Search of sub-parsec massive binary black holes through line diagnosis

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ABSTRACT

We investigate on the spectral properties of an active black hole, member of a massive $(10^7 - 10^9 \, \mathrm{M_\odot})$ sub-parsec black hole binary. We work under the hypothesis that the binary, surrounded by a circum-binary disc, has cleared a gap, and that accretion occurs onto the secondary black hole fed by material closer to the inner edge of the disc. Broad line emission clouds orbit around the active black hole and suffer erosion due to tidal truncation at the Roche Lobe surface, following gap opening and orbital decay. We consider three of the most prominent broad emission lines observed in the spectra of AGNs, i.e. CIV, MgII and Hβ, and compute the flux ratios between the lines of MgII and CIV ($F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$) and those of MgII and Hβ ($F_{\mathrm{MgII}}/F_{\mathrm{H}\beta}$). We find that close black hole binaries have $F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$ up to one order of magnitude smaller than single black holes. By contrast $F_{\mathrm{MgII}}/F_{\mathrm{H}\beta}$ may be significantly reduced only at the shortest separations. Peculiarly low values of line flux ratios together with large velocity offsets between the broad and narrow emission lines and/or periodic variability in the continuum (on timescales $\gtrsim$ years) would identify genuine sub-pc binary candidates.

Key words: black hole physics – galaxies: kinematics and dynamics – galaxies: nuclei – quasars

1 INTRODUCTION

Massive black hole *binaries* are considered to be a direct outcome of galaxy mergers. They form in the advanced stages of the galactic interaction as soon as the mass of the two black holes (BHs) exceeds the gas/stellar mass enclosed within their orbit, on scales of $\sim 1 - 10$ pc (Begelman, Blandford & Rees 1980; Merritt & Milosavljevic 2005; Mayer et al. 2007; Colpi & Dotti 2009). In gas rich environments and in the advanced stages of BH hardening, the binary is likely to be surrounded by a circum-binary accretion disc. In the interaction with the disc the binary transfers orbital angular momentum through gravitational torques after having excavated a gap, i.e. a hollow density region (e.g. Artymovicz & Lubow 1994). Migration of the secondary BH toward the primary is then regulated by the rate at which viscous torques in the disc respond to the tidal field of the binary. If migration continues to be effective the BH binary is expected to enter the gravitational wave (GW) driven regime, and the transit to this state is expected to be the longest-lived one

(e.g. Ivanov et al. 1999; Gould & Rix 2000; Milosavljevic & Phinney 2005; Armitage & Natarajan 2002; MacFadyen & Milosavljevic 2008; Lodato et al. 2009; Cuadra et al. 2009; Loeb 2010). The observability of BH binaries with separations $\lesssim 0.1$ pc, at the stage of disc/GW driven migration, is the focus of our study.

Sub-parsec binary AGN, if the BHs are active, can be viewed as key tracers of galactic mergers along the co-evolution of BHs and spheroids (Ferrarese & Ford 2005). Direct imaging of binary AGN on parsec scales however can be carried on, in the near Universe, only in the radio band, when both BHs are active, thanks to the use of radio interferometers such as the very long baseline array (VLBA). This technique needs to point precisely at the source whose position in the sky should be known in advance. So far, this method yielded one candidate, 0402+379, a source with two compact radio cores seen at a projected separation of ~ 7 pc, representing the closest system imaged to date (Rodriguez et al. 2006).

Spectroscopic studies may provide an alternative method for revealing binary AGN, at even closer separations, through the search of velocity shifts in the multiple

line systems resulting from the Keplerian motion of the two BHs.

Peculiar spectra with large velocity shifts of the order of $\sim 10^3 \, \mathrm{km \, s^{-1}}$ are easily selected among thousands of quasar spectra, and five spectroscopic BH binary candidates have been found so far in the public archives of SDSS survey: J092712.65+294344.0 (Bogdanovic et al. 2009; Dotti et al. 2009), J153636.22+044127.0 (Boroson & Lauer 2009), J105041.35+345631.3 (Shields et al. 2009), J100021.80+223318.6, also known as 4C+22.25 (Decarli et al. 2010), and J093201.60+031858.7 (Barrows et al. 2010). All these sources show shifted line systems, but their spectra differ significantly from one another and the interpretation of their physical nature is not unique (Eracleous et al. 2004; Komossa et al. 2008; Shields et al. 2009, 2009b; Heckman et al. 2009; Wrobel & Laor 2009; Decarli et al. 2009, 2009b; Chornock et al. 2010; Barrows et al. 2010). We further note that despite it's simplicity this method is biased in favour of binary systems whose orbital configuration maximizes the velocity shifts between different line systems. Moreover it can not be applied to search for BHB candidates at redshift $z \gtrsim 2$ since the rest-frame wavelength of the main narrow emission lines is $\gtrsim 3000$ Å.

