

# Super-Eddington accretion rates in Narrow Line Seyfert 1 galaxies

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**Abstract.** We use the BH masses deduced from the empirical relation of Kaspi et al. (2000) between the size of the Broad Line Region (BLR) of Active Galactic Nuclei (AGN) and the optical luminosity, to compute their accretion rates in four samples of AGN, assuming that the optical luminosity is provided by the accretion disc. We show that Narrow Line Seyfert Galaxies 1 (NLS1s) accrete at super-Eddington rates, while their luminosity stays of the order of the Eddington limit. We take into account the possibility of a non-viscous energy release inversely proportional to the square of the distance in the gravitationally unstable region of the disc emitting a fraction of the optical luminosity. It leads to a smaller accretion rate and to a redder continuum than a standard disc, which agrees better with the observations. The observed bolometric luminosities appear to saturate at a few times the Eddington luminosity for super-Eddington accretion rates, as predicted by slim disc models. They favor a Kerr BH rather than a Schwarzschild one. Even when the accretion rate is super-Eddington, it stays always of the order of a few  $M_{\odot}/\text{yr}$ , irrespective of the BH mass, indicating that the growing of the BH is mass-supply-limited and therefore regulated by an exterior mechanism, and not Eddington-limited. The mass of the BH increases by one order of magnitude in a few  $10^7$  years, a time smaller than that necessary for changing the bulge mass. This is in agreement with recent claims that the BHs of NLS1s do not follow the same black hole – bulge relation as other galaxies. Since they represent about 10% of AGN up to a redshift of 0.5, these “super-active” phases should play an important role in shaping the mass function of local BHs. We finally discuss the possibility that the masses could be systematically underestimated due to an inclination effect, and we conclude that this could indeed be the case, and that the accretion rates could thus be strongly overestimated in a small fraction of objects, possibly explaining the existence of apparently extremely high accretors.

**Key words.** galaxies: quasars: general – accretion, accretion disks – galaxies: active – galaxies: Seyfert

## 1. Introduction and rationale

The evolution of massive black holes (BHs) in relation with their host galaxy is presently intensively debated. Massive black holes seem present in all galactic nuclei, independently of their level of activity. In about 40 inactive nearby galaxies, their mass was found proportional to the luminosity of the bulge of the host galaxy (Magorrian et al. 1998). Ferrarese & Merritt (2000) and Gebhardt et al. (2000a) showed that a tight relation exists between the mass of the BH,  $M$ , and the dispersion velocity  $\sigma_B$  of the bulge. The slope of the relation is still debated, and the recent work of Tremaine et al. (2002) gives a value close to 4. Several mechanisms accounting for this relation have been proposed (Silk & Rees 1998; Umemura 2001; King 2003). When  $\sigma_B$  is expressed in terms of the bulge mass, it leads to  $M \sim 0.002 M(\text{Bulge})$ . It is thus clear that the growth of the BH and the evolution of the host galaxy are related, so it is generally assumed that their co-evolution is mainly the result of merger events within the hierarchical scenario of large

structure formation (Haehnelt et al. 1998; Kaufman & Haehnelt 2000; Menou et al. 2001; Hatziminaoglou et al. 2003).

However this scenario is beginning to be questioned seriously. It is indeed difficult to explain how smaller BHs grow at lower redshifts and more massive ones at higher redshift. So Marconi et al. (2004) propose that local BHs grow mainly during Active Galactic Nuclei (AGN) phases. This raises immediately the question whether BHs in local AGN and in quasars follow the same BH/bulge relationship as in other galaxies.

The BH masses in AGN are not determined like in inactive galaxies by the study of the stellar rotation curve close to the center. In about 40 AGN, they are determined directly through reverberation mapping (Wandel et al. 1999a; Kaspi et al. 2000), which yields an empirical relation between the luminosity and the size of the Broad Emission Line Region (BLR), and then to the BH mass, using the Full Width at Half Maximum *FWHM* of the broad lines as a surrogate of their dispersion velocity and assuming that the BLR is gravitationally bound to the BH, an assumption confirmed by detailed studies (Peterson & Wandel 1999, 2000). In the other AGN the BH masses are determined indirectly assuming that the same relations

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hold. Wandel (1999a) showed that Seyfert galaxies have lower BH to bulge mass ratios than inactive galaxies, but the revision of the Magorrian relation leads the final conclusion that it is not the case (Laor 2001; Wandel 2002; Gebhardt et al. 2000b).

However, the status of Narrow Line Seyfert 1 galaxies (NLS1s) is not well established in this context. NLS1s constitute about 10% of Seyfert nuclei and quasars up to a redshift of 0.5 (Williams et al. 2002). Though they have been known for a long time (Osterbrock & Pogge 1985), their nature is still not well understood. Beside the “narrowness” of their broad lines, these galaxies share common properties, such as strong FeII permitted lines and weak forbidden [OIII] lines, a strong X-ray variability and a big soft X-ray hump (see several reviews in Boller et al. 2000). Mathur et al. (2001) suggested that the BH/bulge mass ratio is smaller in NLS1s, and Wandel (2002) found that  $M \sim 10^{-3}$  to  $10^{-4} M(\text{Bulge})$ , a smaller value than for broad line AGN (BLS1s). Both papers are based on a very limited sample, and are subject to statistical uncertainties. Moreover, in NLS1s the bulge mass is generally not deduced from the stellar dispersion velocity but from the width of the [OIII]5009 line assumed to be proportional to it, following a suggestion of Nelson & Whittle (1996) for Seyfert 1 galaxies (actually Wandel 2002, used direct measurements of the bulge luminosity). Wang & Lu (2001) argued that the [OIII] width is not accurately determined in NLS1s, owing to the weakness of the line and to the presence of a blue wing, both effects leading to an overestimate of  $\sigma(\text{[OIII]})$  and therefore of the bulge mass. However Grupe & Mathur (2004) confirmed the previous result of Mathur et al. (2001) with a complete X-ray selected sample of NLS1s, even when taking into account the presence of the blue wing of the [OIII] line, and they claim that NLS1s occupy distinct regions in the BH/bulge mass relation. Botte et al. (2004) do not confirm this result, and from a study of the photometric properties of the host galaxies they find that the NLS1 galaxies seem to have the same BH/bulge mass relation as ordinary Seyfert, and simply occupy the lower ranges of the  $M - M(\text{Bulge})$  plane. Bian & Zhao (2003) came to the opposite conclusion, based also on the bulge luminosity (we recall that the relation deduced from the bulge luminosity and the host properties has a larger scatter than that deduced from the dispersion velocity), but found that NLS1s do not follow the ordinary relation when the [OIII] line is used as an indicator of the dispersion velocity (Bian & Zhao 2004). Finally Botte et al. (2004) show that there is a smooth relation between the BH mass and the bulge luminosity for different classes of AGN, while there is a jump between the BH mass and the [O III] width. The latter finding is consistent with what was claimed by Grupe & Mathur (2004) and by Bian & Zhao (2004).

One sees that the problem of the BH/bulge mass relation in NLS1s is presently highly controversial. It has important cosmological consequences. If BHs in NLS1s are undermassive with respect to their host bulge, it would imply that these galaxies are “young”, in the sense that they are still in the process of building their BH. This would mean that BHs and galaxies do not evolve concomitantly (Mathur 2000; Grupe & Mathur 2004). We will show here that there is a strong reason to believe this is true, because NLS1s seem to be accreting at

super-Eddington rates and therefore the time scale for the growing of their central black holes could be extremely short.

It is now widely admitted that NLS1s are radiating close to the Eddington luminosity  $L_{\text{Edd}}$ . This result is simply obtained from the mass-luminosity-*FWHM* relations mentioned above. A few objects might even have super-Eddington bolometric luminosities, depending on the conversion factor used to transform the optical-UV luminosity into a bolometric one and on the adopted Hubble constant, but these never exceeds a few  $L_{\text{Edd}}$ . From this result many people, assuming that the efficiency factor for conversion of mass into energy is constant and of the order of 0.1, deduce that these objects are also *accreting* close to their Eddington limit.

