbing region (denoted by crosses in the right panel) are

Table 1
Parameters of Perturbing Region Obtained by Fitting the Observed Spectra

| Date       | JD (2,400,000) | \(x[R_g]\) | \(y[R_g]\) | \(u[R_g]\) | \(d[R_g]\) | \(v(\text{km s}^{-1})\) | RMSD |
|------------|----------------|------------|------------|-----------|-----------|-------------------------|------|
| 1995 Nov 17| 50039.156      | −30        | 175        | 100       | 100       | 0.09730                 | 0.09460 |
| 1996 Feb 14| 50127.602      | −40        | 200        | 105       | 130       | 0.09680                 | 0.09900 |
| 1996 Mar 20| 50162.580      | −50        | 208        | 106.5     | 140       | 0.08476                 | 0.09138 |
| 1996 Jul 12| 50276.567      | −75        | 230        | 110       | 180       | 0.08518                 | 0.08178 |
| 1996 Jul 17| 50281.434      | −76.3      | 231.3      | 110       | 180       | 0.08820                 | 0.08249 |
| 1996 Aug 10| 50305.489      | −90        | 235        | 112       | 190       | 0.09435                 | 0.09201 |
| 1996 Sep 11| 50338.309      | −115       | 238        | 120.5     | 200       | 0.12337                 | 0.12426 |
| 1997 Mar 4 | 50511.622      | −165       | 245        | 130       | 260       | 0.11448                 | 0.12082 |
| 1997 Aug 30| 50691.463      | −160       | 100        | 100       | 100       | 0.13717                 | 0.13593 |
| 1997 Sep 10| 50701.576      | −165       | 105        | 105       | 110       | 0.12034                 | 0.11905 |
| 1997 Dec 30| 50813.195      | −205       | 120        | 145       | 175       | 0.09499                 | 0.09398 |
| 1998 Jan 22| 50835.631      | −215       | 121.5      | 155       | 195       | 0.10690                 | 0.10949 |
| 1998 Feb 23| 50867.560      | −225       | 125        | 165       | 215       | 0.09825                 | 0.09618 |
| 1998 May 6 | 50940.354      | −245       | 129        | 185       | 265       | 0.08867                 | 0.08965 |
| 1998 Jun 25| 50990.302      | −265       | 132        | 205       | 285       | 0.07229                 | 0.07387 |
| 1998 Jul 16| 51010.719      | −275       | 134        | 210       | 295       | 0.06809                 | 0.07141 |
| 1998 Jul 25| 51019.723      | −278       | 134.5      | 212       | 300       | 0.06548                 | 0.06615 |
| 1998 Aug 30| 51055.551      | −285       | 135.5      | 215       | 320       | 0.07590                 | 0.07638 |
| 1998 Sep 26| 51082.429      | −293       | 136        | 218       | 340       | 0.07948                 | 0.07788 |
| 1999 Aug 19| 51410.309      | −300       | 140        | 250       | 400       | 0.10645                 | 0.11163 |
| 1999 Sep 4 | 51426.208      | −305       | 140        | 252       | 400       | 0.09147                 | 0.09232 |
| 1999 Oct 3 | 51455.172      | −310       | 140        | 254       | 400       | 0.09977                 | 0.10270 |

Notes. Column 1: date of observation; Column 2: epoch of observation (in JD); Columns 3 and 4: \(x\) and \(y\) coordinates of the moving bright spots; Column 5: widths (\(w = w_x = w_y\)) of the moving bright spots; Column 6: widths (\(w = w_x = w_y\)) of the stationary bright spots, positioned at \(x = −100 \ R_g\), \(y = 220 \ R_g\) during the first outburst and at \(x = −220 \ R_g\), \(y = 125 \ R_g\) during the second outburst; Column 7: linear distance crossed by the moving bright spots between two successive observations; Column 8: average speed of the moving bright spots between two successive observations; Column 9: rms deviation between the observed and fitted Hβ line profiles in the case of the moving bright spots; Column 10: the same as Column 9, but in the case of the stationary bright spots.

observed during the analyzed period (Shapovalova et al. 2001), and therefore each bright spot can be assigned to one of them: the bright spot whose positions are denoted by squares corresponds to the 1994 October–1997 July outburst, while the other one, whose positions are denoted by triangles, corresponds to the 1997 July–1999 June outburst. Using the time differences between two successive observed spectra we were able to estimate the speeds of both moving bright spots (see Table 1). For an average velocity of the first bright spot we obtained the value of 7298 km s\(^{-1}\) and for the second one 6575 km s\(^{-1}\). As can be seen from Table 1, the widths of the bright spots are increasing with time, indicating that they decay until they completely
disappear. It should be noted that, inevitably, there is a certain degree of degeneracy in the parameter space, since similar results could be obtained with somewhat different combinations of perturbing region positions and widths.

4. DISCUSSION

Several physical mechanisms could be responsible for perturbations in accretion disk emissivity, i.e., for bright spot formations. The most plausible candidates for such mechanisms are disk self-gravity, baroclinic vorticity, disk–star collisions (Flohic & Eracleous 2008, and references therein), tidal disruptions of stars by central BHs (Strubbe & Quataert 2009, and references therein), and fragmented spiral arms (Lewis et al. 2010, and references therein).

