

Are the black hole masses in narrow-line Seyfert 1 galaxies actually small?

Roberto Decarli,[★] Massimo Dotti, Marcella Fontana and Francesco Haardt

Dipartimento di Fisica e Matematica, Università dell'Insubria, via Valleggio 11, 22100 Como, Italy

Accepted 2008 January 29. Received 2008 January 3; in original form 2007 August 8

ABSTRACT

Narrow-line Seyfert 1 galaxies (NLS1s) are generally considered peculiar objects among the broad class of type 1 active galactic nuclei, due to the relatively small width of the broad lines, strong X-ray variability, soft X-ray continua, weak [O III], and strong Fe II line intensities. The mass M_{BH} of the central massive black hole (MBH) is claimed to be lighter than expected from known MBH–host galaxy scaling relations, while the accretion rate on to the MBH larger than the average value appropriate to Seyfert 1 galaxies. In this Letter, we show that NLS1 peculiar M_{BH} and L/L_{Edd} turn out to be fairly standard, provided that the broad-line region is allowed to have a disc-like, rather than isotropic, geometry. Assuming that NLS1s are rather ‘normal’ Seyfert 1 objects seen along the disc axis, we could estimate the typical inclination angles from the fraction of Seyfert 1 classified as NLS1s, and compute the geometrical factor relating the observed full width at half-maximum of broad lines to the virial mass of the MBH. We show that the geometrical factor can fully account for the ‘black hole mass deficit’ observed in NLS1s, and that L/L_{Edd} is (on average) comparable to the value of the more common broad-line Seyfert 1 galaxies.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert.

1 INTRODUCTION

Seyfert 1 galaxies (Sy1s) are often divided into two distinct classes, namely broad-line Sy1s (BLS1s), whose $H\beta$ line has full width at half-maximum (FWHM) $\gtrsim 2000 \text{ km s}^{-1}$ (hence, as standard type 1 active galactic nuclei AGN), and narrow-line Sy1s (NLS1s), with lower velocities (e.g. Goodrich 1989). NLS1s are a minority, $\simeq 15$ per cent of all the Sy1s, according to the optical spectroscopic classification of the SDSS general field (Williams, Pogge & Mathur 2002), the fraction depending on the AGN luminosity (with a peak at $M_g' \sim -22$), and on the radio loudness (radio-loud NLS1s account only for ~ 7 per cent of the class, Komossa et al. 2006, but it is still debated if the NLS1s can be considered a peculiar radio-quiet subclass among Sy1s, see e.g. Sulentic et al. 2007; Doi et al. 2007). NLS1s also show weak [O III] and strong Fe II emission line (Osterbrock & Pogge 1985), strong variability, and a softer than usual X-ray continuum (Boller, Brandt & Fink 1996; Grupe et al. 1999).

Grupe & Mathur (2004a) found that NLS1s have, on average, lower M_{BH} than expected from M_{BH} –host galaxy relations such as $M_{\text{BH}}-\sigma_*$ (see Tremaine et al. 2002, and references therein), while BLS1 M_{BH} is in fairly good agreement to the same relation. The estimated low values of M_{BH} lead to an average Eddington ratio L/L_{Edd} for the NLS1 population which is almost an order of magnitude larger than the average value of BLS1s ($L/L_{\text{Edd}} \simeq 1$ to be compared

to $\simeq 0.1$, Grupe 2004). Further evidence of low M_{BH} in NLS1s comes from the observed rapid X-ray variability (see e.g. Green, McHardy & Lehto 1993; Hayashida 2000).

Such results were interpreted as indications of a peculiar role of NLS1s within the framework of the cosmic evolution of massive black holes (MBHs) and of their hosts. In a MBH–galaxy co-evolution scenario, NLS1s are thought to be still on their way to reach the $M_{\text{BH}}-\sigma_*$ relation, that is, their (comparatively) small MBHs are highly accreting in already formed bulges. Recently Botte et al. (2005) and Komossa & Xu (2007) came to the conclusion that NLS1s have indeed smaller masses and higher L/L_{Edd} than BLS1, nevertheless they both do follow the $M-\sigma_*$ relation for quiescent galaxies. The authors argued that the customarily used [O III] line is not a reliable surrogate for the stellar velocity dispersion σ_* .