But why would it have to be so? Super-Eddington accretion is indeed theoretically allowed. Near the BH, the gas forms an accretion disc, which is supposed to emit the “Big Blue Bump” (BBB). The accretion rate and the BH mass determine the spectral distribution and the flux of the BBB. It is thus possible to determine the accretion rate when the mass is known. This was done by Collin et al. (2002, hereafter referred as C02), using the sample of Kaspi et al. (2000) for which the BH masses are deduced from reverberation mapping, and assuming that the optical luminosity is provided by a standard accretion disc (once the luminosity of the underlying galaxy has been subtracted). They found that a fraction of objects is accreting at super-Eddington rates, while their optical luminosity stays lower than or of the order of the Eddington luminosity. Actually, when the accretion rate is close to, or larger than the Eddington limit, accretion close to the BH does not proceed through a “thin”, but a “slim” disc whose cooling time is larger than the viscous time, so energy is advected towards the BH before being radiated. The mass-energy conversion efficiency  $\eta$  thus decreases as the accretion rate increases, and the luminosity increases only logarithmically with the accretion rate (Abramowicz et al. 1988; Wang et al. 1999; Fukue 2000; Mineshige et al. 2000; Wang & Netzer 2003; Kawaguchi 2003). The emission of such a disc is characterized by a soft X-ray bump like those observed in NLS1s. Kawaguchi (2003), and Kawaguchi et al. (2004, hereafter called KPH) have confirmed that the overall Spectral Energy Distribution (SED) of the two most super-Eddington accretors are well fitted by the emission of a slim disc. Finally, Wang (2003) noted that super-Eddington accretion should lead to a limit relation between the BH mass and the *FWHM* of the lines, and he found several objects satisfying this relation, indicating that they radiate close to their Eddington luminosity, but accrete above the Eddington limit.

There were only a few NLS1s in the Kaspi et al. sample studied in C02. Moreover the sample is not statistically complete since half of the objects are nearby Seyfert nuclei chosen mainly for their high degree of variability. The recent release of several complete samples including a large number of NLS1s, and the renewed interest in these objects since a few years, motivated us to conduct the same study on these new samples. While only standard discs were assumed in C02, here we take into account the deviation from the standard disc due to the disc

self-gravity, which is particularly important in super-Eddington objects (cf. KPH). We also use the slim disc model to compute the bolometric luminosity as a function of the accretion rate. We finally discuss some observational consequences not envisioned in C02. The model can account for the fact that the optical-UV continuum of NLS1s is redder than that of ordinary Seyferts (Constantin & Shields 2003). The variation of the bolometric luminosity with the accretion rate agrees with the slim disc model. It explains why the  $FWHMs$  of the broad lines are larger than  $700 \text{ km s}^{-1}$ .

In this paper, we only want to show some general trends and draw qualitative conclusions concerning the accretion rates of NLS1s, using rough theoretical models of accretion discs and applying them to entire samples.

Finally we stress that throughout this paper we accept the commonly admitted statement that the narrowness of the lines of NLS1s is not due to an inclination effect, i.e. that NLS1s do not constitute a sample of normal Seyfert 1 nuclei whose broad line region is a rotating disc seen almost face-on. In this case, it is clear that the masses derived from the reverberation mapping formulae would be strongly underestimated, and consequently their luminosities (in terms of Eddington luminosity) overestimated.

In the following section, we recall first how BH masses are determined and we present the samples. We incidentally discuss the explanation of the empirical relation between the luminosity and the size of the BLR. In Sect. 3 we summarize the theoretical model. Section 4 is devoted to a discussion of the results, and in the last section we discuss the alternative possibility that the masses of NLS1s could be underestimated and the accretion rates overestimated.

## 2. Determination of the BH masses

### 2.1. The empirical mass-luminosity relation

Reverberation mapping studies made it possible to determine the sizes of the BLR in about 40 objects. It led to the discovery of a correlation between the radius of the region emitting the  $H\beta$  line, which we will call  $R(\text{BLR})$ , and the monochromatic luminosity at  $5100 \text{ \AA}$ ,  $L(5100) = \nu L_\nu(5100)$  (Kaspi et al. 2000):

$$R(\text{BLR}) = 32.9 \times L(5100)_{44}^{0.7} \text{ light days}, \quad (1)$$

where  $L(5100)_{44}$  is expressed in  $10^{44} \text{ erg/s}$ . Though there is some uncertainty in the functional form of the relation (cf. Laor 2003; Netzer 2003), all recent papers adopt this relation to compute  $R(\text{BLR})$  in quasars and Seyfert galaxies, when it has not been determined by reverberation mapping.

It is now well demonstrated that the broad  $H\beta$  emitting region is gravitationally bound to the BH (Peterson & Wandel 2000). This gives another relation,  $M_{\text{BH}} = R(\text{BLR})V^2/G$ , where  $G$  is the gravitational constant.  $V$  is generally taken equal to  $\sqrt{3}/2 FWHM$ , corresponding to BLR clouds in random orbital motion. The relation becomes, using Eq. (1):

$$M_{\text{BH}} = 5.8 \times 10^5 \times R(\text{BLR}/\text{lt days}) \times (FWHM)_{2000}^2 M_\odot, \quad (2)$$

where  $(FWHM)_{2000}$  is the  $FWHM$  of the  $H\beta$  line expressed in  $2000 \text{ km s}^{-1}$  (we choose this value since NLS1s are defined by  $FWHM \leq 2000 \text{ km s}^{-1}$ ). Using Eqs. (1) and (2), one gets a relation between  $M_{\text{BH}}$  and  $L(5100)$  which allows to determine  $M_{\text{BH}}$  as a function of the optical luminosity and the  $FWHM$ , without the need to know the size of the BLR. We stress however that the use of the  $FWHM$  as a surrogate of the dispersion velocity can lead to a systematic underestimation of the mass, if the BLR is a relatively flattened structure dominated by rotation, in which case the inclination of the system would play an important role (see Sect. 5).

These relations have important consequences. If one assumes that  $L_{\text{bol}} \sim 10 L(5100)$ , a canonical value for the quasar continuum (cf. Elvis 1994; Laor et al. 1997), one gets from Eqs. (1) and (2):

$$\begin{aligned} R_{\text{Edd}} &= 0.35 L(5100)_{44}^{0.3} (FWHM)_{2000}^{-2} \\ &= 0.28 M_7^{0.43} (FWHM)_{2000}^{-2.86}, \end{aligned} \quad (3)$$

where we call  $R_{\text{Edd}}$  the Eddington ratio, i.e. the ratio of the bolometric upon the Eddington luminosity  $L_{\text{Edd}} = 1.5 \times 10^{45} M_7$ , and  $M_7$  the BH mass expressed in  $10^7 M_\odot$ . It is obvious from this relation that NLS1s have larger Eddington ratios than BLS1s for a given BH mass.

### 2.2. Comments on the luminosity-size relation

There are several possible explanations for this relation. Line emission can be suppressed by dust beyond the radius of sublimation, which corresponds to a given heating flux  $\propto L_{\text{bol}}/R^2$  (Netzer & Laor 1993). But this constraint provides only an outer boundary of the BLR. Nicastro (2000) proposed that clouds are formed in a wind above the disc, close to the transition region between the gas and the radiation pressure dominated zones of the disc. However the size of the BLR depends both on the BH mass and on the luminosity, while the observations give only a luminosity dependence. The striking similarity of AGN spectra led also to the idea that the ‘‘ionization parameter’’ (i.e. the radiation pressure to gas pressure ratio or the photon density to gas density ratio,  $\propto L_{\text{bol}}/(nR^2)$ ,  $n$  being the electron number density) is constant among all objects. Actually the size-luminosity relation rather implies that the product of the density with the ionization parameter is constant. This is consistent with the so-called ‘‘LOC’’ model.

In 1995, Baldwin et al. proposed that the observed spectrum of AGN is simply a consequence of the ability of a photoionized medium to reprocess the underlying continuum ‘‘as long as there are enough clouds at the correct radius and with the correct gas density to efficiently form a given line’’. In this ‘‘Locally Optimally Emitting Clouds’’ (or LOC) model, each line is emitted preferentially at an appropriate ionizing flux  $L/4\pi R^2$  corresponding to a given distance from the source<sup>1</sup>. According to the grid of photoionized models published by Korista et al. (1997) the ‘‘optimal’’ ionizing flux  $F_{\text{optimal}}$  for

<sup>1</sup> This is actually closely related to the old idea of line saturation due to thermal quenching (Ferland & Rees 1988; Collin-Souffrin & Dumont 1989).

the  $H\beta$  line is almost independent of the density and of the spectral distribution of the ionizing continuum. It is of the order of  $10^8 \text{ erg s}^{-1} \text{ cm}^{-2}$ . This means that as long as there are clouds in a large range of radius with the appropriate density (i.e. between  $10^9$  and  $10^{14} \text{ cm}^{-3}$ ) the ionizing continuum will be reprocessed in the  $H\beta$  line with a maximum efficiency at an optimal distance  $R_{\text{optimal}} \sim 2 \times 10^{17} L_{\text{ion},44}^{0.5} \text{ cm}$ , where  $L_{\text{ion}}$  is the ionizing luminosity. From the Gru03 sample, one gets  $L(5100) \sim 0.1 L_{\text{bol}}^{0.7}$  (precisely  $L(5100) = 0.21 L_{\text{bol}}^{0.6}$  and  $L_{\text{bol}} = 17 L(5100)^{1.13}$ , with a correlation factor of 0.9). Thus the observed relation transforms into  $R_{\text{BLR}} \sim \text{a few } 10^{17} L_{\text{ion},44}^{0.5} \text{ cm}$ , which is similar to the relation expected for the LOC model (the ionizing luminosity being slightly smaller than the bolometric luminosity).

