Black hole growth by accretion

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Abstract.

We show that black holes grow substantially by accretion at close to Eddington rates. Using a complete sample of soft X-ray selected AGNs, Grupe & Mathur (2004) have shown that narrow line Seyfert 1 galaxies, as a class, lie below the $M_{BH}-\sigma$ relation of normal galaxies. Some NLS1s, however, lie on or close to the $M_{BH}-\sigma$ relation. Here we show that not all NLS1s accrete at close to Eddington rates: those with low $L/L_{Eddington}$ are close to the $M_{BH}-\sigma$ relation, and those with high $L/L_{Eddington}$ are far. With various tests in this paper, we argue that black holes grow in mass substantially in their high-accretion phase and approach the $M_{BH}-\sigma$ relation over time. The mass growth in a low accretion phase, as in BLS1s and also in some NLS1s, appears to be insignificant. Any theoretical model attempting to explain the $M_{BH}-\sigma$ relation will have to explain the above observations.

Key words. Black hole physics – Galaxies: active – Galaxies: evolution – X-rays: galaxies

1. Introduction

The observation of a tight correlation between the velocity dispersion $\sigma$ of the the bulge in a galaxy and the mass of its nuclear black hole $M_{BH}$ was a surprising discovery over the last few years (Gebhardt et al. 2000, Ferrarese & Merritt 2000, Merritt & Ferrarese 2001). Even more surprisingly, the above relation for normal galaxies was also found to extend to active galaxies (Gebhardt et al. 2000, Ferrarese et al. 2001). Moreover, dead black holes were found in the nuclei of all the observed nearby galaxies (e.g. Ho 1999). This was an important result because it implies that nuclear activity was perhaps a part of the life of every galaxy and that the quasar phenomenon is not just a spectacular but cosmologically uninteresting event. A lot of theoretical models attempt to provide explanation for the $M_{BH}-\sigma$ relation in the framework of models of galaxy formation, black hole growth and the accretion history of active galactic nuclei (Haehnelt 2003, Haehnelt et al. 1998, Adams et al. 2001 and King 2003). To understand the origin of the $M_{BH}-\sigma$ relation, and to discriminate among the models, it is of interest to follow the tracks of AGNs on the $M_{BH}-\sigma$ plane.

Mathur et al. (2001) suggested that the narrow line Seyfert 1 galaxies (NLS1s), a subclass of Seyfert galaxies believed to be accreting at a high Eddington rate, do not follow the $M_{BH}-\sigma$ relation. [NLS1s are defined as Seyfert galaxies with full width at half maximum of H$\beta$ lines less than 2000 km s$^{-1}$ (Osterbrock & Pogge 1985)]. This result was later confirmed by Wandel (2002) and Bian & Zhao (2003). Using a complete sample of soft X-ray selected AGNs, Grupe & Mathur (2004, Paper I hereafter) determined black hole mass–bulge velocity dispersion relation for 43 broad line Seyfert 1s and 32 narrow line Seyfert 1s. In all the three papers listed above, the authors use luminosity and FWHM(H$\beta$) as surrogates for black hole mass and FWHM([OIII]) as a surrogate for the bulge velocity dispersion. Grupe & Mathur (2004) found that NLS1s lie below the $M_{BH}-\sigma$ relation of BLS1s, confirming the Mathur et al. (2001) result. The statistical result was robust and not due to any systematic measurement error. As noted by Grupe & Mathur (2004), this result has important consequences towards our understanding of black hole formation and growth: black holes grow by accretion in well formed bulges, possibly after a major merger. As they grow, they get closer to the $M_{BH}-\sigma$ relation for normal galaxies. The accretion is highest in the beginning and dwindles as the time goes by. While a theoretical model to explain all the observations has yet to come, the above result allows to rule out a class of models: e.g. the above result does not support theories of $M_{BH}-\sigma$ relation in which the black hole mass is a constant fraction of the bulge mass/velocity dispersion at all times in the life of a black hole or those in which bulge growth is controlled by AGN feedback. A broad consistency is found with the model of Miralda-Escudé & Kollmeier (2004).