In light of these findings, is it still possible to identify other complementary signatures of a binary system at the stage of viscous-driven migration or GW-inspiral?

High resolution numerical simulations can play an important role in predicting the electromagnetic signatures associated with binary systems. Nevertheless hydrodynamical simulations with full radiative transfer are still out of reach due to the very high computational cost. As illustrated in Bogdanovic et al. (2008; 2009b), the use of photoionization codes in combination with hydrodynamical simulations allows to analyse the observational features of a sub-pc binary system, interacting with a gaseous disc, just for few orbital periods. Relying on a different approach, Shen & Loeb (2009) studied the potential signature left in the spectra by two active BHs surrounded by BEL clouds that initially are inside the hole's Hill spheres. The spectra display double peaked features which over years show coherent radial velocity drifts due to the Keplerian motion. However, since BELs carry individually large widths, only in a restricted range of binary separations BELs display line-of-sight orbital velocity differences larger than that of their intrinsic FWHM. Furthermore, line profiles become complex as soon as the two BLRs start to move in the combined gravitational potential of the BH binary.

Here we devise a new approach to search for BHB candidates starting from single-epoch, optical spectroscopy datasets, relying on the possibility that the presence of a binary system can affect the flux ratios between broad emission lines. We explore the case where one BH (the lighter secondary) is active after the BH binary has cleared a gap inside the circum-binary disc, and compute line flux ratios emerging from a BEL system anchored to the secondary BH. This configuration differs from that considered in Bogdanovic et al. (2008) and in Shen & Loeb (2009) and is motivated by the results of previous numerical studies on the evolution of black hole binary systems within gaseous environment.

The outline of the paper is as follows: in Section 2 we briefly describe the accretion and BH binary evolution

model. In Section 3 we describe how we model the BLR and compute the flux ratios of different lines using the photoionization code CLOUDY. In Section 4 we present our results. The possible use of these results as tool in the search of new secure spectroscopic BHB candidates is described in Section 5. In Section 6 are our discussion and concluding remarks.

2   BINARY BLACK HOLES IN CIRCUM-BINARY ACCRETION DISCS

Consider a circular BH binary with semimajor axis a and mass ratio $q \equiv M_2/M_1$ between the secondary (M_2) and primary (M_1) BH, and let $q = 0.3$, in accordance with recent findings that indicate the formation of close BH pairs (and so of binaries) only in mergers with sufficiently large mass ratios to avoid premature disruption of the less massive galaxy by tides and ram-pressure stripping (Kazantzidis et al. 2005; Callegari et al. 2009).

The BH binary is assumed to be embedded in a circumbinary geometrically thin accretion disc coplanar with the orbital plane of the BH binary (Ivanov et al. 1999). For $q \gtrsim 0.1$, the binary strongly perturbs the disc by exchanging angular momentum with the gas and excavates a gap, i.e. a cavity extending up to $r \sim 2a$, where a is the orbital separation (e.g. Artymovicz & Lubow 1994). Following gap opening, the primary, left in a state of low accretion, consumes most of its disc over the inner viscous time scale. The secondary, instead, that moves closer to the inner rim of the circum-binary disc, has lower speed relative to the gas, and continues to accrete higher density material growing its own disc (e.g. Hayasaki et al. 2007, 2008; Cuadra et al. 2009).

Here we work under the hypothesis that the lighter secondary is the only active member of the binary, and that a BEL system is maintained around the secondary BH, through binary evolution. BEL-clouds orbit inside the Roche lobe of M_2, and their localized emission represents here the main contribution to the emitted spectrum as it originates in the high density region of the inner disc bound to M_2. Due to the orbital decay induced by viscous torques or GW emission, the Roche radius $R_{\rm L} \sim 0.49 \, a \, q^{2/3}/[0.6q^{2/3} + \ln(1 + q^{1/3})]$ (Eggleton 1983) decreases and we expect a progressive erosion of the BLR: the BLR gas, no longer bound to the secondary BH, experiences, outside $R_{\rm L}$, the tidal torque from the binary and is dragged away. We thus work under the hypothesis that the BLR is tidally truncated at $R_{\rm L}$ as the binary orbit shrinks under the action of external torques.