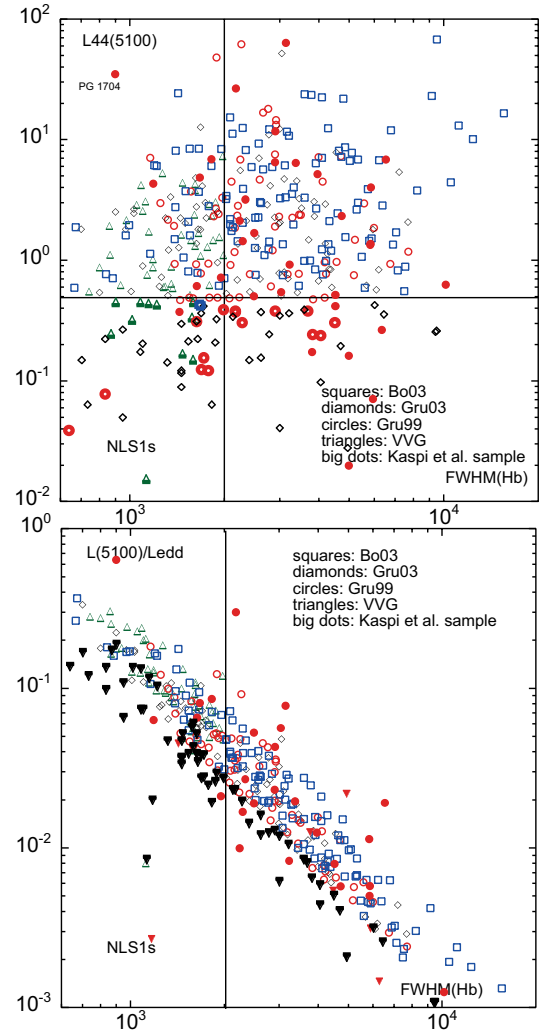
So the only necessary condition for the observed relationship is the existence of clouds within a broad range of densities at a radius smaller than the typical distance of the BLR, say  $10^4 R_G$ . Collin & Huré (2001) suggested that such clouds form above the gravitationally unstable region of the disc. Since the disc becomes gravitationally unstable at small radii compared with the size of the BLR (cf. later), this condition is satisfied. The BLR clouds would thus constitute simply the outer part of the region emitting the optical continuum. Laor (2003) objected to this idea that “since all accretion discs must become gravitationally unstable far enough from the center, this mechanism does not provide a natural explanation for the apparent absence of a BLR in some Agn”. But there are actually several possible explanations for the absence of BLR. For instance, in low luminosity objects, it can be due to the suppression of the ionizing radiation in an Advection Dominated Accretion Flow (ADAF). It can also simply be caused by the absence of adequate physical conditions in the gravitationally unstable disc, like a too high or to low density.

### 2.3. The samples

We use two complete samples including both NLS1s and BLS1s.

The recent data release of the Sloan Digital Sky Survey (SDSS) allowed Boroson to build a homogeneous sample of 107 low-redshift radio-quiet QSOs and Seyfert 1 galaxies (Boroson 2003). It is aimed at comparing the BH masses determined from the empirical relations with those deduced from the dispersion velocity of the [OIII] line, used as a surrogate of the stellar velocity dispersion. About one third of objects in this sample are NLS1s. It makes it possible to study a large range of masses and luminosities. For each object the redshift, the  $FWHM(H\beta)$  and the BH mass are given, and we deduce the optical luminosity at emission from Eqs. (1) and (2). We call this sample Bor03.

The second one is a complete sample of X-ray selected AGN (Grupe et al. 2004). According to the selection procedure, about half of the objects are NLS1s.  $L(5100)$  is given, but for an empty universe, so we made the conversion to  $q_0 = 0.5$ . We call this sample Gru03. It is particularly interesting for us as it gives an estimate of the bolometric luminosity of the objects based on the observed spectral energy distributions, which we will be able to compare with our models.



**Fig. 1.**  $L(5100)$  (top) and  $L(5100)/L_{\text{Edd}}$  (bottom) versus the  $FWHM$  for all samples. The black (resp. red) triangles indicate the objects with  $L(5100) \leq 0.5 \times 10^{44} \text{ erg/s}$  for all samples (resp. the Kaspi et al. sample). The object lying much below the others is NGC 4051.

We also use two other heterogeneous samples. Wang & Lu (2001) deduced  $L(5100)$  from the  $B$ -magnitude using the Véron-Cetty et al. (2001) sample, which contains 59 NLS1s, and they estimated the BH masses using the previous empirical relations. After rejection of a few objects for which the  $FWHM$  are controversial, the sample was reduced to 54 NLS1s. We call it the VVG sample. We also used a heterogeneous sample of soft X-ray selected AGN (Grupe et al. 1998, 1999), which has the advantage of giving optical indices useful for checking our models. We also made the conversion from  $q_0 = 0$  to  $q_0 = 0.5$ . We call it Gru99. Note that a few objects are also in Gru03.

The samples have not been corrected for the stellar contribution of the host galaxy to the optical luminosity. It is certainly important for low luminosity AGN, but not when the optical luminosity is larger than a few  $10^{43} \text{ erg/s}$ . In the following we will distinguish or suppress all weak objects from the samples, so we can be fairly confident that the results will not be contaminated by the host galaxy.

Figure 1 displays respectively  $L(5100)$  (top) and  $L(5100)/L_{\text{Edd}}$  (bottom) versus the  $FWHM$  for all samples.

We note immediately the strong difference between these two graphs. While the first one shows a very loose correlation, corresponding to the absence of low luminosity objects with large  $FWHMs$  and of high luminosity objects with small  $FWHMs$ , the second one shows a tight correlation with a slope equal to  $-2$ , which is expected according to the first line of Eq. (3). The black triangles indicate the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s: note that these low luminosity objects have the same relation as the others.

For comparison, we have added on these figures the objects where the BH masses have been determined directly by reverberation mapping (we call these objects the ‘‘Kaspi et al. sample’’, though half of them were not observed by Kaspi et al. 2000). They span the same range of luminosities as the other samples. But first, they show a looser correlation between  $L(5100)/L_{\text{Edd}}$  and the  $FWHMs$ ; this is expected as the determination of the mass in the other objects makes use of an exact relation  $L - R(\text{BLR})$ , not taking into account its errors. And second, the relation should be extrapolated to values of the mass and of the Eddington ratio smaller by a factor of 5. This should be kept in mind in the following analysis. Note that the values of the luminosities used in this figure are for  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , while C02 assumed  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

### 3. The accretion disc model

For more than fifteen years it has been widely admitted that the ‘‘infrared bump’’ at a few microns and the ‘‘Big Blue Bump’’ observed in radio quiet quasars and Seyfert nuclei are both due to thermal emission, respectively by hot dust heated by the UV-X continuum, and by the accretion disc (Sanders et al. 1989). In this picture, the observed ‘‘dip’’ at  $\sim 5000 \text{ \AA}$  in the  $\log(\nu F_\nu)$  versus  $\log \nu$  curve corresponds to the junction between these two processes, the hot dust close to the sublimation temperature (1700 K) being unable to radiate appreciably below  $1 \mu\text{m}$ . In particular the idea of an underlying non-thermal power law continuum which was invoked in the past and used to model the infrared to UV emission of AGN has been completely left. So *the emission at 5000 \AA should be due entirely to the accretion disc*, unless another medium can give rise to a smooth featureless optical continuum. The problem was discussed in C02, and they showed that it would require the existence of a very dense, optically thick and relatively cold medium. It is difficult to find another location for such a medium than an optically thick accretion disc.

For a ‘‘standard’’ thin Keplerian disc where gravitational energy is released locally through turbulent viscosity, the effective temperature  $T_{\text{eff}}$  at a distance  $R$  from a BH of mass  $M$  is:

$$\sigma T_{\text{eff}}^4 = \frac{3GM\dot{M}}{8\pi R^3} f(R), \quad (4)$$

where the non-dimensional factor  $f(R)$  takes into account the boundary conditions, and is equal to unity at large radii (cf. for instance Frank et al. 2002).

