HOKKAIDO UNIVERSITY

Title	The impact of dust in host galaxies on quasar luminosity functions
Author(s)	Shirakata, Hikari; Okamoto, Takashi; Enoki, Motohiro et al.
Citation	Monthly notices of the royal astronomical society, 450(1), L6-L10 https://doi.org/10.1093/mnrasl/slv035
Issue Date	2015-06-11
Doc URL	https://hdl.handle.net/2115/59549
Rights	This article has been accepted for publication in Monthly Notices of the Royal Astronomical Society ©: 2015 The Authors Published by Oxford University Press on behalf of The Royal Astronomical Society. All rights reserved.
Type	journal article
File Information	MNRAS-2015-450_L6-L10.pdf

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **450,** L6–L10 (2015) doi:10.1093/mnrasl/slv035

The impact of dust in host galaxies on quasar luminosity functions

Hikari Shirakata,[1]★ Takashi Okamoto,[1] Motohiro Enoki,[2] Masahiro Nagashima,[3] Masakazu A. R. Kobayashi,[4] Tomoaki Ishiyama[5] and Ryu Makiya[6]

[1]*Department of Cosmosciences, Graduates School of Science, Hokkaido University, N10 W8, Kitaku, Sapporo 060-0810, Japan*
[2]*Faculty of Business Administration, Tokyo Keizai University, Kokubunji, Tokyo 185-8502, Japan*
[3]*Faculty of Education, Bunkyo University, Koshigaya, Saitama 343-8511, Japan*
[4]*Research Center for Space and Cosmic Evolution, Ehime University, Matsuyama, Ehime 790-8577, Japan*
[5]*Center for Computational Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan*
[6]*Institute of Astronomy, The University of Tokyo, Mitaka, Tokyo 181-0015, Japan*

Accepted 2015 February 23. Received 2015 February 23; in original form 2014 December 3

ABSTRACT

We have investigated effects of dust attenuation on quasar luminosity functions at $z \sim 2$ using a semi-analytic galaxy formation model combined with a large cosmological *N*-body simulation. We estimate the dust attenuation of quasars self-consistently with that of galaxies by considering the dust in their host bulges. We find that the luminosity of the bright quasars is strongly dimmed by the dust attenuation, ∼2 mag in the *B*-band. Assuming the empirical bolometric corrections for active galactic nuclei (AGNs) by Marconi et al., we find that this dust attenuation is too strong to explain the *B*-band and X-ray quasar luminosity functions simultaneously. We consider two possible mechanisms that weaken the dust attenuation. As such a mechanism, we introduce a time delay for AGN activity, that is, gas fuelling to a central black hole starts sometime after the beginning of the starburst induced by a major merger. The other is the anisotropy in the dust distribution. We find that in order to make the dust attenuation of the quasars negligible, either the gas accretion into the black holes has to be delayed at least three times the dynamical time-scale of their host bulges or the dust covering factor is as small as ∼0.1.

Key words: galaxies: active – galaxies: nuclei – quasars: general.

1 INTRODUCTION

The mass of supermassive black holes (SMBHs) correlates with the properties of their host galaxies, such as stellar mass and velocity dispersion of their bulges (e.g. Magorrian et al. 1998; Ferrarese & Merritt 2000; Häring & Rix 2004; McConnell & Ma 2013). These facts suggest that SMBHs have co-evolved with their host galaxies. The most straightforward way to understand the co-evolution is studying the properties of active galactic nuclei (AGNs), which emit light when materials get accreted by the SMBHs.

Quasars are the brightest class of AGNs. There have been many observational studies of AGN luminosity functions in several bands (e.g. Croom et al. 2009, 2001; Ueda et al. 2014). Effects of dust attenuation have also been studied for various classes of AGNs, including quasars (e.g. Sanders et al. 1988; Gaskell & Benker 2007; Lacy et al. 2007). These studies suggest the existence of obscured quasars, which are hidden by the surrounding dust and can be observed only in X-ray. Lacy et al. (2007) suggest that only 33 per cent of luminous AGNs selected based on their mid-infrared colours are unobscured (Type 1) quasars. This picture is in good accord with the simulation results by Hopkins et al. (2005); they suggest that quasars are buried in the dust in merger remnants and only become observable at their late evolutionary stage.

Semi-analytic (SA) galaxy formation models are powerful tools to study rare objects like AGNs theoretically since they can calculate properties of individual galaxies in large cosmological *N*-body simulations. SA models have thus been widely used to investigate AGN properties (e.g. Kauffmann & Haehnelt 2000; Enoki, Nagashima & Gouda 2003; Cattaneo et al. 2005b; Monaco, Fontanot & Taffoni 2007; Lagos, Cora & Padilla 2008; Marulli et al. 2008; Fanidakis et al. 2012; Hirschmann et al. 2012). Many of them considered dust attenuation and attempted to reproduce observed luminosity functions (e.g. Cattaneo et al. 2005b; Fanidakis et al. 2012) by utilizing the empirical relations (e.g. Ueda et al. 2003; Szokoly et al. 2004; Barger et al. 2005; Hasinger 2008). None of them however consider effects of the dust attenuation on quasar luminosity self-consistently with properties of their host galaxies. In order to investigate effects of the dust on quasar luminosity functions self-consistently with galaxy formation, we employ an SA model, based on νGC (Nagashima et al. 2005) that is a galaxy formation model combined with high-resolution cosmological *N*-body simulations

★ E-mail: shirakata@astro1.sci.hokudai.ac.jp

© 2015 The Authors
Published by Oxford University Press on behalf of the Royal Astronomical Society

Downloaded from http://mnrasl.oxfordjournals.org/ at Hokkaido University on July 27, 2015

in a Λ-dominated cold dark matter (ΛCDM) universe. This model well reproduces the quasar luminosity functions around $z \sim 2$ and naturally explains the cosmic downsizing of quasars (Enoki et al. 2014, hereafter E14) together with many observed properties of galaxies (Nagashima et al. 2005). Our model is identical to that used in E14, unless otherwise stated. In this Letter, we consider the dust in quasar host bulges, which attenuates the starlight from the bulge stars during starbursts; the same dust must attenuate the quasars, while this effect has been neglected in our previous studies (Enoki et al. 2003; E14).