At a first glance, the above result is at odds with the observation that some NLS1s, at the low end of the observed range of velocity dispersion, lie on/close to the $M_{BH}-\sigma$ relation (Mathur et al. 2001, Ferrarese et al. 2001, Bian & Zhao 2003, and...
Fig. 1. Cumulative fraction for a K-S test of \( \frac{L}{L_{\text{Edd}}}, \sigma < 2.25 \) (solid line) and \( \sigma > 2.25 \) (dashed line). The two distributions are clearly different, showing that NLS1s with high \( \frac{L}{L_{\text{Edd}}} \) occupy a distinct region on the \( M_{\text{BH}}-\sigma \) plane.

Grupe & Mathur (2004)). As mentioned above, the Grupe & Mathur (2004) statistical result is robust, in that NLS1s as a class do lie below the \( M_{\text{BH}}-\sigma \) relation of normal galaxies. However, the observation of some NLS1s on close to the relation affects the interpretation of the result. If we are to interpret the observations in terms of black hole growth by the highly accreting NLS1s, why have some NLS1s already reached their “final” mass? In these Research Notes we propose a solution to this apparent contradiction.

2. The Hypothesis

The first hint towards the resolution of the above conflict came from the observation of Williams, Mathur & Pogge (2004). In Chandra observations of 17 NLS1s, they find a correlation between the soft X-ray power-law slope \( \alpha \) and the 1keV luminosity (see also Grupe et al. 2004). It has been known for many years that not all NLS1s have steep soft X-ray spectra (Boller et al. 1996). The results of Williams et al. (2004) and Grupe et al. (2004) have shown that a significant fraction of NLS1s have flat X-ray spectra and those with flatter spectra are preferentially lower luminosity objects (and that absorption is not the cause of the observed flatness of X-ray spectra in most of them).

The paradigm that NLS1s are highly accreting AGNs came from the analogy with X-ray binaries having steep X-ray spectra in high state (Pounds et al. 1995). Theoretical models of accretion disk plus corona also confirmed that a high accretion rate relative to Eddington \( (\dot{m}) \) leads to steep soft X-ray spectra while low \( \dot{m} \) accretion results in flatter spectra (Kuraszkiewicz et al. 2000). The soft X-ray power-law slope was found to correlate strongly with \( \frac{L}{L_{\text{Edd}}} \) in Williams, Mathur & Pogge (2004) and in Grupe et al. (2004). The relatively flatter spectra in some NLS1s suggest that these objects are accreting at a substantially sub-Eddington rate, compared to the NLS1s with steep X-ray spectra. In the framework of the black hole growth scenario of Mathur et al. (2001) and Grupe & Mathur (2004), these objects may then be the ones close to the \( M_{\text{BH}}-\sigma \) relation, as they would have already gone through their high \( \dot{m} \) state and their black holes have accumulated most their mass. In the following section we test this hypothesis.
Fig. 2. Same as figure 2, but for the soft X-ray spectral index $\alpha$. Again, the two distributions are found to be statistically different. Objects with high $L/L_{\text{Eddington}}$ also have steep spectra and are the ones lying below the $M_{\text{BH}}-\sigma$ relation of normal galaxies.