Each spectral band is emitted near a given radius, and the optical band corresponds to a large distance from the black hole, typically  $10^3 R_G$  ( $R_G$  being the gravitational radius  $GM/c^2$ ). At such large radii, the disc is dense, relatively cold

and optically thick, and its local emission spectrum is close to a black body at the temperature  $T_{\text{eff}}$  (cf. Collin 2001; note that this is not the case at smaller radii, i.e. in the EUV band). Integrating the Planck law with  $T \propto R^{-3/4}$  over the disc, one finds for the luminosity at a frequency  $\nu$ :

$$\nu F_\nu = \frac{8\pi^2 h \nu^4}{c^2} \int_{R_{\text{in}}}^{R_{\text{out}}} \frac{R dR}{\exp(h\nu/kT) - 1} \propto \nu^{4/3}, \quad (5)$$

where  $R_{\text{in}}$  ( $R_{\text{out}}$ ) is the inner (the outer) radius of the accretion disc.

So it is possible, using Eqs. (4) and (5), to deduce the accretion rate when the mass is known. One sees also from these equations that  $L(5100)$  is approximately proportional to  $(M\dot{M})^{2/3}$ . This is not true for very large masses and small accretion rates, where  $kT(R_{\text{in}})$  is of the order of  $h\nu_{\text{opt}}$ , or for truncated discs.

For super-Eddington accretion rates this picture is changed. The radiative efficiency per unit mass accretion is expected to decrease due to the onset of photon trapping (Begelman 1978). As a result, the emergent luminosity from an accretion flow starts to saturate at a few times  $L_{\text{Edd}}$  (Abramowicz 1988). Self-similar solutions with super-Eddington accretion rates (Fukue 2000; Wang & Netzer 2003) are only valid inside the photon trapping radius, where soft X-ray photons are emitted. However, full integration of differential equations from far outside the photon trapping radius to the vicinity of the central BH (Shimura & Manmoto 2003; Kawaguchi 2003) is necessary in order to discuss the broad-band spectra of NLS1s. We use the slim disc model for a Schwarzschild BH computed as in Kawaguchi (2003), which is based on the code developed by Matsumoto et al. (1984). The effects of electron scattering (both in opacity and Comptonization) and relativistic correction are included. We take the viscosity parameter  $\alpha$  equal to 0.1. Note that the slim disc is used here only to compute the bolometric luminosity.

Even if the accretion rate is very high (in Eddington value) the optical luminosity is still emitted at a large radius where the accretion flow is not influenced by advection and photon trapping, except in the case of very high accretion rates ( $\dot{M} \geq 3 \times 10^3 L_{\text{Edd}}/c^2$ , cf. KPH), and the standard disc model is valid. The only deviation to the local blackbody in the optical region is due to electron scattering (as modified blackbody, see Czerny & Elvis 1987), which distorts the spectrum for super-Eddington accretion rates. It is negligible as long as viscosity is small ( $\alpha \leq 0.1$ ) and the BH mass is small ( $M \leq 10^7 M_\odot$ ), so the distortion is not very important for NLS1s (cf. KPH), and we will neglect it in this paper.

However, one important fact should not be forgotten, which acts also for modest accretion rates but is very important for super-Eddington accretion rates.

At about the distance of the optical emitting region, the disc becomes self-gravitating, i.e. the vertical component of the BH gravity becomes smaller than the disc’s own gravity. This occurs beyond a critical radius  $R_{\text{sg}}$  corresponding to a density:

$$\rho_{\text{sg}} = \frac{\Omega_K^2}{4\pi G} \quad (6)$$

where  $\Omega_K$  is the keplerian velocity. The disc is then locally gravitationally unstable (Goldreich & Lynden-Bell 1965). At radii larger than  $R_{\text{sg}}$ , the structure of the disc is completely unknown. It could break into fragments, which can collapse and even form stars, or it can stay at the marginal instability limit if it can be sustained by some extra heating mechanism. In all cases the region emitting the 5100 Å flux stays optically thick, and the local black body assumption is valid (cf. Collin & Huré 1999).

Koratkar & Blaes (1999) stressed that the standard disc model leads to a continuum bluer than the average AGN continuum, which has a mean spectral index of 0.3 to 0.5 (we define the spectral  $\alpha_{\text{opt}}$  as  $L_\nu \propto \nu^{-\alpha_{\text{opt}}}$ ). Actually this is a problem only for small BH masses and large accretion rates. In the case of large BH masses and small accretion rates, the optical spectrum-UV spectrum is emitted by the Wien part of the Planck function, and is redder than  $\nu^{1/3}$ .

Several sources of heating can overcome the gravitational viscous release beyond the self-gravitational radius. The disc can be irradiated by the central source of UV-X continuum if it is “flaring” (i.e. if its thickness varies more rapidly than the radius). It can be heated by gravitational instabilities (Lodato & Bertin 2003), by the collisions of clumps (Krolik & Begelman 1988), or by embedded stars (Collin & Zahn 1999). In all cases,  $T_{\text{eff}}$  will decrease less rapidly with increasing  $R$  than in a “standard” disc, and the observed continuum will be redder. For instance Soria & Puchnarewicz (2002) fit the spectrum of the NLS1 1 RE J1034+396 (this object is included in the following computations) by an irradiated accretion disc for which the ratio  $H/R$  of the scale height to the radius increases rapidly with  $R$ ,  $T_{\text{eff}}$  being thus proportional to  $R^{-1/2}$ . C02 have shown that in this case, to get a smooth optical continuum without an intense Balmer discontinuity the density and the optical thickness of the irradiated medium should be very large. This is impossible with a strongly flaring disc; a warped thin disc would be a more appropriate solution. As we explained previously, such a disc would be gravitationally unstable at the distance of the region emitting the optical luminosity, and most likely very different from a standard one. In the case of heating by embedded stars, a very large number of massive stars would be necessary to account for the whole optical luminosity (Collin & Zahn 1999).

Since the status of the unstable part of the disc is not known, we parametrize these effects by assuming that the energy release is proportional to  $R^{-\beta}$ , with  $\beta$  smaller than 3 in the self-gravitating region. In this paper we will assume the extreme case  $\beta = 2$ : it corresponds to  $L_\nu \propto \nu^{-\gamma}$ , with  $\gamma = 1/2$ . In the following computations this value is used into Eq. (5) instead of Eq. (4) for  $R \geq R_{\text{sg}}$ , with the continuity of the energy release at  $R_{\text{sg}}$ . Doing this we obtain an optical spectral index between  $-0.3$  (corresponding to the standard disc) and  $+0.5$ , depending on the fraction of the disc which is self-gravitating. It is closer to the observed AGN continuum. The effect on the bolometric luminosity of this additional energy release is negligible, but it increases the computed emission in the optical and near-infrared spectral bands, and therefore decreases the accretion rate necessary to account for a given optical luminosity.  $R_{\text{sg}}$  is small for small values of  $\alpha$ . We have thus chosen a relatively small value of the viscosity parameter (0.01) in order to

underestimate  $R_{\text{sg}}$ , and therefore to *underestimate also the accretion rate* with respect to a standard disc.

However, we have to take into account the fact that the accretion disc cannot extend too much in the self-gravitating region, unless a mechanism can act to limit the disc density at exactly the marginal instability. Since we will see below that the self-gravitation radius is always smaller than  $10^4 R_g$ , we have decided in the following to cut off the radius of the accretion disc at a value of  $10^5 R_g$ . It is an arbitrary value, but we have no way to estimate the real extension of the accretion disc. Note that the dimension of the BLR is at most of this order in NLS1s, and it is difficult to accept the idea that the disc extends much further out. Note also that for such a radius, the gravity of the galaxy does not dominate the BH.

If the disk is not self-gravitating and extends further out, it does not influence the optical emission. Indeed in this case one finds that  $\lambda(10^5 R_g) \sim 20M_7^{1/4}\dot{m}^{-1/4} \mu\text{m}$ , which ensures that the optical emission is entirely produced inside  $10^5 R_g$ . On the contrary, if the disk extends only up to  $10^3 R_g$  or  $10^4 R_g$ , the computed optical emission would be smaller than for  $R_{\text{out}} = 10^5 R_g$ , and *the accretion rate would therefore be larger*.