The disk self-gravity, driven by Jeans instability, could cause production of clumps in the disk which have typical sizes in the range from 10 to 1000 gravitational radii for a $10^8 M_\odot$ central BH. Such clumps do not shear with differential rotation and they have high brightness that varies very little over time. Since the obtained results indicate that bright spots decay by time and spiral along the disk, it is not likely that these bright spots could be identified as clumps created by self-gravity, although their sizes are comparable.

Baroclinic vorticity appears in the accretion disk due to its differential rotation in combination with the radial temperature gradient, causing the material in the disk to spiral around the center of the vortex. Such a vortex would have higher density, and hence higher brightness, causing the formation of a bright spot. The typical sizes of such spots, as well as their shearing with differential rotation of the disk, are still unknown since different numerical simulations gave contradictory results (for more details, see e.g., Flohic & Eracleous 2008, and references therein). Therefore, in the case of 3C 390.3, this mechanism still cannot be either ruled out or accepted.

Disk–star collisions are assumed to be very frequent events which happen on daily timescales and which could increase disk surface temperature in the region of collision, and thus, create a bright spot. Such bright spots shear with differential rotation of the disk and decay as the material cools down. However, the typical size of such a bright spot immediately after collision is close to the size of the star, which is very small when expressed in gravitational radii. Therefore, this mechanism could not be accepted as a potential cause of two bright spots, detected in the case of quasar 3C 390.3.

The tidal disruption of stars by a central BH (Strubbe & Quataert 2009, and references therein) happens when a star passes the tidal radius of the BH, i.e., when the BH’s tidal gravity exceeds the star’s self-gravity. Gas of a disrupted star falls back to the BH at a super-Eddington rate, releasing a flare of energy which then blows away a significant fraction of the falling gas as an outflow. Such super-Eddington flares and outflows could induce instabilities in the accretion disk in the form of bright spots. However, this mechanism is an unlikely candidate for a potential cause of the bright spots in the case of 3C 390.3 due to the following weaknesses: (1) super-Eddington outflows are short lived ($\sim$10 days); (2) frequency of star disruptions in a typical elliptical galaxy is very low, between $10^{-5}$ and $10^{-4}$ yr$^{-1}$, and in the case of the BH of 3C 390.3 whose mass is $\sim$$5 \times 10^8 M_\odot$ (Lewis & Eracleous 2006), it is near the low end of this range (see, e.g., Wang & Merritt 2004; Magorrian & Tremaine 1999); (3) any stellar debris could hardly be released in the case of 3C 390.3 since the main sequence stars are disrupted within the innermost stable orbit around a non-rotating BH as massive as that in 3C 390.3; and (4) it is unclear how the bright spots produced by this mechanism should evolve with time.

Spiral arms in AGN disks could be formed spontaneously due to self-gravity instabilities (see, e.g., Flohic & Eracleous 2008, and references therein) or could be triggered by the close passage of some massive object such as another supermassive BH or a star cluster (see, e.g., Lewis et al. 2010, and references therein). Spiral arms increase the flux variability of AGNs on timescales of a year to several years, but as noted before, they are unable to reproduce all aspects of the observed variability. However, they are also subject to fragmentation, causing small variations in the flux on timescales of several months. The fragments in spiral arms can be due to sub-structures in a non-uniform accretion disk, such as isolated clumps which could pass through the arm and dominate in its emissivity, causing the discrete “lumps” of excess emission (Lewis et al. 2010). The observed variability on timescales from a few months to several years in the difference spectra of some AGNs is probably caused by such lumps. It is quite possible that some of these lumps are long-lived and that they do not vary significantly in strength, shape, or position over a period of several years (Lewis et al. 2010). As the obtained results show, it is the same case with the large bright spots which are responsible for amplitude outbursts of the 3C 390.3 H$\beta$ line because they have constant emissivity and they are either stationary or spiralling over small distances during a period of several years. The only feature which significantly varies with time is their width. Therefore, these bright spots could most likely be explained by the emissivity lumps caused by fragments in spiral arms of the accretion disk.

5. CONCLUSIONS

We developed a model of the disk perturbing region in the form of a single bright spot (or flare) by a modification of the power-law disk emissivity and used this model to simulate the disk line profiles. This model has been used to fit the observed H$\beta$ line of 3C 390.3 observed from 1995 to 1999. From this investigation we can point out the following results:

1. The model which includes perturbation (bright spot) in the accretion disk can successfully explain the difference in DP line profiles, as e.g., a higher red peak even if we have the standard circular disk. The position of a bright spot has a stronger influence on one particular part of spectral line profiles (such as, e.g., its core if the spot is in the central part of the disk, or the “red” and “blue” wings if the spot is located on the receding and approaching parts, respectively).

2. Using the model for a perturbing region we were able to successfully model and reproduce the observed variations of the H$\beta$ line profile in the case of 3C 390.3, including the two large amplitude outbursts observed during the analyzed period. Therefore, the observed variations of the 3C 390.3 H$\beta$ line could be caused by perturbations in the disk emissivity.

3. We found that two outbursts noted by Shapovalova et al. (2001) could be explained by successive occurrences of two different bright spots on the approaching side of the disk which are either moving, originating in the inner regions of the disk and spiralling outward, or stationary. Both bright spots decay over time until they completely disappear.

4. Our results support the hypothesis that the perturbations in accretion disk emissivity are probably caused by fragments in the spiral arms of the disk.
The results presented above show that a circular disk with perturbations (bright spots) can be applied to explain different DP line profiles and can also be used to trace perturbations (as well as their characteristics) from the broad DP line shapes.

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