In the interpretation of the results it is important to define a particular phase, referred to as binary-disc decoupling, that occurs at the bridge between the viscous and the GW driven domains. As described in Haiman, Kocsis & Menou (2009), there exists a time in which the inner edge of the circum-binary thin disc can no longer follow the migration of the secondary as the inward viscous diffusion timescale in the disc becomes longer than the timescale of GW-driven inspiral ($t_{\rm GW}$). At such a separation the circum-binary disc decouples and the secondary might be no longer fueled. In this case, from the decoupling time on, the secondary active BH is expected to consume its disc on a timescale that is $\gtrsim t_{\rm GW}$ (see eq. 21 of Haiman et al. 2009 for an expression of the viscous time in the case of a steady-state thin accretion

disc). Thus we can assume that the activity of the secondary BH can be sustained throughout the binary orbital decay.

The question we want to address is the following: is there an observable signature in the emitted spectrum associated to this evolutionary scenario? We expect that the emission from the peripheral BELs becomes inefficient below some critical orbital separation. This can be especially relevant for low-ionization lines, such as that of MgII and Hβ, in comparison to high-ionization ones, since the former are emitted preferentially at greater distances from the source of the ionizing flux. To this purpose, in the next Section we devise a method to compute the expected effects of the BLR tidal truncation on the flux ratios.

3   FLUX RATIOS

We consider three of the most prominent BLR lines observed in the spectra of AGNs: CIV, MgII and Hβ. We then focus on the flux ratios between those lines that can be simultaneously observed in an optical survey, such as the SDSS, up to redshift $z \sim 2$. In particular we compute the flux ratios between the lines of MgII and CIV ($F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$) and those of MgII and Hβ ($F_{\mathrm{MgII}}/F_{\mathrm{H}\beta}$). The flux ratios are calculated for different sizes of the BLR around the secondary according to the scenario outlined above. For a circular binary of mass ratio q, secondary mass M_2 and separation a, the BLR is truncated at the Roche radius R_{L}. The secondary is assumed to emit a luminosity $L = f_{\mathrm{Edd}}L_{\mathrm{Edd}}$ with a constant Eddington factor f_{Edd}. The greatest orbital separation a_{o} is set under the assumption that $R_{\mathrm{L}}(a_{\mathrm{o}})$ coincides with the size R_{BLR} of a BLR of an isolated BH accreting at f_{Edd} as expected from the observational relation of R_{BLR} with the luminosity at 5100 Å (Kaspi et al. 2005), considering $\lambda L_\lambda(5100) \sim (1/9)\, L$ (Kaspi et al. 2000).

In order to compute the flux ratios at each separation, i.e. at each orbital period $P(a)$, we use the photoionization code CLOUDY (version 08.00; Ferland et al. 1998). To map the BELs we refer to the "locally optimally cloud" model (LOC; e.g. Baldwin et al. 1995).[1] Following Korista et al. (1997) and Korista & Goad (2000), we compute a grid of photoionization models assuming each cloud as a slab of constant gas density with solar metallicity and a clear view to the ionizing flux. The shape of the ionizing continuum is taken as one of the templates for a radio-quiet active galaxy stored as part of the CLOUDY code.[2] The column density is set to $N_{\mathrm{H}} = 10^{23}\,\mathrm{cm}^{-2}$ and is kept fixed for all clouds. We consider the contribution of clouds with $8 \leqslant \log\,(n_{\mathrm{H}}/\mathrm{cm}^{-3}) \leqslant 14$ and hydrogen ionizing flux $18 \leqslant \log\,(\Phi_{\mathrm{H}}/\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}) \leqslant 24$.[3] According to the LOC

model the main properties of quasar spectra are dominated by selection effects of atomic physics and radiative transfer that determine, for each individual BLR cloud, the reprocessing efficiency of the ionizing continuum into line radiation. In this contest, it is assumed that there exists a spread in gas properties at each radius in the BLR. Therefore in order to compute the total BELs flux, we have to consider the contribution of each cloud lying in the density-flux plane spanned by the photoionization grid models. In particular it was shown that one can sum over all these contributions by making the simplifying assumption that clouds are distributed in gas density and distance following a weighting function separable in both variables (e.g. Baldwin et al. 1997).[4]