As an accretion disc with a super-Eddington accretion rate behaves like a standard disc outside the photon trapping radius (KPH), we compute  $R_{\text{sg}}$  with the same analytical approximation as KPH, which gives expressions similar to the previous detailed computations of Huré (1998):

$$R_{\text{sg}} = \left( R_{\text{sg,a}}^3 + R_{\text{sg,b}}^3 + R_{\text{sg,c}}^3 \right)^{1/3} \quad (7)$$

where  $R_{\text{sg,a}}$ ,  $R_{\text{sg,b}}$ , and  $R_{\text{sg,c}}$  are the self-gravitation radius in respectively the inner region dominated by radiation pressure and Thomson opacity, the intermediate region dominated by gas pressure and Thomson opacity, and the outer region dominated by gas pressure and atomic opacity:

$$R_{\text{sg,a}} = 500 \left( \frac{\alpha}{0.1} \right)^{2/9} M_7^{-2/9} \left( \frac{\dot{M}}{L_{\text{Edd}}/c^2} \right)^{4/9} R_G \quad (8)$$

$$R_{\text{sg,b}} = 11400 \left( \frac{\alpha}{0.1} \right)^{14/27} M_7^{-26/27} \left( \frac{\dot{M}}{L_{\text{Edd}}/c^2} \right)^{-8/27} R_G$$

$$R_{\text{sg,c}} = 13400 \left( \frac{\alpha}{0.1} \right)^{28/45} M_7^{-52/45} \left( \frac{\dot{M}}{L_{\text{Edd}}/c^2} \right)^{-22/45} R_G.$$

These expressions depend on the viscosity parameter  $\alpha$ . We will use  $\alpha = 0.3$ ,  $\alpha = 0.1$ , and  $\alpha = 0.01$ . A smaller value of  $\alpha$  has a more profound influence on the disc structure, as it corresponds to a denser standard disc, and therefore a smaller value of  $R_{\text{sg}}$ .

Let us now discuss the consequences of these relations in an approximate way. As we shall see later, none of the free parameters has a strong influence on the computed accretion rate, the main quantity that we want to determine. We have seen that for a standard disc,  $L(5100) \propto (M\dot{M})^{2/3}$ . Using this relation, and Eqs. (1) and (2), we get:

$$\dot{m} \propto FWHM^{-4.28} M^{0.14}, \quad (9)$$

where  $\dot{m}$  is the accretion rate expressed in Eddington units,  $\dot{m} = \frac{\dot{M}}{L_{\text{Edd}}/c^2}$ . This is actually a very interesting result, which comes from the dependence of the size of the BLR on the luminosity

and which shows that  $\dot{m}$  depends almost only on the *FWHM*, and very little on the BH mass. It is only approximate if the self-gravitating region of the disc is large. It means that  $\dot{m}$  can be deduced directly from the measurement of the *FWHMs* alone.

#### 4. Results and discussion

We have applied our model to the samples, and we now present the results. We use  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}$ , and  $q_0 = 0.5$ . When the luminosities were given for another cosmological constant, we have made the conversion.

We first draw the attention to a fact that is sometimes forgotten. Generally it is not the fluxes at Earth but the luminosities that are published in the literature, and they are computed assuming isotropic emission. The monochromatic luminosity is thus equal to:

$$\nu_e L(\nu_e) = 4\pi D^2 (1+z)^2 \times \nu_e F(\nu_e) / \text{Abs}(\nu_e), \quad (10)$$

where  $F$  is the flux observed at Earth,  $\nu_e$  (resp.  $\nu_o$ ) is the frequency at emission (resp. at Earth),  $D$  is the proper distance of the object,  $z$  is the redshift,  $\text{Abs}(\nu_e)$  the external (galactic) absorption. But an accretion disc does not emit isotropically. The computed monochromatic luminosity given by Eq. (5) or by its equivalent for the self-gravitating region should thus be multiplied by a factor  $2\cos(i)$ , where  $i$  is the inclination of the disc axis to the line of sight, to be identified with the published values.

##### 4.1. Accretion rates

Figure 2 display  $\dot{m}$  as a function of the BH mass for the four samples.  $\dot{m}$  is computed according to both the standard disc model, and the self-gravitating disc model as explained in the previous section. In this latter case, the results are shown for a viscosity parameter  $\alpha = 0.01$ . In all computations,  $\cos(i)$  is set equal to 0.75. The objects with  $L(5100) \leq 0.5 \times 10^{44} \text{ erg/s}$  are indicated in the figures. There are only two such objects (actually lying close to the limit) in Bor03. The Gru03 sample contains many low luminosity objects, but a large number of NLS1s are above the luminosity limit.

We see that the self-gravitation correction can decrease  $\dot{m}$  by about a factor of three for large values of  $\dot{m}$ , but has no influence on small  $\dot{m}$ . For larger values of  $\alpha$  and of  $\gamma$ , the difference between the standard and the self-gravitating disc would be smaller. So we can consider that the two models here correspond to a kind of “error bar” on  $\dot{m}$ , for given BH mass and  $L(5100)$ . Figure 2 also shows the “observed” ratio  $L(5100)/L_{\text{Edd}}$ . We have noted the NLS1s, and the thick dotted lines delineate the position of  $\dot{m}$  for NLS1s. NLS1s always have BH masses smaller than  $10^8 M_\odot$ , and they are located in the higher range of  $L(5100)/L_{\text{edd}}$  and  $\dot{m}$ . It is interesting to note that the four samples do not differ except for the range of masses and luminosities, though they have been selected quite differently.

Again we added for comparison to these figures the results for the Kaspi et al. sample, computed using only the standard disc emission (we recall that the results differ from C02 because we use here  $H_0 = 75$  instead of 50). As expected,

the extrapolation by a factor 5 in mass range of the empirical relationship translates in an extrapolation of  $\dot{m}$  by about a factor 30, as  $\dot{m} \propto \dot{M}/M_{\text{BH}} \propto L_{5100}^{3/2} \times M_{\text{BH}}^{-2}$ .

Several other results appear in these figures.

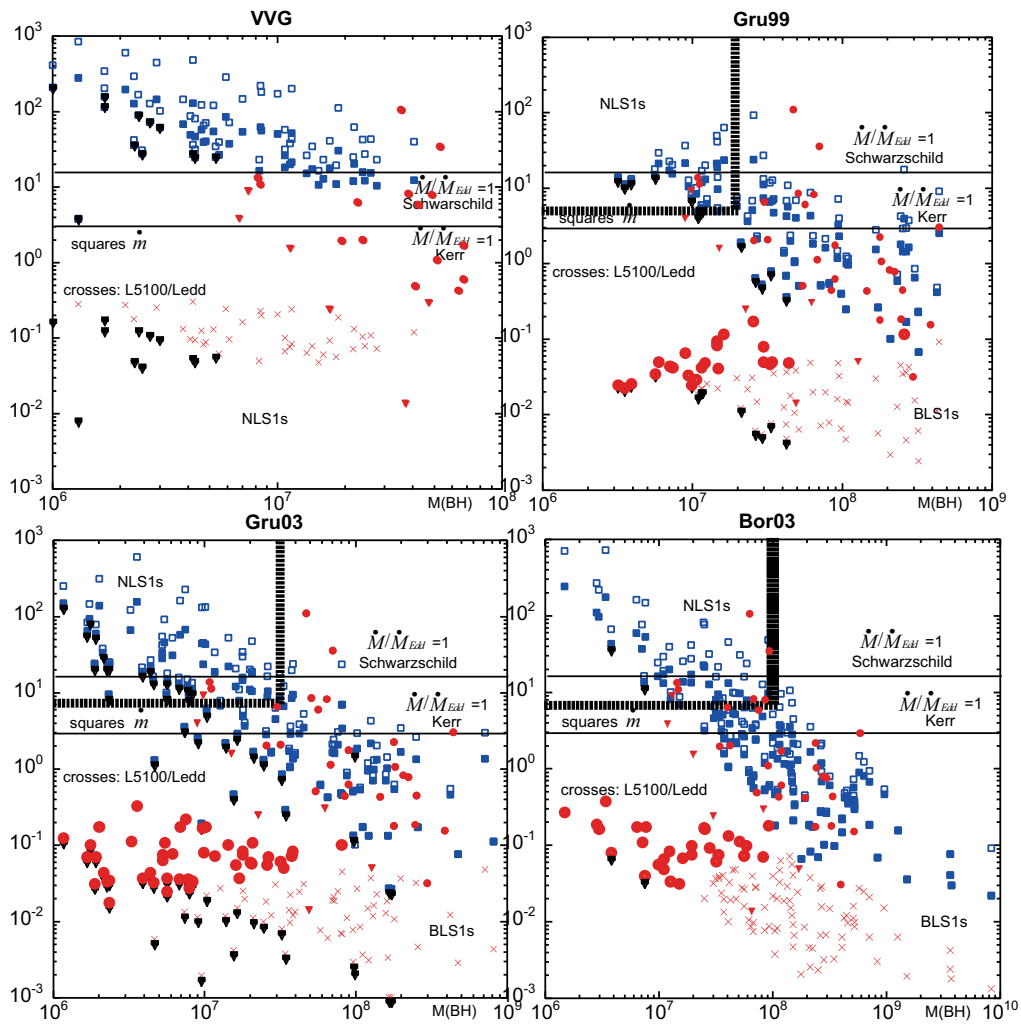
First,  $\dot{m}$  increases as the BH mass decreases. On the contrary, the ratio  $L(5100)/L_{\text{Edd}}$  is always smaller than 0.3, and seems about constant for the NLS1s. When applying a standard correction  $L_{\text{bol}} \sim 10 \times L(5100)$ , one concludes that  $L_{\text{bol}}$  saturates at about the Eddington luminosity, whatever the BH mass. This excludes the existence of the large super-Eddington ratios proposed by Begelman (2002) due to the photon bubble instability. Thus, according to Eq. (3), there should be a lower limit to the *FWHMs* of the order of  $1000 M_7^{0.15} \text{ km s}^{-1}$  unless the empirical relations do not apply to these objects. And indeed *FWHMs* of the order of  $100\text{--}500 \text{ km s}^{-1}$  which would imply Eddington ratios larger than 10 have never been observed in Seyfert 1 nuclei.