The Grupe and Mathur’s results and interpretation have been recently confirmed and supported by several other groups (see e.g. Zhou et al. 2006 and Ryan et al. 2007). Ryan et al. (2007) pointed out that IR-based mass measurements might be unreliable because of the extra IR contribute from the circum-nuclear star-forming regions in NLS1s. Notwithstanding, they suggested that this contamination cannot significantly affect their data, and thus is insufficient to account for the MBH mass deficit. In the aforementioned papers, M_{BH} was computed as

$$M_{\text{BH}} = \frac{R_{\text{BLR}} v_{\text{BLR}}^2}{G}, \quad (1)$$

where R_{BLR} is the broad-line region (BLR) scale radius, and v_{BLR} the typical velocity of BLR clouds. R_{BLR} is found by means of the

[★]E-mail: roberto.decarli@mib.infn.it

reverberation mapping technique (Blandford & McKee 1982), or by exploiting statistical R_{BLR} –luminosity relations (see Kaspi et al. 2000, 2005, 2007); v_{BLR} can be inferred from the $H\beta$ width as

$$v_{\text{BLR}} = f \times (\text{FWHM}), \quad (2)$$

where the FWHM refers only to the broad component of the line, and f is a fudge factor which depends on the assumed BLR model. For an isotropic velocity distribution, as generally assumed, $f = \sqrt{3}/2$.

Labita et al. (2006) and Decarli et al. (in preparation) found that in quasi-stellar objects an isotropic BLR fails to reproduce the observed linewidths and shapes, and a disc model should be preferred. A disc-like geometry for the BLR has been proposed by several authors in the past (e.g. Wills & Browne 1986; Vestergaard, Wilkes & Barthel 2000; Bian & Zhao 2004). In this picture, the observed small FWHMs of NLS1 broad lines are ascribed to a small viewing angle with respect to the disc axis, and no evolutionary difference is invoked whatsoever.

In this Letter, we adopt the disc-like model for the BLR of Seyfert galaxies. We use the observed frequency of NLS1s to estimate their typical viewing angle, and then compute the appropriate geometrical factor f . Using equation (1), we will show that the new estimates of M_{BH} for NLS1s nicely agree with the standard $M_{\text{BH}}-\sigma_*$ relation. In turn, the accretion rate of the class is found to be similar to that of BLS1s.

2 MODEL AND RESULTS

We model the BLR as a thin disc, and define ϑ as the angle between the line of sight and the normal to the disc plane. The FWHM is a measure of the velocity projected along the line of sight. In the assumption of a 2D, Keplerian BLR, the observed FWHM is correlated to the rotational velocity of the disc as

$$\text{FWHM} = 2 v_{\text{Kep}} \sin \vartheta, \quad (3)$$

where v_{Kep} is the Keplerian velocity of the disc-like BLR. In this model the differences between the FWHM of NLS1s and BLS1s depend only on ϑ , so that the Sy1s observed nearly face-on are classified as NLS1s, while the ones observed at higher angles are considered BLS1s. As mentioned in the Introduction section, the fraction of NLS1s we consider is $\simeq 15$ per cent. In our unification scheme, the relative fraction R_{NLS1} is related to the maximum inclination angle of the subclass ϑ_{cr} as $R_{\text{NLS1}} = (1 - \cos \vartheta_{\text{cr}})/(1 - \cos \vartheta_{\text{max}})$, where $\vartheta_{\text{max}} \sim 40^\circ$ is the maximum inclination angle for type I AGN in the unification model (e.g. Antonucci & Miller 1985; Antonucci 1993; Storchi-Bergmann, Mulchaey & Wilson 1992).

Some authors suggested that the BLR cannot be completely flat (see e.g. Collin et al. 2006). Alternatively, discs may have a finite half thickness (H), or a ‘flared’ profile (with H increasing more than linearly with the disc radius R , see e.g. Dumont & Collin-Souffrin 1990). Other models proposed include warped discs (Wijers & Pringle 1999), and the superposition of discs and wind components (Murray & Chiang 1995, 1998; Elvis 2000; Proga & Kallman 2004). In this Letter, we employ the simplest model, that is, a disc with finite thickness, a choice minimizing the number of required parameters. As it will be shown in the following, this minimal set-up can resolve the apparent dichotomy between NLS1s and BLS1s.