In our study, we consider the case of a uniform distribution of cloud distances and densities, and a second case in which the weighting function is a power law with index -1 in both variables (power-law model, here on). We set the density range for the two different distributions such that at the largest orbital separation the computed flux ratios are consistent with the typical values observed in the AGN spectra, in particular: $9 \leqslant \log\,(n_{\mathrm{H}}/\mathrm{cm}^{-3}) \leqslant 13$ for the homogeneous model, and $9 \leqslant \log\,(n_{\mathrm{H}}/\mathrm{cm}^{-3}) \leqslant 14$ for the power-law model. Considering the adopted cloud distributions in density and space, the resulting mean number density as function of distance are: $n_{\mathrm{H}} \sim 5 \times 10^{12}\,\mathrm{cm}^{-3}$, constant with radius for the uniform BLR model, and $n_{\mathrm{H}} \sim 8 \times 10^{12}\,(r_{\mathrm{in}}/r)\,\mathrm{cm}^{-3}$ for the power law case, where r_{in} is the inner BLR radius. In the power law case the contribution from higher density gas at greater distances is less relevant than in the uniform model. The need of a higher density limit in the power law model to reproduce the observed values of the $F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$ ratio can be therefore understood considering that the MgII line is more efficiently reprocessed at higher densities and lower fluxes than that of CIV.

4   RESULTS

Figure 1 shows the flux ratios $F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$ and $F_{\mathrm{MgII}}/F_{\mathrm{H}\beta}$ as a function of the Keplerian orbital period of the BH binary, for $q = 0.3$ and for a secondary with $M_2 = 10^7, 10^8, 10^9\,\mathrm{M}_\odot$. The upper panel refers to the case of uniformly distributed BLR clouds, while the lower to the power-law model.

We find that the ratio $F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$ is a decreasing function of the orbital separation, and so of P, and therefore it can be regarded as a possible diagnostic tool in the spectroscopic search of binary systems (see Sec. 5). On the

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[1] Considering current uncertainties on the nature and geometry of the BLR, we choose this model compared to more complex ones (see review of Gaskell 2009 and references therein).

[2] In particular we set the incident continuum with the "table AGN" command.

[3] These limits are motivated by physical or observational considerations: clouds located further away from the ionizing source ($\log\,(\Phi_{\mathrm{H}}/\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}) < 18$) give a very low contribution to the emission and form graphite grains, while the absence of broad forbidden lines implies that clouds with lower density are not present.
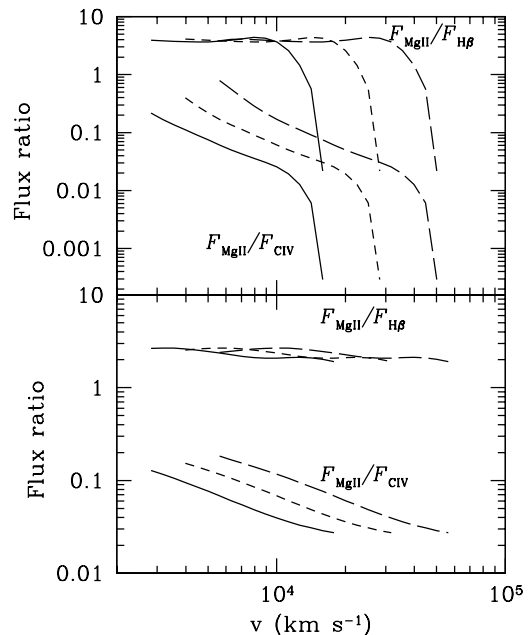
[4] These assumptions usually refer to a spherically symmetric distribution of BLR clouds but they are still consistent with the case of a thick disc, which is the expected distribution for the BLR gas in the model described in section 2. Both geometries imply a high covering factor which is in agreement with the observations (e.g. Gaskell 2009). On the other hand a high covering factor and a disc like geometry imply that the effect of cloud self-shielding may become relevant. In this case it has been shown that regions emitting BELs of different ionization potential are more clearly spatially separated (Gaskell 2009 and references therein). We expect that accounting for BLR self-shielding the effect of the the BLR erosion on the $F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$ ratio would be even stronger than what obtained in our calculations.
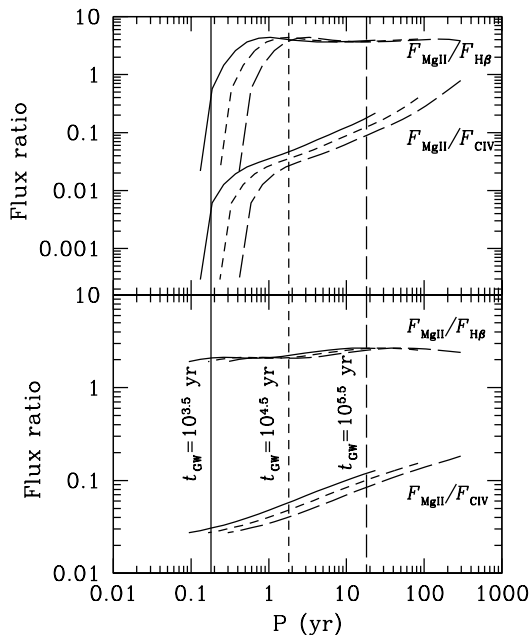
Figure 1. Flux ratios between the broad emission lines of MgII and CIV ($F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$) and those of MgII and Hβ ($F_{\mathrm{MgII}}/F_{\mathrm{H}\beta}$) as function of the orbital period P for a BH binary with different total masses. The mass ratio is set to $q = 0.3$ and the Eddington factor to $f_{\mathrm{Edd}} = 0.1$. Solid/dashed/long-dashed lines refer to a secondary mass of $M_2 = 10^7 - 10^9\,\mathrm{M_\odot}$, respectively. The vertical lines mark the orbital period at the time the binary detaches from the circum-binary disc. Upper (Bottom) panel corresponds to the uniform cloud (power-law) model.