Second, the two horizontal lines correspond to  $\dot{M}/\dot{M}_{\text{Edd}} = 1$ , where  $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/(\eta c^2)$ , in the case of a Schwarzschild BH ( $\eta = 0.057$ ) and of an extremely rotating Kerr BH ( $\eta = 0.30$ ). We see that the accretion rates of NLS1s are always larger than the Eddington rate for Kerr BHs, and mostly larger for Schwarzschild BHs.

There are several causes of uncertainties in the results (cf. Krolik 2001 and C02), which might introduce errors on the BH masses as large as one order of magnitude, because one should not forget that even the masses determined directly with reverberation mapping are known with an uncertainty of a factor 3. It seems however implausible that all the uncertainties would systematically act towards an underestimation of the mass and an overestimation of the luminosity, avoiding the conclusion of super-Eddington accretion rates. Only the uncertainty in the correcting factor of the *FWHM* due to the geometry and kinematics of the BLR could lead to a *systematic* underestimation of the mass, if the BLR is a rotating flat structure. It can be large when the objects are seen almost face-on. We shall discuss this point in the last section.

Figure 3 displays  $R_{\text{sg}}/R_{\text{G}}$  versus  $M$  for all samples, for the self gravitating disc with  $\alpha = 0.01$ . We note that it is always quite small (in particular smaller than  $R(\text{BLR})/R_{\text{G}}$ , which has typical values of  $10^3$  for high BH masses and  $10^5$  for NLS1s), justifying our previous claim that the BLR is always located in, or above, the unstable part of the disc. As expected  $R_{\text{sg}}/R_{\text{G}}$  decreases with the BH mass, except at the high mass limit, and there is a strong correlation between the two parameters.

Although the choice of parameters for the self-gravitating disc does not influence strongly  $\dot{m}$ , it has an effect on the optical spectral index. As an illustration, Fig. 4 shows the computed optical spectral index  $\alpha_{\text{opt}}$  defined as  $F_\nu \propto \nu^{-\alpha_{\text{opt}}}$  between 4400 and 7000 Å (rest frame), for the Bor03 sample. The computation is performed with the self-gravitating correction, for a viscosity parameter  $\alpha$  equal to 0.01, 0.1, and 0.3. A systematic correction  $E(B - V) = 0.05$  for the galactic absorption has been applied (certainly an underestimation). For  $\alpha = 0.01$ , the continuum is red except for very broad line objects. The trend that broader objects have bluer optical spectra is consistent



**Fig. 2.**  $\dot{m}$  as a function of the BH masses for the four samples. The squares give  $\dot{m}$  computed according both to the standard disc model (open squares), and to the self-gravitating disc model with a viscosity parameter  $\alpha = 0.01$  (filled squares). The crosses give  $L(5100)/L_{\text{edd}}$ , and the crosses with open circles mark the NLS1s. The two thick solid lines delineate the position of  $\dot{m}$  for the NLS1s. The two horizontal lines correspond to  $\dot{M}/\dot{M}_{\text{Edd}} = 1$ , where  $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/(\eta c^2)$ , in the case of a Schwarzschild BH and of a Kerr BH. The black (resp. red) triangles indicate the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s (resp. for the Kaspi et al. sample). Note that the VVG sample consists only of NLS1s, thus circle symbols are not shown.

with the observational results of Constantin & Shields (2003). The continuum is globally bluer for smaller values of  $\alpha$  (0.1 and 0.3). We also see that  $\alpha_{\text{opt}}$  almost never reaches the value of the standard disc ( $-0.33$ ). A detailed comparison with the observed values is postponed to a next paper.

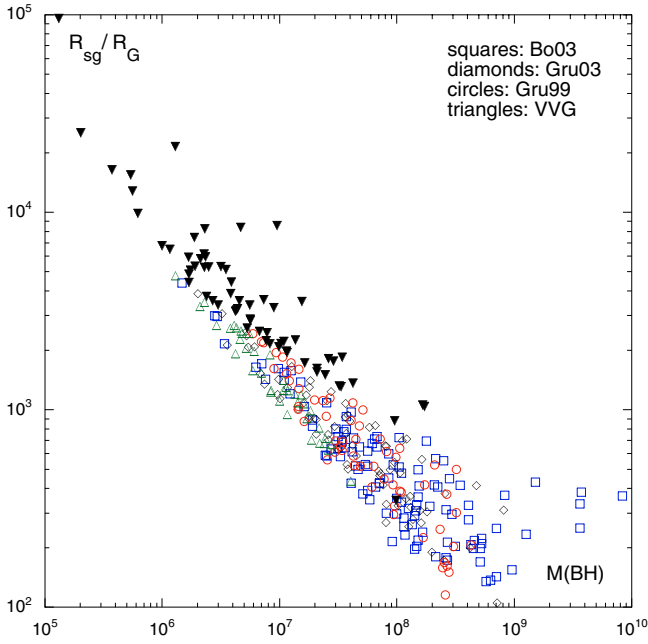
Figure 5 shows a comparison between the observed and computed spectral indices for the Gru99 sample, excluding the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s. According to Grupe et al. (1999), the observed values of  $\alpha_{\text{opt}}$  are given with an uncertainty of  $\pm 0.4$ . With  $\alpha = 0.1$ , many of the computed indices are close to the value of the standard disc, while the objects of the samples are particularly red, with an average index of 0.8. The agreement is much better for the smallest viscosity parameter  $\alpha = 0.01$ . The very red spectra observed in a fraction of objects might be due to intrinsic reddening having not been taken into account in the computed values. If this is the case, it would imply that the observed  $L(5100)$  is underestimated in these objects, but again it is not important for the determination

of  $\dot{m}$ . Note that in this sample NLS1s do not seem to have redder continua than BLR1s.

It is therefore impossible from this comparison to decide which are the best values of  $\alpha$  and  $\gamma$  to choose for the disc. Our model is clearly oversimplified, and would require a more sophisticated parametrization. The only conclusion which can be drawn is that a non-standard disc with an additional release of energy in its external region gives a better fit to the average optical continuum of AGN than a standard disc. However, this problem does not question the existence of super-Eddington accretion rates for NLS1s.

Finally, Fig. 6 displays the accretion rates in  $M_{\odot}/\text{yr}$  for the four samples, excluding the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s, and computed according to the self-gravitating disc model with a viscosity parameter  $\alpha = 0.01$ . Note that the imposed limit on  $L(5100)$  creates the sharp limitation on the left side, as  $\dot{M}$  is proportional to  $M^{-2/3}$  (for a fixed  $L_{\text{opt}}$ ). The limitation on the right side is due to a limitation of  $\dot{m}$  at about 0.03



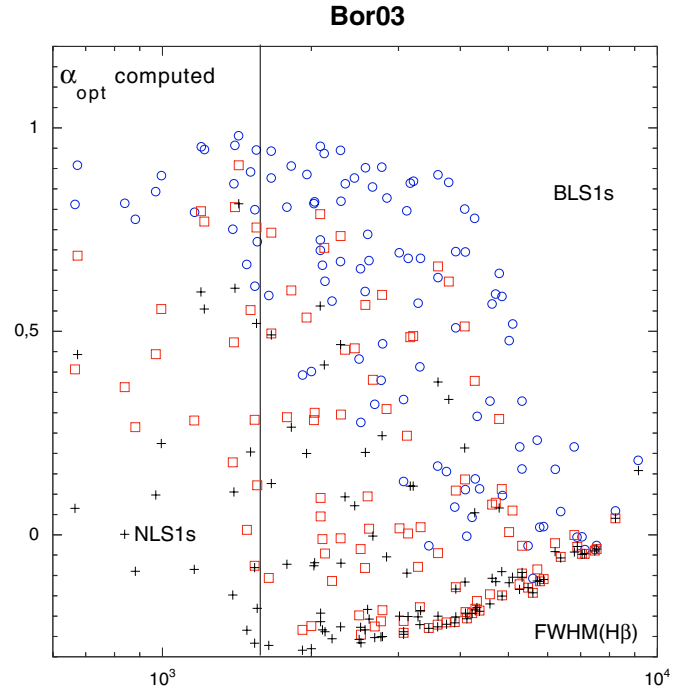


**Fig. 3.**  $R_{\text{sg}}/R_{\text{G}}$  versus  $M$  for all samples, for a self-gravitating disc with  $\alpha = 0.01$ . The black triangles indicate the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s for all samples.

