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Eddington ratios of faint AGN at intermediate redshift

Evidence for a population of half-starved black holes

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Abstract. We use one of the deepest spectroscopic samples of active galaxy nuclei (AGN) currently available, extracted from the VIMOS VLT Deep Survey (VVDS), to estimate the masses and accretion ratios of super-massive black holes (SMBH) at intermediate redshifts. We find that the mass-luminosity relation at $z > 1$ shows considerably enhanced dispersion towards low AGN luminosities ($\log L_{\rm bol} \sim 45$). At these luminosities, there is a substantial fraction of BHs accreting far below their Eddington limit ($L_{\rm bol}/L_{\rm Edd} < 0.1$), in marked contrast to what is generally found for AGN of higher luminosities. We speculate that these may be AGN on the decaying branch of their light-curves, well past their peak activity. This would agree with recent theoretical predictions of AGN evolution.

1. Introduction

The mass scaling relations of SMBHs in present-day galaxies imply that BH growth must be closely connected to the overall formation and evolution of galaxies. Most of the mass locked up in BHs today was probably accumulated through accretion in discrete phases of nuclear activity, as suggested by the consistency between the estimate of the BH mass density at $z \approx 0$ and that derived from the integrated AGN luminosity density.

Accretion histories of individual BHs are essentially unconstrained from observations. By looking at AGN one may at least catch snapshots of the BH growth process, especially when BH masses and thus accretion ratios can be estimated. There has been significant progress in this direction over the last years, and it has been demonstrated that single-epoch spectroscopic and photometric measurements of AGN with broad emission lines (type 1 AGN) allow one to estimate BH masses to an accuracy of the order of ±0.5 dex.With this approach it has been possible to explore the distribution of accretion ratios for large AGN surveys.

These studies have shown that powerful type 1 AGN appear to accrete at ratios close to the Eddington limit with remarkable uniformity. Yet, periods of activity must be followed by a transition from states of high-luminosity near-Eddington to almost quiescent BHs. Unless this transition is rather abrupt, there should therefore also be a population of AGN of significantly lower accretion ratios, but still recognizable as bona-fide AGN. In this paper we report on observations of such a population at intermediate redshifts, based on BH mass estimates that we derive for a new sample of faint AGN with complete spectroscopic identification.

2. The sample

A detailed description of our sample, BH masses and Eddington ratio estimates is provided in Gavignaud et al. (2008).

The VVDS (VLT-VIMOS Deep Survey) is a purely I-band flux limited spectroscopic survey designed to study the evolution of galaxies, AGN, and large scale structure. It comprises a 'deep' survey with a limit of $I_{AB} \leq 24$ (Le Fèvre et al. 2005) and a 'wide' survey with $I_{AB} \leq 22.5$ (Garilli et al. 2008). About 1 % of all VVDS targets were classified as type 1 AGN on the basis of their broad emission lines. The two advantages over most other surveys of the resulting AGN sample is: (i) a very faint limiting magnitude; and (ii) a selection function free of morphological or color preselection biases. The initial sample used for this work contains 222 and 76 AGN respectively in the 'wide' and the 'deep' survey.

Black hole masses: we have then selected objects with visible Mg II ($1.0 \lesssim z \lesssim 1.9$) or C IV ($2.6 < z < 4.3$) broad emission-line and used the virial relation calibrated by McLure & Dunlop (2004, for Mg II) and Vestergaard & Peterson (2006, for C IV).

Bolometric luminosities were derived from the monochromatic ones, multiplied by a correction luminosity dependant factor $f_{\rm bol}$, derived from Hopkins et al. (2007) empirical model of AGN SED.

3. Results

The distribution of the inferred BH masses versus bolometric luminosities is shown Fig. 1a. As expected, there is a trend of $M_{\rm BH}$ increasing with $L_{\rm bol}$. However, the trend is not consistent with the assumption of $L_{\rm bol} \propto M_{\rm BH}$, i.e. with an Eddington ratio ϵ independent of AGN luminosity. This is highlighted in Fig. 1b, where we plot ϵ versus $L_{\rm bol}$ for the same objects.