In a finite thickness disc model for the BLR, the geometrical factor f , as defined in equation (2), is related to the inclination angle

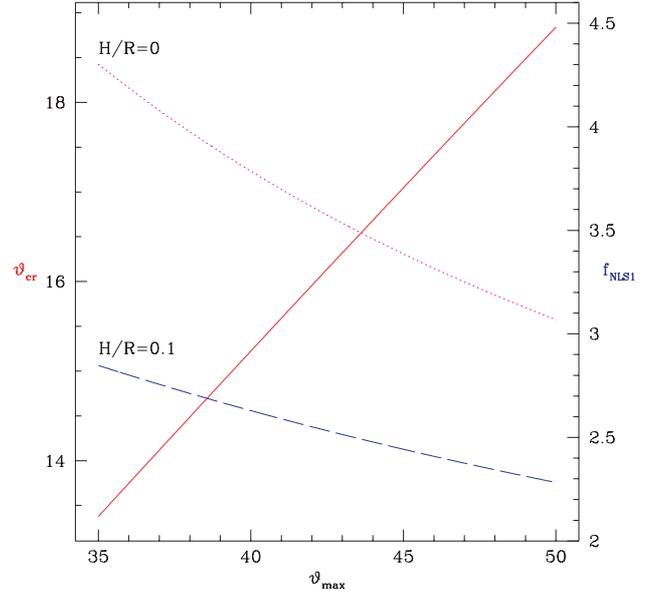


Figure 1. The dependence of ϑ_{cr} (red, solid line) and f_{NLS1} on ϑ_{max} . The blue dashed line and the magenta dotted line refer to values of f_{NLS1} calculated assuming $H/R = 0.1$ and 0 , respectively.

ϑ of the disc as

$$f = \left[2 \sqrt{\left(\frac{H}{R}\right)^2 + \sin^2 \vartheta} \right]^{-1}. \quad (4)$$

The ratio H/R is related to the relative importance of isotropic (e.g. turbulent) versus rotational motions.

The average geometrical factor for each class, f_{NLS1} and f_{BLS1} , is computed by averaging equation (4) over the relevant solid angle ($0 < \vartheta < \vartheta_{\text{cr}}$ for NLS1s, $\vartheta_{\text{cr}} < \vartheta < \vartheta_{\text{max}}$ for BLS1s).

Fig. 1 shows the dependence of ϑ_{cr} and f_{NLS1} on ϑ_{max} , with $35^\circ \lesssim \vartheta_{\text{max}} \lesssim 50^\circ$. The critical angle ranges between 13° and 19° , while f_{NLS1} is found between $\simeq 3$ and 4.5 in the limit $H/R = 0$, and between $\simeq 2.2$ and 2.9 for $H/R = 0.1$. We also find $0.9 \lesssim f_{\text{BLS1}} \lesssim 1.2$ independently of $0 < (H/R) < 0.1$.

We adopt a fiducial value $\vartheta_{\text{max}} = 40^\circ$, leading to $f_{\text{NLS1}} \simeq 3.8$ and $\simeq 2.6$ for $H/R = 0$ and 0.1 , respectively, and $f_{\text{BLS1}} \simeq 1$.

The new estimates of the geometrical factor allow us to reconsider the values of M_{BH} for the sample of Sy1s presented in Grupe & Mathur (2004a), who instead employed a fixed $f = \sqrt{3}/2$ for all objects. Our results are shown in Fig. 2. In the upper panel, the blue long-dashed (magenta dotted) line refers to the corrected M_{BH} of NLS1s for $H/R = 0.1$ ($H/R = 0$). NLS1 black hole masses are increased by $\simeq 0.84$ ($\simeq 1.16$) dex, while BLS1 black hole masses by a mere $\simeq 0.05$ ($\simeq 0.07$) dex, with respect to the Grupe & Mathur values. The mass distributions for the two classes are now remarkably similar, without any significant difference between NLS1s and BLS1s.

