The correlation of black hole mass with metallicity index of host spheroid

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ABSTRACT

We investigate the correlation between the mass of the supermassive black holes (SMBHs) and metal abundance, using existing data sets. The SMBH mass $M_{bh}$ is well correlated with integrated stellar feature of Mgb. For 28 galaxies, the best-fit $M_{bh}$-Mgb relation has a small scatter, which is an equivalent level with other well-known relation, such as a correlation between the stellar velocity dispersion and the mass. An averaged iron index $\langle Fe \rangle$ also positively correlates with $M_{bh}$, but the best-fit $M_{bh}$-$\langle Fe \rangle$ relation has a larger scatter. The difference comes from the synthesis and evolution mechanisms, and may be important for the SMBH and star formation history in the host spheroid.

Key words: black hole physics – galaxies:bulges – galaxies:abundances.

1 INTRODUCTION

Recent observations of nearby massive spheroids (ellipticals, lenticular and spiral bulges) have established that supermassive black holes (SMBHs) are present in the nuclei of galaxies. The mass $M_{bh}$ of SMBHs ranges from $10^6$ to $10^9 M_\odot$. Several statistical correlations with characteristic parameters of the host spheroids are explored: relation with the luminosity $L$ (Kormendy & Richstone 1995, Marconi & Hunt 2003, Graham 2007), the mass $M_s$ of the spheroids (Magorrian et al. 1998, Haring & Rix 2004), the stellar velocity dispersion $\sigma$ (Gebhardt et al. 2000, Ferrarese et al. 2000, Tremaine et al. 2002), the light concentration or Sérsic index $n$ (Graham et al. 2001, Graham & Driver 2007), gravitational binding energy $E_g$ (Aller & Richstone 2007) and so on. The recent updated survey for various galaxy parameters is given in Aller & Richstone (2007). If the fitting models are good, the correlations may provide some clues to the coevolution of SMBHs and the host spheroids. Some tentative theories have been proposed to clarify the origin of these correlations, e.g., Silk & Rees (1998); Umemura (2001).

The galaxies have some aspects as an assemble of stars, gases and dark matters. The quantities $M_s$, $\sigma$, $E_g$ represent the dynamical aspect, while $L$, $n$ represent the photometric one, although they are closely related each other. Very little attention is paid to the chemical one. The observation is not so easy and therefore the correlation between SMBH mass and spheroid chemical property is not well studied so far. Both the metal abundance and black hole mass increase with time and we therefore expect some correlations between them. It is important to clarify the correlation, and the extent, if any. The chemical parameter using Lick/IDS absorption line indices, e.g., Worthey et al. (1994), especially Mg and Fe is systematically studied in literatures Trauger et al. 2006, Denicoló et al. 2005, Kuntschner et al. 2006 for the galaxies in which presence of SMBH is reliable. Using the published data, we investigate the correlation with SMBH mass in this paper.

As a sample we select only 28 galaxies, for which SMBH masses are measured by dynamical methods. In section 2, we describe the sample of galaxies and criterion of our choice. In section 3, we derive the correlation between $M_{bh}$ and $\sigma$, and that between $M_{bh}$ and the B-band magnitude $M_B$ from our sample. These correlations are known to be good, and are used in order to check no serious bias involved in the sample. Our results for $M_{bh}$-$\sigma$ and $M_{bh}$-$M_B$ relations are not so different from those by Aller & Richstone (2007), Graham (2007), although the source sample is not the same. We also show the correlation between black hole mass and metal abundance index using our sample. Finally, a discussion of our results is given in section 4.