Figure 2. Line flux ratio (as in Figure 1) as a function of the secondary BH orbital velocity relative to the center of mass. The velocity reported here would express the velocity offset between the BEL and the NEL systems for a BH binary seen edge-on and at one of the two orbital nodes.

other hand the $F_{\mathrm{MgII}}/F_{\mathrm{H}\beta}$ ratio is fairly constant apart from a sharp decline present only in the case of a uniform clouds distribution, that will be discussed below. Therefore $F_{\mathrm{MgII}}/F_{\mathrm{H}\beta}$ is not sensitive to the truncation of the BLR while $F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$ shows lower values for closer separations in both BLR models and is already reduced of an order of magnitude before the drop that occurs in the uniform distribution case. These results are consistent with what expected considering that lines of different ionization potential, such as those of CIV and MgII, are preferentially emitted in spatially separated regions. As mentioned before, in the case of a uniform BLR, both flux ratios decrease rapidly around a critical orbital period P_{drop}. This rapid decay is not observed for the case of a power-law BLR distribution. As described in Section 3, observations require that the BLR cloud density does not exceed $\log(n_{\mathrm{H}}/\mathrm{cm}^{-3}) \lesssim 13$ for the uniform model. Higher densities needed in the power-law model can still contribute to the MgII line emission at closer orbital separations, preventing the occurrence of the drop in the line flux ratio. However we expect to observe at most a few binary systems at such small periods ($P < P_{\mathrm{drop}}$) because of the short coalescing timescale for GW emission.

Vertical lines refer to the orbital period P_{dec}, for a selected binary, below which the binary decouples from the circum-binary disc. As described in Section 2, at this stage the BH binary is already in the GW-driven inspiral regime and in Figure 1 we report the corresponding times for GW-driven coalescence, in the range $3 \times 10^3 - 10^5$ yr. This criti-

cal period is computed following Haiman et al. (2009) for a steady geometrically thin accretion disc (see their equations 30). We notice that for the parameters chosen in our calculation the binary-disc decoupling occurs at $P_{\mathrm{dec}} \gtrsim P_{\mathrm{drop}}$ where there is more chance to observe binary systems and the values of the $F_{\mathrm{MgII}}/F_{\mathrm{CIV}}$ ratio can be already reduced up to an order of magnitude, as discussed before.

Figure 2 carries the same information of Figure 1 but expresses the decrease in the flux ratios as a function of the velocity of the secondary BH relative to the center of mass of the binary. The velocity is in principle measurable as Doppler shift between the BELs and the Narrow Emission Lines (NELs) that are emitted from gas at much larger distances and that provide the rest-frame redshift of the host galaxy. The velocity reported in Figure 2 refers to the maximum observable velocity offset, corresponding to a binary seen edge-on and at at one of the two orbital nodes, and can exceed $\gtrsim 10^4\,\mathrm{km\,s^{-1}}$ in the region of interest.