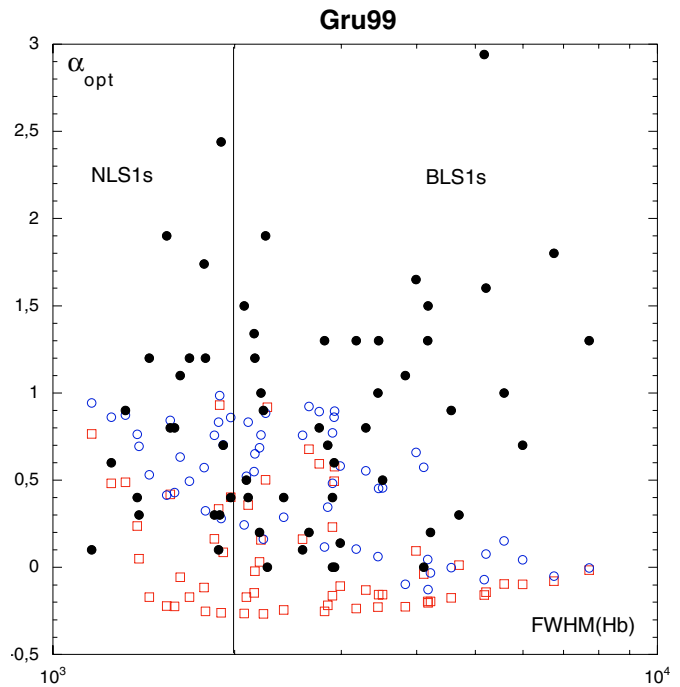
(perhaps due to the fact that the accretion disc changes into an ADAF below this value). NLS1s are indicated as red dots. Despite the large values of  $\dot{m}$  of NLS1s, we see that *the maximum accretion rate is of the order of one  $M_{\odot}/\text{yr}$  whatever the BH mass. This is a strong indication of an exterior regulation of the accretion, rather than self-regulation of the disc.* Note that it is a modest value when compared to the rate of star formation in a starburst nucleus.

#### 4.2. Comparison with the slim disc model

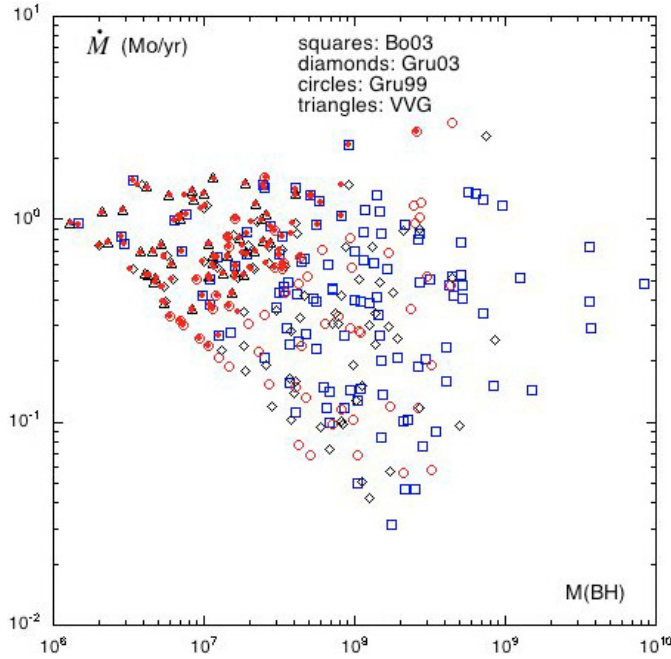
It is interesting to compare the observed SED of super-Eddington objects with the slim disc model. As we mentioned in the introduction, this was done in detail for the two highest  $\dot{m}$  objects (Kawaguchi 2003; KPH; Kawaguchi, Matsumoto, Leighly in preparation; see Kawaguchi 2004). and it will be performed for the objects of the samples in a future paper. Here we simply compute the bolometric luminosity, and we compare it with the observed values. Only the Gru03 sample provides bolometric luminosities based on the observed SEDs. Figure 7 shows the observed ratio  $R_{\text{Edd}}$  versus  $\dot{m}$  for this sample. The low luminosity nuclei ( $L(5100) \leq 0.5 \times 10^{44}$  erg/s) have been suppressed. Also shown are the theoretical curves obtained for the slim disc model with a Schwarzschild and a Kerr BH. These curves depend very little on the BH mass and on the viscosity parameter. In spite of the large dispersion of the “observations”, it is clear that the majority of points lie above the Schwarzschild curve, meaning that the efficiency of the Schwarzschild BH is insufficient, i.e. *a Kerr BH with an efficiency of about 0.15 would better fit the observations unless there is a systematic underestimation of the BH masses.* On the other hand, the shape of the curve agrees well with the observed points, in particular in the “saturation” of  $R_{\text{Edd}}$  above  $\dot{m} = 10$ .



**Fig. 4.** The computed optical spectral index  $\alpha_{\text{opt}}$  between 4400 and 7000 Å (rest frame), for the Bor03 sample, excluding the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s.  $\alpha_{\text{opt}}$  is computed with the self-gravitating correction, for  $\alpha$  equal respectively to 0.01 (blue circles), 0.1 (red squares), and 0.3 (black crosses). We recall that  $\alpha_{\text{opt}} = 0.3$  for a standard disc.



**Fig. 5.** Comparison between the observed and computed optical spectral index  $\alpha_{\text{opt}}$ , for the Gru99 sample, excluding the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s. The black filled circles are the observed values, the open symbols are computed with the self-gravitating correction, for  $\alpha$  equal respectively to 0.01 (blue circles) and 0.1 (red squares). We recall that  $\alpha_{\text{opt}} = 0.3$  for a standard disc.



**Fig. 6.** Accretion rates in  $M_{\odot}/\text{yr}$  for the four samples as a function of the BH masses, excluding the objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s, and computed according to the self-gravitating disc model with a viscosity parameter  $\alpha = 0.01$ . NLS1s are indicated as red dots.

Three objects reach an Eddington ratio of the order of 10, for  $50 \leq \dot{m} \leq 1000$ .

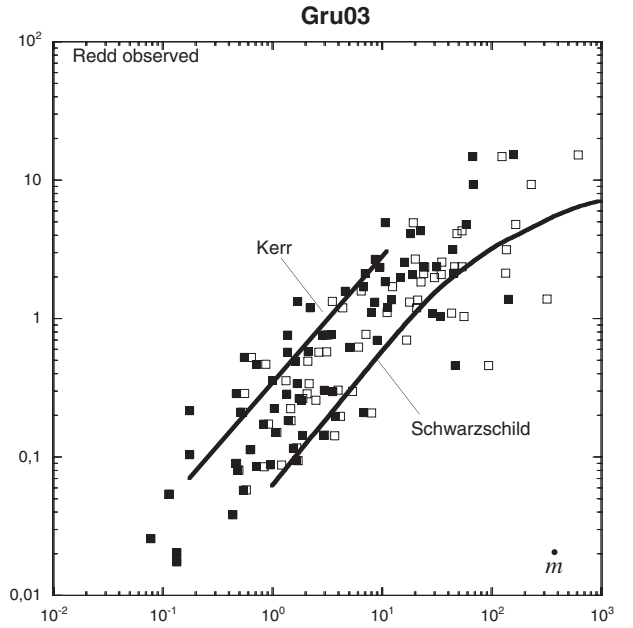
## 5. Influence of the inclination on the masses and accretion rates

In all mass determinations, the *FWHM* is used instead of the dispersion velocity. It makes the implicit assumption that the velocities are distributed at random in the BLR. However, if the BLR is a flat structure dominated by rotation, the *FWHM* is proportional to  $\sin(i)V_{\text{Kep}}$ , where  $i$  is the angle between the normal and the line of sight (the inclination). It is clear that a small inclination can lead to a large underestimation of  $V_{\text{Kep}}$  and therefore of the mass.