3. Tests

If the above resolution to the black hole growth scenario is correct, then we should find that the NLS1s close to the $M_{\text{BH}}-\sigma$ relation to have low $L/L_{\text{Eddington}}$ compared to those lying below the $M_{\text{BH}}-\sigma$ relation. To test this prediction, we divided our NLS1 sample from Grupe & Mathur (2004) in two parts, with low and high values of $\sigma$ with a boundary at $\log \sigma_{[\text{OIII}]}$=2.25. The choice of the boundary came from the visual inspection of figure 1 of Grupe & Mathur (2004), where it was found that the NLS1s with $\log \sigma_{[\text{OIII}]}$ below this value tended to be much closer to the $M_{\text{BH}}-\sigma$ relation. Figure 1 compares the distribution of $L/L_{\text{Eddington}}$ for the two samples. The values of $L/L_{\text{Eddington}}$ are given in Grupe et al. 2004 and those of $\sigma_{[\text{OIII}]}$ are as in Grupe & Mathur (2004, their figure 4). The Kilogram-Smirnoff (K-S) cumulative distribution for the two samples is significantly different with the formal K-S test probability of being drawn from the same population $P=0.1$. This result is statistical in nature. The error on values of $L/L_{\text{Eddington}}$ for each object, as determined in Grupe et al. 2004, assuming a bolometric correction factor, may be a factor of several. The point to note here is the difference in the two populations with low and high $\sigma$ which correspond to objects close to and away from the $M_{\text{BH}}-\sigma$ relation respectively. Figure 1 thus shows that the objects closer to the $M_{\text{BH}}-\sigma$ relation have lower $L/L_{\text{Eddington}}$ and those lying below the relation have statistically higher $L/L_{\text{Eddington}}$.

One has to be cautious interpreting the above result, because one may obtain high values of $L/L_{\text{Eddington}}$ if black holes masses are underestimated. We have emphasized in Paper I that this is not the case; the BH masses in our sample are unlikely to be systematically underestimated because the relationship between H$\beta$ FWHM and the broad line region radius is well calibrated and extends to NLS1s as well. Secondly, there is no reason for only the high $\sigma$ objects to have the BH masses underestimated. Moreover, BH mass estimates using two completely different methods give the same result: in Mathur et al. 2001, $M_{\text{BH}}$ was determined by fitting accretion disk models to SEDs and in Czerny et al. 2001, power-spectrum analysis was used. Nonetheless another test of the above hypothesis may be a comparison of the X-ray power-law slopes of the two populations of high and low $\sigma$. If our hypothesis is correct, and if steep and flat X-ray spectra result in NLS1s with high and low $L/L_{\text{Eddington}}$ respectively, then we should find that the NLS1s with low values of $\sigma$ i.e. those close to the $M_{\text{BH}}-\sigma$ relation to have flatter $\alpha$ (and lower $\dot{m}$) compared to NLS1s with high values of $\sigma$. In figure 2 we plot the K-S cumulative distribution of $\alpha$ for the two populations, again using the values from Grupe et al. 2004. We find again that the two populations are very different with the low $\sigma$ population having flatter spectra. The K-S test probability of being drawn from the same population is $P=0.2$. 

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It is also interesting to note that the objects with high $\sigma$ are also the ones with large FeII equivalent widths (figure 3). While this fact is not directly related to the proposed BH growth hypothesis, it once again shows that NLS1s is a mixed bag. Only NLS1s with steep X-ray spectra appear to be those with high $L/L_{\text{Eddington}}$ and large FeII equivalent widths.

All these results clearly depend upon the chosen boundary between the low and high $\sigma$ objects. The boundary at $\log \sigma_{\text{OIII}}=2.25$ used above divides the total NLS1 sample of 32 into two subsamples of 18 and 14 objects with low and high $\sigma$ respectively. Moving the boundary significantly either to a lower or higher value of $\sigma$ would result in less than 10 objects in one data set or the other. Nonetheless, to test the robustness of the above results we moved the $\sigma$ boundary to $\log \sigma_{\text{OIII}}=2.3$ which resulted in 20 objects in low $\sigma$ and 12 objects in high $\sigma$ sets. We find that the subsamples are still different with a probability of being drawn from the same population $P=0.2$ for $L/L_{\text{Eddington}}$ and $P=0.3$ for $\alpha$. Even though the significance of the difference goes down away from the middle boundary, the high $\sigma$ objects always have preferentially high $L/L_{\text{Eddington}}$.