Figure 3 illustrates the effect of varying the Eddington factor for the case of a secondary with $\mathrm{M_2} = 10^7\mathrm{M_\odot}$, $q = 0.3$ and for a uniform BLR. The flux ratios curves shift to shorter periods for lower Eddington factors. The unperturbed outer radius of the BLR of the secondary is proportional to its luminosity through the $R_{\mathrm{BLR}} - L$ relation of Kaspi et al. (2005), as in the case of isolated BHs. This implies that the smaller BLR of a secondary accreting at a lower pace starts to be tidally perturbed at smaller binary separations. On the other hand for lower values of f_{Edd} the binary-disc decoupling may occur at greater orbital separations, due to the longer viscous time scale. As will be discussed in Section 6 this may affect the relevance of the possible contribution to
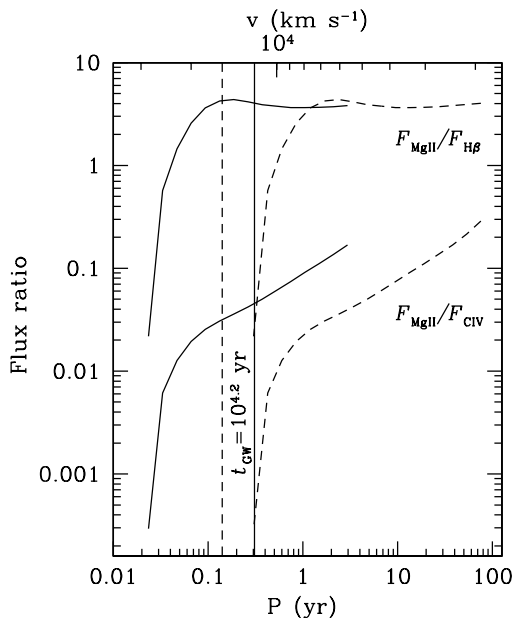
Figure 3. Line flux ratios for two different values for $f_{\rm Edd}$, for the uniform cloud model with $q = 0.3$ and $M_2 = 10^7 \, \rm M_\odot$. Solid (dashed) lines refer to $f_{\rm Edd} = 0.01 \, (0.3)$. The line ratio curves shift to shorter periods for lower values of $f_{\rm Edd}$ while the opposite occurs for higher Eddington factors. As explained in the text, this is due to the correlation between the unperturbed outer radius of the secondary BLR and it's luminosity. Lower values of $f_{\rm Edd}$ imply longer periods in correspondence of binary-disc decoupling because of the longer viscous time scale.

the observed BELs from the circum-binary disc, not included in our work.

5   SPECTROSCOPIC SEARCH OF BINARY CANDIDATES

The huge quantity of data collected by recent surveys give a unique chance to look for the still elusive observational evidences of close BH binary systems. This opportunity leads us to consider the possible implications of our results in the spectroscopic search of new BHB candidates among the public archive of the SDSS survey.

Firstly we notice that the wavelength range covered by the SDSS does not allow to simultaneously observe both line ratios considered in our work. In particular, it is possible to measure the ratio $F_{\rm MgII}/F_{\rm H\beta}$ for those sources in the redshift bin between ~ 0.4 and ~ 0.8, while the ratio $F_{\rm MgII}/F_{\rm CIV}$ targets objects at redshifts $z \sim 2$. Among the three lines considered here only Hβ is emitted both in the BLR and in the NLR. Accordingly, measures of $F_{\rm MgII}/F_{\rm H\beta}$ with a lower value than observed for isolated AGN, around redshift $0.4 \lesssim z \lesssim 0.8$, accompanied by the rapid periodic luminosity variability and velocity offset between BELs and NELs are in favour of the BH binary hypothesis (we refer to Sec. 6 for a more detailed discussion on these last two spectroscopic signatures). However it has to be taken into account that the expected number of sub-pc binary systems
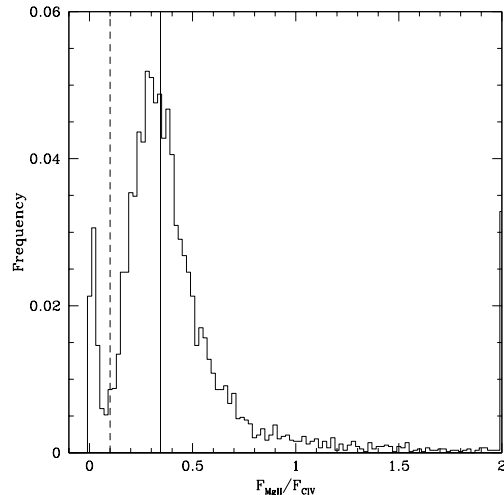
Figure 4. Normalized distribution of the flux ratio $F_{\rm MgII}/F_{\rm CIV}$ measured from the SDSS spectra of 5820 quasars at redshift ~ 2. The vertical solid line marks the median value of the flux ratio distribution (~ 0.3). Sources with flux ratios lower than 0.1 are located on the left of the dashed vertical line and among them it is possible to look for sub-pc BH binary candidates according to our results discussed in the text.