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The sample consists of 28 nearby galaxies, which are listed in Table 1. We put two criteria to pick up the sample from literatures. First, the BH masses are measured by good spatial resolution. The sources are limited to $M_{bh} > \sigma^2 r_{es}/(2G)$, where $\sigma$ is stellar velocity dispersion, $r_{es}$ the instrumental spatial resolution. This condition is used by e.g., Marconi & Hunt (2003); Hu (2008). Second, metal indices of Mg or Fe are measured. Most of our sample corresponds to that of Tremaine et al. (2002). 21 galaxies are drawn from their table and 7 galaxies are added: NGC 2974, NGC 3414, NGC 4552, NGC 4621, NGC 5813 and NGC5846 from Cappellari et al. (2007); Hu (2008), and NGC 4374 from Maciejewski & Binney (2001). The masses of SMBHs are updated for 3 galaxies, NGC 224 (Bender et al. 2003), NGC 821 (Richstone et al. 2004) and NGC 3379 (Shapiro et al. 2004). The galaxy morphology class is also listed in Table 1 from the NASA Extragalactic Database (NED). However, some corrections are added to the data: NGC 4564 (Tritillo et al. 2004) and NGC 221 (Graham 2002) are now recognized as SO galaxies. In Table 1, effective velocity dispersion $\sigma$ is tabulated as an indicator of the dynamical parameter of spheroids. Following Tremaine et al. (2002), the relative errors in $\sigma$ are estimated as 5% (0.021 dex). As the photometric parameter of spheroids, the B-band magnitude $M_B$ is tabulated. Following Graham (2007), the relative errors in $M_B$ are 0.3
mag. For the chemical parameter of spheroids, we use spectral absorption line indices in the visual as defined by the Lick group, e.g., [Burstein et al. 1984]; [Faber et al. 1983]. Lick indices have proven to be a useful tool for the derivation of ages and metallicity of unresolved stellar populations [Dencil’o et al. 2005]. In this paper, we use Mgb, Fe5270, Fe5335 indices, measuring respectively the strength of MgI at \( \lambda \approx 5197 \) Å, Fe at \( \lambda \approx 5246 – 5286 \) Å and Fe at \( \lambda \approx 5312 – 5352 \) Å. These indices in mag are calculated by the standard equations:

\[
EW_{\text{mag}} = -2.5 \log \left( \frac{\int \lambda^2 [F(\lambda)/C(\lambda)] d\lambda}{\lambda_2 - \lambda_1} \right),
\]

where

\[
C(\lambda) = F_r \frac{\lambda - \lambda_b}{\lambda_r - \lambda_b} + F_i \frac{\lambda_r - \lambda_b}{\lambda_r - \lambda_i}
\]

and \( \lambda_r \) and \( \lambda_i \) are the mean wavelength in the blue and red pseudo-continuum intervals, respectively. We have adopted the spectral pseudocontinuum and band passes of the Mgb, Fe5270, Fe5335 Lick/IDS indices defined in [Worthey et al. 1994]. We use a combined “iron” index, \((Fe)\) defined by

\[
\langle Fe \rangle \equiv \frac{1}{2} (Fe5270 + Fe5335).
\]

This index has smaller random error than either that of Fe5270 or that of Fe5335 [Gorgas, Efstathiou & Aragon-Salamanca 1990]. These index values used from the literature, are the measurements within the central region \( r < r_c/8 \), where \( r_c \) is effective radius of the spheroids. The properties of the spheroids and SMBHs are listed with their references in Table 1.

3 RESULTS

In order to fit the data to the linear relation \( y = a + bx \), we use a version of the routine FITEXY [Press et al. 1992] modified by [Tremaine et al. 2002]. [Novak et al. 2006] showed that this algorithm is the most efficient and least biased among a set of algorithms explored by them. The best-fit values \( a \) and \( b \) are calculated from data \( (x_i, y_i) (i = 1, \cdots, N) \) by minimizing the quantity

\[
\chi^2 = \sum_{i=1}^{N} \frac{(y_i - a - bx_i)^2}{\delta y_i^2 + \sigma^2 + b^2 \delta x_i^2},
\]