The lower panel of Fig. 2 shows the BLS1 and NLS1 populations in the $M_{\text{BH}}-\sigma_*$ plane. The black empty circles refer to BLS1s, assuming $f_{\text{BLS1}} \simeq 1$. The red, solid squares are NLS1s for $f_{\text{NLS1}} = \sqrt{3}/2$, while the blue solid triangles refer to the NLS1s after the correction described in the text is applied, assuming $H/R = 0.1$. The estimates of σ_* are from Grupe & Mathur (2004a), and are derived from $[\text{O III}]$ linewidth. It should be noted that, as Botte et al. (2005) and Komossa & Xu (2007) pointed out, the $[\text{O III}]$ surrogate

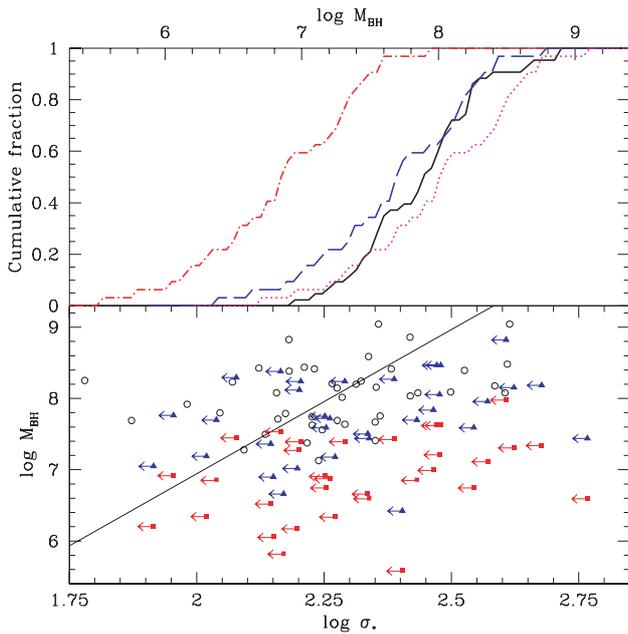


Figure 2. Upper panel: the cumulative fraction distribution of Grupe & Mathur (2004a) sample as a function of M_{BH} . The black, solid line refers to BLS1s, after applying our correction. The red, dot-dashed line refers to NLS1s with $f_{\text{NLS1}} = \sqrt{3}/2$. The blue dashed and the magenta dotted lines refer to NLS1s assuming $H/R = 0.1$ and 0 , respectively. Lower panel: the distribution of the Grupe & Mathur (2004a) sample on the $M_{\text{BH}}-\sigma_*$ plane. The black empty circles refer to BLS1s, when $f_{\text{BLS1}} \simeq 1$ is adopted. The red filled squares are NLS1 values, using $f_{\text{NLS1}} = \sqrt{3}/2$. The blue filled triangles refer to the NLS1s after the correction described in the text, assuming $H/R = 0.1$. The arrows highlight that the values of σ_* for NLS1s have to be considered upper limits, as discussed in the text. The Tremaine et al. (2002) relation is also plotted for comparison.

poorly correlates with σ_* measured from stellar absorption lines, so that the plotted σ_* values have to be considered upper limits, as indicated by the arrows. This caveat is particularly important for X-ray selected samples, as the one used here (Marziani et al. 2003), as wind components to [O III] lines may be significant.

We can now estimate the corrected Eddington ratio for the same sample (Grupe 2004). The cumulative fractions of NLS1s and BLS1s versus L/L_{Edd} are shown in Fig. 3. Not surprisingly, having comparable luminosities, and now, comparable masses, NLS1s and BLS1s radiate at the same Eddington ratio. This result supports the pole-on orientation model for NLS1s.

3 DISCUSSION AND CONCLUSIONS

In this Letter, we have assessed the claimed peculiarity of NLS1s within the framework of cosmic evolution of MBHs, and their host bulges. Indeed, the optical properties of NLS1s, their X-ray fast variability and the faintness of their bulges can be accounted for if one admits lower black hole masses and higher accretion rates (in Eddington units) than standard broad-line Seyfert 1 galaxies (BLS1s), placing NLS1s in an early evolutionary stage (Grupe & Mathur 2004a; Grupe 2004; Botte et al. 2004; Zhou et al. 2006; Ryan et al. 2007). If this is true, by observing local NLS1s we can have hints of the infancy of the ubiquitous population of super-MBHs.