The large number of low-ϵ AGN at low luminosities produces an apparent trend of ϵ increasing with $L_{\rm bol}$. A formal regression gives $\log\epsilon \propto 0.29 \log L_{\rm bol}$. We caution however against an over interpretation of that trend, as our sample covers only a limited range of luminosities. Moreover, as discussed below, the slope of the relations depends on the choice of the exponent of the empirical luminosity-size relation adopted in the virial scaling relations. The linear-Pearson correlation coefficient between $\log L_{\rm bol}$ and $\log\epsilon$, $r = 0.40$, indicate a somewhat mild correlation.

These results are based mainly on the Mg II subsample and thus hold for redshifts around $z \simeq 1.5$. In the overlapping luminosity range, our high redshift sample have similar mean accretion rates or BH masses. However the high redshift objects seem to follow a steeper $\log\epsilon \propto \alpha \log L_{\rm bol}$ and a tighter relation ($\alpha = 0.40$, $r = 0.75$) than the low redshift sample ($\alpha = 0.22$, $r = 0.24$). In fact, the difference of slope α between the two samples disappears if one adopts scaling relations with the same luminosity exponent γ. However the correlation remain much stronger for the C IV objects than for the Mg II objects (which show more scatter).

We now consider possible sources of systematic errors, starting with sample incompleteness. Obviously, a selection bias against low mass BHs with high Eddington ratios would depopulate the lower left part of the left panel in Fig. 1, where AGN with high ϵ would be located. AGN with low $M_{\rm BH}$ and high ϵ are characterized by relatively narrow emission lines. As the VVDS AGN sample is defined through the detection of broad emission lines in low-resolution spectra, such a selection bias can in principle exist. However, we expect the

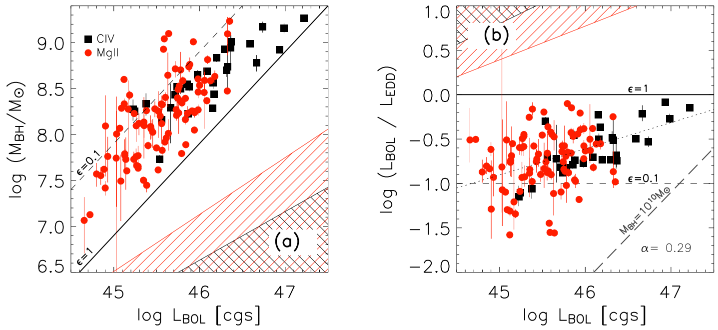

Fig. 1. Distribution of inferred BH masses (left) and Eddington ratios (right) versus AGN bolometric luminosities for the VVDS sample. Error bars correspond to our uncertainties on the line width measurements. Inside the hashed regions, AGN would have emission lines with FWHM < 1000 kms^{-1} implying that they would have been missed in our sample. The dotted line in panel b shows a linear regression relation.

sample to be complete for lines intrinsically broader than $\sim$ 1000 kms^{-1}. The areas of incompleteness are marked Fig. 1 as hashed regions. It is clear that the lack of high ϵ objects among the low luminosity AGN cannot predominantly be due to limited spectral resolution.

Since we are probing the AGN population down to low luminosities, host galaxy contamination could cause us to over-estimate AGN continuum luminosities. This would lead to an overestimation of BH masses ($M_{\mathrm{BH}} \propto L^{\gamma}$) as well as Eddington ratios ($\epsilon \propto L^{1-\gamma}$). We use here the result of the SED analysis presented in Bongiorno et al. (2007) to estimate the host galaxy contribution to the total continuum flux. We find that host contamination at 1500 Å is negligible for all our objects. At 3000 Å, $\sim$ 30% of the low luminosity AGN, are likely to have smaller Eddington ratios than our above estimates, strengthening our conclusions.