where \( \delta x_i \) and \( \delta y_i \) are the measurement uncertainty in \( x_i \) and \( y_i \). We use a constant value of 5% (0.021 dex) for velocity dispersion \( \sigma \), and 0.3 mag for the B-band magnitude \( M_B \). The uncertainty for the metal abundance is listed in Table 1, and is used for each source. The intrinsic scatter \( \epsilon \) in the linear relation is calculated when the reduced chi-squared value \( \chi^2/(N - 2) \) is equal to 1, after many trials to fit it for various \( \epsilon \). The upper and lower uncertainties of \( \epsilon \) are estimated by the values for \( \chi^2/(N - 2) = 1 \pm \sqrt{2/N} \).

3.1 Dynamical and Photometric Properties

In order to check the dependence on the sampling data, we derive \( M_{bh-\sigma} \) and \( M_{bh-M_B} \) relations from our sample. First, for the dynamical aspect, we show a relation between the SMBH mass and the stellar velocity dispersion derived from Table 1. Our result of \( M_{bh-\sigma} \) relation is given by

\[
\log(M_{bh}/M_\odot) = (3.98 \pm 0.35) \log(\sigma/200) + 8.23 \pm 0.06
\]

with \( \epsilon = 0.25^{+0.09}_{-0.06} \) dex in \( \log(M_{bh}) \). This relation is consistent with previous relations. For example, recent updated one by [Aller & Richstone 2007] using a sample of 23 galaxies is

\[
\log(M_{bh}/M_\odot) = (3.79 \pm 0.32) \log(\sigma/200) + 8.16 \pm 0.06
\]

with \( \epsilon = 0.23 \) dex. Figure 1 shows our \( M_{bh-\sigma} \) relation [3] in comparison with [6].

Next, for the photometric aspect, we derive the \( M_{bh-M_B} \) relation. Our result is

\[
\log(M_{bh}/M_\odot) = (-0.42 \pm 0.05)(M_B + 19.5) + 8.14 \pm 0.08
\]

with \( \epsilon = 0.36^{+0.07}_{-0.05} \) dex [Graham 2007] obtained

\[
\log(M_{bh}/M_\odot) = (-0.40 \pm 0.05)(M_B + 19.5) + 8.27 \pm 0.08
\]

We have also derived the relation of \( M_{bh} \) with the K-band magnitude, but there is no significant difference in the scatters of both relations.
Figure 1. Relationship between SMBH mass and effective stellar velocity dispersion for 28 galaxy samples. The solid line represents our best fit relation (5). For a comparison, the relation by (Aller & Richstone 2007) is shown by a dashed line. Elliptical galaxies are denoted by open circles, lenticulars and spirals by filled circles.

Figure 2. Relationship between SMBH mass and absolute B-band luminosity of the spheroid for 28 galaxy samples. The solid line represents our best fit relation (7). For a comparison, the relation found by (Graham 2007) is shown by a dashed line. The symbols are the same as Figure 1.

Figure 3. Relationship between SMBH mass and Mgb index value within a circular aperture of \( r_e/8 \) for our samples. The symbols and line are the same as in Figure 1.

Figure 4. Relationship between SMBH mass and \( \langle \text{Fe} \rangle \) index within \( r_e/8 \) for our samples. The symbols and line are the same as in Figure 1.

with \( \epsilon = 0.30^{+0.04}_{-0.03} \) dex. Although intrinsic scatter in our relation is a little high, both two relations agree within the uncertainties. Both relations (7) and (5) are plotted in Figure 2. By comparing with previous results, we may say that there is no serious bias in our sampling data.