at low redshift is at most of the order of a few (Volonteri, Miller & Dotti 2009).

On the other hand, at higher redshift, $z \sim 2$, where the predicted number of such systems increases, the observation of reduced $F_{\rm MgII}/F_{\rm CIV}$ can be indicative of the presence of a BH binary and can be confirmed again by searching for luminosity variability on scale $\gtrsim$ years. We further notice that at redshifts $z \geqslant 2$, it is difficult to find evidences of velocity offsets between BELs and NELs since the wavelength of the most common NELs is longer than ~ 3000 Å (e.g. Osterbrock & Ferland 2006). The signature of binary orbital motion in the AGN spectrum at redshift $\geqslant 2$ would require spectroscopic studies in the IR band. Therefore our results can be useful to look for BHB candidates in a redshift range that has been not yet explored.

Fig. 4 represents the normalized distribution of the ratio $F_{\rm MgII}/F_{\rm CIV}$ for 5820 quasars at $1.9 \leqslant z \leqslant 2.1$ from SDSS DR6 catalog. The median value of the distribution (~ 0.3) is marked by the solid vertical line. About 500 objects located on the left of the dashed vertical line are characterized by a flux ratio value of a factor of $\geqslant 3$ lower that what typically observed. The existence of these peculiar sources offers a key chance to test the findings of our study. Hence we intend to analyse in a following work (Montuori et al., in prep) the spectroscopic optical (rest-frame) features of BHB candidates selected among those objects which in Fig. 4 show unusually reduced values of $F_{\rm MgII}/F_{\rm CIV}$. NIR observations of these selected sources will allow to measure velocity offsets between BELs and NELs, in particular between the Hβ and [OIII]$_{\lambda 5007}$ lines.

6   DISCUSSION & CONCLUSIONS

According to our model hypothesis, the spectra of a massive BH binary, at the orbital stage of viscous/GW driven migration, show decreased line flux ratios, compared to what observed for single black holes, due to the erosion of the BLR at the Roche lobe radius of the active secondary. In light of our findings, AGN spectra characterized by $F_{\rm MgII}/F_{\rm CIV} \leqslant 0.1$ could be interpreted as a signature of BH binaries with separations in the range of $0.001 - 0.1$ pc, and orbital periods P between $0.1 - 10$ yr, depending on the total binary mass in the range of $10^7 - 10^9 {\rm M}_\odot$. This flux decrease amounts to nearly three orders of magnitude for binary systems at the shortest separations, in the case of BELs emitted by a uniform distribution of cloud properties. For clouds with steeper distributions in space and density the flux ratios can be diminished of a factor $\lesssim 10$.

We note that the flux ratio is particularly low when the BHB is in the the short-lived evolutionary stage of GW inspiral. In this phase, the binary often reaches the critical orbital distance below which the circum-binary disc decouples from the inspiralling BHs. This can be important when considering the potential contributions to the observed BELs not included in our calculations. Depending on the uncertain physical conditions of the gas in the surroundings of the binary (e.g., disc orientation relative to the binary orbital plane, disc geometry, degree of illumination/ionization) the gas located at the inner edge of the circum-binary disc may contribute to the BELs, making the predicted diminished values of the flux ratios more difficult to observe. We expect however a weakening of the potential emission from clouds residing in the circum-binary disc, should the emission be present, since the disc edge freezes and the distance between the emitting BH and this gas keeps increasing.