We have explored an alternative explanation to the narrowness of $H\beta$ lines in NLS1s, namely, pole-on orientation of a disc-like

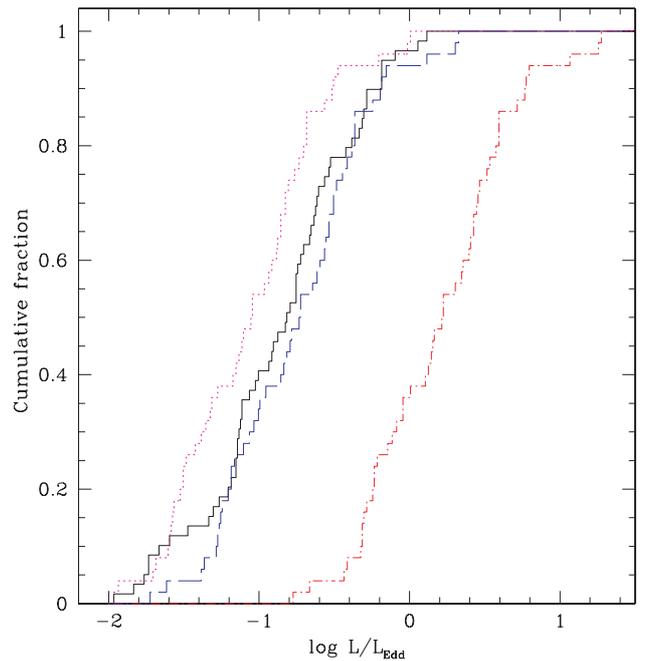


Figure 3. Cumulative fractions of NLS1s and BLS1s as a function of the Eddington ratio. The color/line-type code is the same as in Fig.2 (upper panel).

BLR. If BLS1s and NLS1s differ only by the observation angle of the BLR disc, the frequency of NLS1s among the Sy1 class gives the limiting viewing angle of NLS1s, assuming $H/R \lesssim 0.1$ for the disc, we then computed corrected geometrical factors linking the observed FWHM to M_{BH} , and found $f_{\text{NLS1}} \gtrsim 2$ and $f_{\text{BLS1}} \simeq 1$, in agreement with recent estimates given by Labita et al. (2006). The idea of a disc-like BLR is not new (e.g. Wills & Browne 1986; Vestergaard, Wilkes & Barthel 2000; Bian & Zhao, 2004), but for the first time, by re-calculating masses and Eddington ratios for a sample of Sy1s, we found that mass and luminosity functions are similar for NLS1s and BLS1s. In a sense, we can say that all Sy1s are normal, but some are more ‘normal’ than others.

We note that, though NLS1s seem to lie in the same region of the $M_{\text{BH}}-\sigma_*$ plane, the adopted σ_* values can be largely overestimated (Komossa & Xu 2007; Mullaney & Ward 2007), and then firm conclusions on the $M_{\text{BH}}-\sigma_*$ issue cannot be drawn at this stage.

Can a simple orientation model, as the one we adopted here, explain the unique observed properties of NLS1s? NLS1s differ from standard Sy1s not just in the width of optical lines, but, more notably, in what are their X-ray properties, both spectral and temporal. The X-ray emission of NLS1s has been studied and discussed in great details by, among others, Boller et al. (1996), using *ROSAT* data, and by Brandt, Mathur & Elvis (1997) using *ASCA* data. NLS1s have generally both soft and hard X-ray spectra which are steeper than normal Sy1s, and show large amplitude, rapid variability. Boller et al. (1996) showed how different models, invoking extreme values of one or more of the followings: pole-on orientation, black hole mass, accretion rate, warm absorption, BLR thickness, all explain some aspects of the complex NLS1 soft X-ray phenomenology, but, still, all appear to have drawbacks. McHardy et al. (2006) showed that the break in the X-ray power spectrum density is correlated with the linewidth of type 1 AGNs. In their picture, NLS1s are peculiar AGNs in that they have small $M_{\text{BH}}/(L/L_{\text{Edd}})$ values.