3.2 Chemical Property

In Figure 3, we plot \( M_{bh} \) as a function of the integrated stellar feature of Mgb for the 28 galaxies. It is found that the mass \( M_{bh} \) significantly correlates with the index Mgb. The best fit relation is obtained as

\[
\log(M_{bh}/M_\odot) = (27.23 \pm 3.00)(\text{Mgb} - 0.16) + 8.13 \pm 0.07
\]

with \( \epsilon = 0.32^{+0.06}_{-0.04} \) dex. The scatter is not so bad as that of well-fitted \( M_{bh}-\sigma \) and \( M_{bh}-M_B \) relations. The index Mgb is a good indicator, but other indicator of the metal abundance is not so good. We have tested the correlation with different index. For instance, we show \( M_{bh} \) as a function of \( \langle \text{Fe} \rangle \) index in Figure 4. The best fit relation is

\[
\log(M_{bh}/M_\odot) = (60.25 \pm 26.01)(\langle \text{Fe} \rangle - 0.083) + 8.34 \pm 0.13
\]

with \( \epsilon = 0.58^{+0.12}_{-0.07} \) dex. This relation has much larger scatter than that of eqs.(5)-(9). It is clear from Figure 4 that the index \( \langle \text{Fe} \rangle \) is not good one. Summarizing the relationships obtained in our own study, we find that \( M_{bh}-\sigma \) is the best, \( M_{bh}-\text{Mgb} \) and \( M_{bh}-M_B \) are moderate, and \( M_{bh}-\langle \text{Fe} \rangle \) is the worst.

4 DISCUSSION

We have shown that a good correlation between SMBH mass and Mgb index value. The best-fitting \( M_{bh}-\text{Mgb} \) relation has small intrinsic scatter 0.32 dex which is comparable one in other strong correlations found so far. Such a new correlation in
The correlation of black hole mass with metallicity index

The chemical aspect is expected through other relations in dynamical/photometric aspects. The metal abundance is roughly correlated with total stellar mass, absolute magnitudes etc. e.g., \cite{Page1997}. In particular, there is a remarkably tight relation between Mg$_2$ and the central velocity dispersion of stars \cite{Terlevich1981, Bender1993}. The positive correlations have been found between some quantities characterizing the hosts and SMBH mass. A positive correlation is also suggested between the SMBH mass and the metallicity derived from emission line ratios in 578 AGNs spanning a wide range in redshifts \cite{Warner2003}. Our result of Mgb for nearby galaxies is more tight. Thus, positive correlation is expected, but the degree was not clear beforehand. It was not clear which indicators of the metal abundance strongly correlate with the SMBH mass. The index $\langle Fe \rangle$ correlates with it, but the intrinsic scatter is not so small as that of Mgb. Heavy elements Mg and Fe are synthesized by two different types of supernovae (Type Ia and II), with different time scales. This evolutionary difference causes the scatter in the correlations.

The growth of black hole mass is mainly determined by the accretion rate and the lifetime of the activity. The environmental factors near the central region of galaxies may partially be affected by some global quantities, such as the mass and size of the host. If the mass $M_{bh}$ of SMBH is determined solely by the spheroid mass $M_s$ as $M_{bh} = \epsilon M_s$ ($\epsilon \sim 10^{-5}$), then we have $M_{bh} \propto M_s \propto L \propto \sigma^4$, where we assume that a constant mass-to-light ratio and the Faber-Jackson relation in elliptical galaxies hold in the spheroids. The features in the host spheroids are transferred to the relations with the black hole mass, $M_{bh}$-$L$ and $M_{bh}$-$\sigma$ relations. Other features in the hosts, binding energy, light concentration and so on also give some relations with $M_{bh}$ \cite{Bender1993}. They discuss that the strength of Mg$_2$ is determined not only by the global mass $M_s$, but also by the local stellar density, which is related with the star-formation rate etc. It is therefore important to examine the correlation of $M_{bh}$ with the other physical quantities of the spheroid, in addition to $M_s$. The metal abundance is a tracer for integrated stellar populations. The tight relation $M_{bh}$-Mgb, which is discovered here but is still tentative, may be useful for the better understanding of the coevolution of SMBH and host spheroid, if it is not accidental. Further work is needed to clarify whether this relation is fundamental or not.

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