All the results discussed in our work assume binary systems on circular orbits as BH inspiral in rotating discs leads to circularization of the initial orbit (Dotti et al. 2006; 2007; 2009b). After gap opening however, the interaction of the binary with the circumbinary disc drives the growth of every small residual eccentricity up to a limiting value of ≈ 0.3 (Armitage & Natarajan 2005; Cuadra et al. 2009). Such a small eccentricity implies a pericenter of the binary orbit ≈ 0.7 times smaller than the semimajor axis. If the disc is tidally truncated at the pericenter and has no time to re-expand at apocenter (e.g. due to periodic accretion from the circumbinary disc) the line ratios would be the same as those corresponding to a slightly closer binary. The period of the binary would be at most twice longer than what expected from the line ratios assuming circular orbits. As a consequence, longer observations would be required to observe the periodicity signatures in the line shifts and in the accretion luminosities discussed hereafter.

Low values of the line flux ratios should be accompanied by at least one or two of the following signatures. The first signature would be the presence of de-projected velocity offsets between the BELs and the NELs up to $\sim 10^4 \, {\rm km \, s^{-1}}$. The second would be a change in luminosity over the orbital period P. Bogdanovic et al. (2008) and Haiman et al. (2009) suggested that the accretion rate on the active BH can be modulated on the timescale of the binary orbital period. The line emission features investigated in our study are occurring at orbital periods of the order of months to years.

As already mentioned in Sec. 4, there is little chance to observe binary systems with periods $P \lesssim 1$ yr due to their shorter lifetimes. Therefore we expect that periodicity both in velocity-offsets and in continuum luminosity can be used to verify the binary hypothesis through spectral monitoring of binary systems on timescales $\geqslant 1 - 10$ yr, as it would be feasible for example in the case of a BHB with $M_2 = 10^8 {\rm M}_\odot$ at $P \sim 15$ yr when $t_{\rm GW} \sim 10^7$ yr.

Can these features possibly disentangle genuine binary candidates from the case of a recoiling BH? The signature of a periodicity in the BELs is not expected in the case of a recoiling BH. The BH ejected from the nucleus of the host galaxy after binary coalescence would carry away a disc with an outer radius of the order of $R_{\rm out} \sim G M_{\rm BH}/v_{\rm kick}^2$, where $M_{\rm BH}$ and $v_{\rm kick}$ are the mass and the velocity of the recoiling BH, respectively. Numerical simulations in general relativity show that the maximum predicted value for the kick velocity is $\lesssim 4000 \, {\rm km \, s^{-1}}$ (Lousto et al. 2009 and references therein). This would correspond to the minimum outer radius for the disc bound to the ejected BH, $R_{\rm out}$, that we can compare with the BLR radius, $R_{\rm BLR}$, for an isolated BH, considering three different values for the mass of the BH remnant, $M_{\rm BH} = 10^7, 10^8, 10^9 \, {\rm M}_\odot$. We find $R_{\rm out}/R_{\rm BLR} \sim 1$ for $f_{\rm Edd} \lesssim 0.3$. In this case we expect that the line ratios between the low and the high ionization lines do not differ from what observed in the case of a standard AGN.

This is a first study that aimed at exploring the potential effect of the erosion of the BEL system due to orbital motion around a BH binary with only one BH active (the secondary). Our next step will focus on the emission of transient streams of matter inflowing from the circum-binary disc on to the BHs (Bogdanovic et al. 2009; Cuadra et al. 2009), the presence of lower density gas in the gap region (Dotti et al. 2009), and the shape of the emission lines as function of the BLR geometry and dynamics.

As an example we notice that the binary candidate 4C+22.25, described in the recent work of Decarli et al. (2010), can represent an ideal case to test and improve the predictions of our study. The binary model consistent with the observations of this source requires the presence of a single active BH, which is supposed to be the secondary, a total mass of $\sim 10^9 {\rm M}_\odot$ and an orbital period of the order of $\gtrsim 30$ yr. According to our findings, these orbital parameters imply that the BLR of the active BH is tidally perturbed with respect to the case of an isolated AGN. As already reported in the letter of Decarli et al. (2010), one of the peculiarities of the optical spectrum of 4C+22.25 is that the BELs are very broad and faint. This can be interpreted as a further observational evidence of the truncation of the secondary BLR that is present together with the reduced flux ratios. Further observations of the source, possibly at different wavelengths, will help to constrain the binary model and in particular the scenario proposed in our work, for example through the analysis of BEL profiles and of flux ratios between BELs of different ionization potential.

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