4. Discussion and conclusions

The main result of our study is a marked increase of the dispersion in Eddington ratios towards lower AGN bolometric luminosities. A substantial fraction of BHs in low-L AGN accretes at less than 10 % of their Eddington limits, whereas such low accretors are rare among AGN with higher L. Babić et al. (2007) argue that this trend as a function of luminosity is expected if one convolves a double power-law BH mass function with a relatively broad distribution of Eddington ratio truncated at $\epsilon = 1$. While this may be an important effect, a careful disentangle of the BH mass function and intrinsic distribution of Eddington ratio would require a sample covering a large luminosity baseline at a given redshift range and is beyond the scope of this paper.

Kollmeier et al. (2006) determined BH masses for a sample of $\sim$ 400 AGN with optical magnitudes $R \leq 21.5$, in the context of the AGES survey. Their compilation shows a nearly constant Eddington ratio of $\sim$ 0.25, with a dispersion of only $\sim$ 0.3 dex, over a wide range of luminosities and redshifts. Our lower redshift sample overlap with their Mg II virial masses in the luminosity range 45 to 46 $\mathrm{erg\,s}^{-1}$. If we superficially compare their results with ours in this range, we find them to be marginally inconsistent. However we could observe that this difference is only caused by the different recipes we used to estimate bolometric luminosities, and in particular, black hole masses. In particular, Kollmeier et al. (2006) adopted a very steep exponent for the empirical luminosity-size relation for the Mg II emission line, $\gamma = 0.88$ ($R \propto L^{\gamma}$), whereas we employed $\gamma = 0.62$.. A larger γ makes the L_{bol}-M_{BH} relation appear steeper and results into smaller

$M_{\rm BH}$ and higher ϵ for the lower luminosity AGN. However, we believe that there are good reasons against such a high value of γ. Recent reverberation mapping studies suggest a rather flat luminosity-size relation with γ even approaching 0.5 (corresponding to an approximately luminosity-independent ionization parameter in the broad-line region of AGN). Our adopted value may therefore even be considered conservative.

Recently, Netzer et al. (2007) also found a positive trend of ϵ with luminosity. The strength of that work is that it is based on virial BH masses derived from the Hβ line observed in the infra-red. Indeed, non-gravitational effects, such as radiation pressure and obscuration, are probably affecting C IV emission lines , and the Hβ emission line is recognized as a better indicator of AGN BH masses (e.g. Baskin & Laor 2005).

The overlap in term of luminosity of our samples is quite limited, but if we take into account the difference of bolometric correction in between our analysis, we find an excellent agreement for our results.

At any fixed redshift, the AGN luminosity function (AGNLF) is generally described as a double power-law. It has now become clear that its shape evolves with redshift, with a marked break for $z > 1$ which almost disappears at lower redshift, as the faint-end slope steepens towards later cosmic times (e.g. Hasinger et al. 2005). The luminous part of the AGNLF seems to be dominated by BHs typically accreting close to the Eddington limit ($\epsilon \sim 0.1$–1), with relatively little dispersion, so that luminosities are roughly proportional to BH masses, and this part of the AGNLF closely mirrors the BH mass function. From an analysis of low redshift ($z < 1$) AGN, Woo & Urry (2002) find that small Eddington ratios are found mainly for $\log L_{\rm bol} \leq 44.5$, which in their sample is fulfilled only by 'local' Seyfert galaxies at $z \leq 0.1$. Comparing their results with our measurements at $z \gtrsim 1$ suggests that the luminosity below which small Eddington ratios are found may evolve with redshift. This is, at least qualitatively, consistent with the observed redshift evolution of the break of the AGN luminosity function.

In the context of a model where BH growth and nuclear activity is triggered by galaxy mergers, Cattaneo (2001) suggested that the faint end slope of the AGNLF could be dominated by objects observed in the decaying phase of their light curve, well past their peak of activity. This idea was recently followed up by numerical simulations of galaxy mergers incorporating AGN feedback (Hopkins et al. 2006).

Our observations are consistent with such a picture. While some of the low-luminosity AGN in our sample have just low $M_{\rm BH}$, many have instead the properties (i.e. high $M_{\rm BH}$, low ϵ) predicted by these models. We suggest that at these redshifts we see glimpses of a population of AGN with BH masses similar to those of luminous quasars, but already half starved and on their way to get extinguished.

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