If pole-on orientation has to be the main cause of the uniqueness of the X-ray features of NLS1s, then a necessary condition is that the hard power-law emission is not intrinsically isotropic, for example, a thermal extended corona (as in Haardt & Maraschi 1991, 1993) is not a viable option. Models in which the X-rays of type I radio-quiet AGN are funnelled or beamed have been proposed by several authors (e.g. Madau 1988; Henry & Petrucci 1997; Malzac et al. 1998; Ghisellini, Haardt & Matt 2004). For example, Ghisellini et al. (2004) showed that an aborted jet model, in which X-rays are produced by dissipation of kinetic energy of colliding blobs launched along the MBH rotation axis, can explain the steep and highly variable X-ray power law. The model, in its existing formulation, does not allow clear predictions of spectral and temporal features other than in the X-rays. To assess its relevance for NLS1s would require a much more detailed modelling. In particular, the peculiar Fe II and [O III] properties must be accounted for.

The statistics of radio-loud NLS1s is low. In several works the existence of differences in the radio properties between NLS1s and BLS1s has been discussed (see e.g. Komossa et al. 2006; Zhou et al. 2006; Sulentic et al. 2007; Doi et al. 2007). Doi et al. (2007) suggested that ~ 50 per cent of radio-loud NLS1s are likely associated with jets with high brightness temperatures, requiring Doppler boosting. This interpretation supports the pole-on orientation model (for a different point of view see Komossa et al. 2006).

Our results, if confirmed, indicate that a population of accreting, undermassive MBHs (with respect to the $M_{\text{BH}}-\sigma_*$ relation) has to be found yet. This may suggest that the $M_{\text{BH}}-\sigma_*$ relation was established long ago, during the MBH accretion episodes following the first major mergers of the host galaxies. Moreover, Komossa & Xu (2007) found that NLS1s do follow the $M_{\text{BH}}-\sigma_*$ relation of non-active galaxies, but still they have smaller M_{BH} and larger L/L_{Edd} than BLS1s. If this is the case, then σ_* of the host bulges of NLS1s needs to evolve accordingly in order to preserve the $M_{\text{BH}}-\sigma_*$ relation, or, alternatively, NLS1s are the low-mass extension of BLS1s, and the NLS1 high L/L_{Edd} is a short-lived phenomenon. We note here that the interpretation of Komossa & Xu (2007), as well as the one of Grupe & Mathur (2004a), implies that M_{BH} and L/L_{Edd} , in principle, independent quantities, somehow conspire to produce comparable luminosities as observed in NLS1s and BLS1s. Applying our correction to M_{BH} as well as the one to σ_* proposed by Komossa & Xu (2007), the NLS1s would be even offset towards higher masses with respect to the $M_{\text{BH}}-\sigma_*$ relation.

There are, however, two possible problems with the pole-on orientation model. First, according to the orientation model, the polarization properties of broad emission lines should depend on the inclination angle, in the sense that nearly pole-on Sy1s should not be polarized. However, Smith et al. (2004) found polarized broad lines in few NLS1s, and traces of broad H α polarization were also found by Goodrich (1989) in six out of 17 NLS1s. A second issue is discussed by Punsly (2007), who finds larger line broadening in face-on quasars, possibly due to large isotropic gas velocities or winds.

In conclusion, we found that orientation effects can account for the different optical properties of NLS1s compared to the more common BLS1s. The model is particularly appealing, as it naturally sets masses and accretion rates of NLS1s to fairly standard values. To validate this interpretation, orientation must be able to explain the extreme X-ray properties of NLS1s. Jetted models for radio-quiet AGN may be promising in this, and we urge a detailed, critical comparison of such models with the bulk of NLS1 data.

ACKNOWLEDGMENTS

We wish to thank M. Labita, A. Treves and M. Volonteri for fruitful discussion and suggestions. We also thank the anonymous referee for his/her thorough report and useful comments that improved the quality of our work.

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