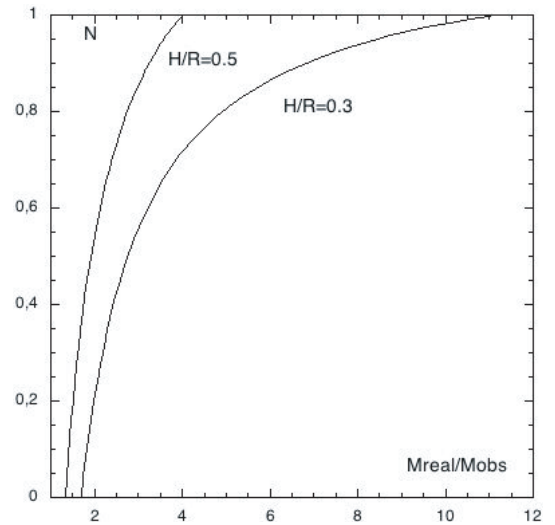
However the BLR cannot be a geometrically thin disc with an exactly Keplerian velocity. Unfortunately its dynamics and its structure are still not well determined from detailed reverberation mappings, but we know that it should be at least a “thick disc”, with an aspect ratio larger than, say,  $H/R \sim 0.3$  ( $H$  being the disc thickness at the radius  $R$ ), since it needs to have a large coverage factor of the central source. Such a disc must be sustained vertically by a turbulent pressure corresponding to a turbulent velocity of the order of  $V_{\text{Kep}}H/R$ . The *FWHM* is then proportional to  $V_{\text{Kep}}\sqrt{(H/R)^2 + \sin^2(i)}$ , and the ratio  $G$  between the real mass and the “observed” mass, is:

$$G = M_{\text{real}}/M_{\text{obs}} = 1/[(H/R)^2 + \sin^2(i)]. \quad (11)$$

We can compute how many objects have a mass underestimated by a given factor  $G$ , assuming that they are distributed at random inside an angle  $i_0$ . We choose  $i_0 = \pi/4$  in the following computations, as it is a commonly accepted value for the



**Fig. 7.** The Eddington ratio  $Redd$  as a function of  $\dot{m}$  for the Gru03 sample, computed with the standard disc (open squares) and the self-gravitating disc,  $\alpha = 0.01$  (filled squares). The objects with  $L(5100) \leq 0.5 \times 10^{44}$  erg/s have been suppressed. The two curves correspond to the slim disc model,  $\alpha = 0.1$ , and respectively a Schwarzschild and a Kerr BH.



**Fig. 8.** Cumulative number of objects (normalized to unity) for which the mass is underestimated by a factor smaller than  $M_{\text{real}}/M_{\text{obs}}$ , in the conditions explained in the text.

opening angle of the dusty torus in Seyfert 1 (according to the Unified Scheme, cf. Antonucci & Miller 1985). The probability of seeing an object at an inclination angle  $i$  per unit angle interval is thus  $\sin(i)/[\cos(i_0) - 1]$ . The number of objects per unit interval of  $G$  is:

$$\frac{dN}{dG} = \frac{[(H/R)^2 + \sin^2(i)]^2}{2[1 - \cos(i_0)]\cos(i)}. \quad (12)$$

Figure 8 shows the integral of this expression, i.e. the cumulative number of objects (normalized to unity) for which the mass

is underestimated by a factor smaller than  $M_{\text{real}}/M_{\text{obs}}$ , for two values of  $H/R$ . Note that  $i_0$  plays a non-negligible role here, as it contributes to increasing the proportion of objects having a large  $G$  by a factor of 3 with respect to an isotropic distribution. We see that the factor  $G$  depends strongly on the aspect ratio of the BLR. For  $H/R = 0.3$ , it can take values as large as 11, but the number of objects reaching this value is small: only about 20% have a  $G$ -factor larger than 6, and 1% a factor larger than 10. For  $H/R = 0.5$ , the maximum value of  $G$  is only 4, and about 60% have a  $G$ -factor of the order of or smaller than 2.

It is important to realize that in this case *not only nearly face-on objects, but all Seyfert 1* will have their BH mass underestimated. This would raise a problem concerning the BH-bulge mass relationship.

Should we then modify our conclusions? For  $H/R = 0.3$ , half of the NLS1s could have their masses underestimated by factors of 3 to 10, leading to underestimations of the accretion rates (in terms of Eddington) by factors 10 to 100. This is clearly very important, but still a large proportion of objects would be accreting above the Eddington limit, however at a smaller rate. On the other hand, it is quite possible that the few extremely high accretors are actually “face-on” objects, and that their mass is indeed underestimated by about one order of magnitude.

## 6. Conclusion

We used the BH masses deduced from the size-luminosity relationship to compute their accretion rates in four samples of AGN, assuming that the optical luminosity is provided by the accretion disc. Thus the empirical relation must be extrapolated in a range of masses almost one order of magnitude smaller than the Kaspí et al. sample. We used a simplified disc model, with a parametrization of the energy release in the self-gravitating region to get the accretion rate, and the slim disc model in the inner regions to get the bolometric luminosity. In spite of the crudeness of the treatment, this study leads to several fairly certain conclusions.

- NLS1s are always accreting at Eddington or super-Eddington rates.  $\dot{m}$  can reach 1000, corresponding to an accretion rate equal to  $60 \dot{M}_{\text{Edd}}$  (for Schwarzschild BH) and to  $300 \dot{M}_{\text{Edd}}$  (for Kerr BH).
- Their observed bolometric luminosities “saturate” at  $\sim 10$  Eddington luminosities, as predicted by slim disc models. This explains why there is a lower limit to the observed *FWHM*.
- The observed values of the bolometric luminosities are in better agreement with a Kerr than with a Schwarzschild BH.
- The computed optical spectral indices agree with the observed trend of redder spectra for NLS1s than for BLS1s.
- And finally the accretion rates have an upper limit of about one  $M_{\odot}/\text{yr}$ , whatever the BH mass. In particular, all NLS1s have an accretion rate of this order. This is a strong indication for a mass limited supply, implying an exterior regulation of the accretion.

With these results we are in a position to say now that NLS1s should have a strong influence on the growth of BHs. This is in agreement with the claim by Mathur et al. (2001), and Grupe & Mathur (2004). Since NLS1s constitute about 10% of normal Seyferts which themselves are about 2% of inactive galaxies, one deduces that all galaxies spend 0.2% of their lifetime in the NLS1 phase, i.e.  $2 \times 10^7$  years. During this time the mass of the BH increases by one order of magnitude (Kawaguchi et al. 2004). This could account both for the observed large dispersion in the BH/bulge mass relation of NLS1s, and for the existence of undermassive BH/bulge ratios during a large fraction of the NLS1 phase. The increase of the bulge mass could have taken place during merger or interaction events. BHs would then grow during intense phases of activity after a time delay, necessary for accumulating matter in the circumnuclear region and for triggering a starburst. In this scenario, the overabundance of iron could be easily explained by the rapid formation of massive stars and supernovae explosions in the outer parts of the accretion disc where the accretion rate is high (Collin & Zahn 1999; Levin 2003; Levin & Belobodorov 2003). The scenario would also account naturally for the presence of outflows giving rise to the blue wing of the [OIII] line, as super-Eddington accretion is expected to generate outflows by strong radiation fields.

Though we have tried to determine a lower limit of the accretion rate, two effects can intervene to still reduce it. They were both discussed in C02.

1. The possibility that the accretion rate decreases with the radius between the optically emitting region and the BH, owing to the creation of a strong outflow due to the radiation pressure. The accretion rate close to the BH would then be just Eddington. In this case, the outflow could well be the origin of the [OIII] wing, and could lead to the escape of a part of the Narrow Line Region, explaining the weakness of the [OIII] line. However, one should realize that in this case the rate of outflow would have to represent 90 or even 99% of the accretion rate, in the highest accretors. This seems unrealistic.
2. The optical luminosity is not provided by the accretion disc. Recently King & Pounds (2003) suggested that BHs accreting at super Eddington rate produce winds which are Thomson thick and can emit a black body spectrum providing the Blue Bump of AGN. Pounds et al. (2003) indeed report that they have found the signature of such an optically thick wind in the X-ray spectrum of the NLS1 PG1211+143. If the existence of such a wind is confirmed in other NLS1s, then it is clear that the present analysis would have to be reconsidered. However, let us recall that Collin et al. (2002) have shown that very strong conditions must be met in such a wind to give rise to the optical-UV featureless continuum: it must have both a large density ( $10^{14} \text{ cm}^{-3}$ ), and a Thomson thickness of at least of unity. Besides, to get the observed luminosity, it should be located far from the center and it should have a large spatial extension. It is thus not obvious that the wind observed by Pounds et al. (2003) satisfies these requirements. It is more

likely that its emission is limited only to the EUV radiation, and that the optical emission is still due to the accretion disc.

We have assumed throughout the paper that the BH masses of NLS1s are correctly estimated by the empirical reverberation relations, even when these relations had to be extrapolated by almost one order of magnitude. On the other hand, we have accepted the usual assumption that the *FWHM* is a good measure of the velocity in the BLR, implicitly assuming that the velocities are distributed randomly. If on the contrary the BLR is a flat structure dominated by rotation, the BH masses of a fraction of objects could be underestimated by factors up to one order of magnitude and the accretion rates (in terms of Eddington) by two order of magnitudes when they are seen nearly face-on. However, since this fraction should be small, we think that the scenario described in this paper is qualitatively correct.

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