As an additional test, we also determined whether the difference $\Delta M_{\text{BH}}$ between expected BH mass (as per the $M_{\text{BH}}-\sigma$ relation) and the observed mass is correlated with $L/L_{\text{Eddington}}$. Using the Spearman rank correlation, we find that $\Delta M_{\text{BH}}$ and $L/L_{\text{Eddington}}$ are correlated to better than 99.9% significance in the entire sample of 75 AGNs in Grupe & Mathur (2004). If $L/L_{\text{Eddington}}$ is proportional to $\dot{m}$, this directly supports the hypothesis of accretion growth of black holes.

4. Discussion

The above tests confirm our hypothesis that NLS1s on/close to $M_{\text{BH}}-\sigma$ relation have flatter $\alpha$ and emit at a lower fraction of their Eddington luminosity. We emphasize again that this result is statistical in nature, and is robust in spite of the large errors on each of the quantities. These results have significant impact on the NLS1 paradigm which we elaborate in Williams et al. (2004); here we concentrate only on the implication for the black hole growth scenario.

The above hypothesis and tests support the scenario first presented in Mathur et al. (2001) and confirmed by Grupe & Mathur (2004): black holes grow in mass substantially in their high accretion phase. As they grow, they approach the $M_{\text{BH}}-\sigma$ relation for normal galaxies. The mass growth in the low accretion phase, as in BLS1s and also in some NLS1s, appears to be insignificant. Any theoretical model attempting to explain the $M_{\text{BH}}-\sigma$ relation will have to explain the above observations.
Needless to say, it is vital to measure $M_{\text{BH}}$ and $\sigma$ accurately to confirm the above result. Black hole mass estimates based on H$\beta$ widths are quite secure, but the same cannot be said about estimates of $\sigma$ based on [OIII] widths. Even if FWHM([OIII]) is not a good surrogate for $\sigma$, the nature of our result is such that $\sigma_{\text{[OIII]}} - \sigma$ will have to be different for BLS1s and NLS1s, and is most likely not the case as discussed in Paper I. Moreover, there is no observational result to support such a difference. If NLS1s had larger outflows, then they could have disturbed their narrow lines regions more compared to BLS1s. Again, there are no observations supporting such a case; on the contrary, absorbing outflows are seen less often in NLS1s (Leighly 1999). Larger $L/L_{\text{Eddington}}$ in NLS1s does not necessarily imply larger effective radiation pressure. On the contrary, in objects with large soft X-ray excesses, like NLS1s, the absorbed radiation is actually much smaller (Morales & Fabian 2002). There is also a general lore that highly accreting sources with large $\dot{m}$ should have large outflows. While low efficiency accretion must lead to outflows (as in ADIOS, Blandford & Begelman 1999), the same is not true for efficient accretion as in bright Seyferts and quasars. Large outflows are observed in highly accreting sources like broad absorption line quasars (BALQSOs), but that depends upon the ratio of gas supply to Eddington accretion rate, and is not inherent to the accretion process itself (R. Blandford, private communication).

Bulge velocity dispersion is usually measured with CaII triplet line and this technique has been used to measure $\sigma$ in two NLS1s (Ferrarese et al. 2001). However, for many of the NLS1s in our sample, the CaII lines fall in the water vapor band in the Earth’s atmosphere. In many NLS1s for which CaII line is accessible from ground, CaII is observed in emission rather than in absorption (Rodriguez-Ardila et al. 2002). This makes the use of CaII absorption features to determine $\sigma$ difficult for the targets of interest. We plan to use two different methods for alternative estimates of $\sigma$: (1) use the CO absorption band-head at 2.29 microns to measure $\sigma$ directly; and (2) use high resolution imaging of NLS1 host galaxies to measure surface brightness distribution of bulges. One can then use fundamental plane relations to determine $\sigma$. Alternatively, we will determine the bulge luminosities and find the locus of NLS1s on the $M_{\text{BH}}$–$L_{\text{bulge}}$ relation. Once again, the objective is to find out if there exists a statistical difference in the relation between black hole mass and bulge luminosity for the two populations of BLS1s and NLS1s. We plan to use all these methods to determine the locus of highly accreting AGNs on the $M_{\text{BH}}$–bulge relations and so fully understand the role of accretion on black hole growth.

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