This Letter is organized as follows: in Section 2, we briefly review our models for the growth of the SMBHs and AGN luminosity. In Section 3, we present our results that indicate the quasars produced by our model are significantly attenuated by the dust in the host galaxies. We also propose two mechanisms which make the dust attenuation weak. Finally, we summarize and discuss our results in Section 4.

2 MODELLING SMBH GROWTH AND QUASAR LUMINOSITY

We create merging histories of dark matter haloes from a large cosmological *N*-body simulation. The baryonic processes in each halo are calculated by using simple, parametric forms of equations. Throughout this Letter, we assume a ΛCDM universe with the following parameters: $\Omega_0 = 0.2725$, $\Omega_\Lambda = 0.7275$, $\Omega_b = 0.0455$, $\sigma_8 = 0.807$, $n_s = 0.961$ and a Hubble constant of $H_0 = 100\,h\,\mathrm{km\,s^{-1}\ Mpc^{-1}}$, where $h = 0.702$ (Komatsu et al. 2011). Our cosmological *N*-body simulation contains 2048^3 particles within a comoving box size of $280\,h^{-1}$ Mpc. The minimum halo mass is $7.72 \times 10^9\,h^{-1}\,\mathrm{M_\odot}$. Further details can be found in E14 and Ishiyama et al. (2014). In this section, we briefly describe the processes that are most relevant to our study.

2.1 Growth of SMBHs

Galaxies in a common dark matter halo sometimes merge together by dynamical friction or random collisions. When two or more galaxies merge, their central SMBHs also coalesce into a single SMBH. We define a major merger as an event where the mass ratio of the secondary progenitor to the primary one is larger than 0.4. In this case, the cold gas in the merger remnant is converted into stars with a short time-scale and a fraction of it gets accreted by the SMBH. The mass of the cold gas accreted by the SMBH, $M_{\rm acc}$, is given by

$$M_{\rm acc} = f_{\rm BH}\Delta M_{*,\rm burst}, \quad (1)$$

where $\Delta M_{*,\rm burst}$ is the mass of stars that form during the starburst and $f_{\rm BH}$ is a free parameter whose value is set to 0.01 in order to reproduce the observed relationship between bulge mass and black hole mass at $z = 0$ (Häring & Rix 2004; McConnell & Ma 2013).

2.2 AGN luminosity

Assuming that a fixed fraction of the rest mass energy of the accreted cold gas by an SMBH is radiated and that an AGN light curve has an exponentially declining form as in E14, we obtain the bolometric luminosity of an AGN at time t after a major merger as

$$L_{\rm bol}(t) = \frac{\epsilon_{\rm bol} M_{\rm acc} c^2}{t_{\rm life}} \exp(-t/t_{\rm life}), \quad (2)$$

where $\epsilon_{\rm bol}$ is the bolometric radiative efficiency, $t_{\rm life}$ is the AGN lifetime and c is the speed of light. We suppose that the AGN lifetime is proportional to the dynamical time-scale of the bulge,[1] $t_{\rm dyn}$, as $t_{\rm life} = f_{\rm life} t_{\rm dyn}$.

Marconi et al. (2004) propose the bolometric corrections for hard X-ray (2–10 keV), soft X-ray (0.5–2 keV) and *B*-band (hereafter 'Marconi relations'). We obtain hard X-ray luminosity, $L_{\rm X}$ and *B*-band luminosity, L_B from Marconi relations as

$$\log[L/L(2\text{-}10\,\mathrm{keV})] = 1.54 + 0.24\mathcal{L} + 0.012\mathcal{L}^2 - 0.0015\mathcal{L}^3,$$
$$\log(L/\nu_B L_{\nu_B}) = 0.80 - 0.067\mathcal{L} + 0.017\mathcal{L}^2 - 0.0023\mathcal{L}^3, \quad (3)$$

where $\mathcal{L} = (\log L - 12)$ and L is the intrinsic bolometric luminosity in units of $\mathrm{L_\odot}$.

We chose the values of $\epsilon_{\rm bol}$ and $f_{\rm life}$ to match the observed AGN luminosity functions in hard X-ray at $z \sim 2$, at which the comoving number density of the quasars is the highest. We employ $\epsilon_{\rm bol} = 0.1$ and $f_{\rm life} = 1.5$ throughout this Letter. If $t_{\rm life}$ is shortened, then the faint end slope of the AGN luminosity function is shallower and the number of bright AGNs increases as mentioned in Cattaneo (2001) and Enoki et al. (2003). We assume that AGNs with $N_{\rm H} > 10^{24}\ \mathrm{cm^{-2}}$ are Compton-thick and that they will be missed even by hard X-ray surveys.

2.3 Dust attenuation

The dust attenuation of galaxies has been an important ingredient in SA models (e.g. Cole et al. 2000; Nagashima et al. 2005). In our model, the optical depth of internal dust in a merger remnant at the *V* band is assumed to be

$$\tau_V = \tau_{V0} \frac{(M_{\rm cold}/\mathrm{M_\odot})(Z_{\rm cold}/\mathrm{Z_\odot})}{(r_{\rm e}/\mathrm{kpc})^2}(1+z)^{-\gamma}, \quad (4)$$

where $\tau_{V0} = 2.5 \times 10^{-9}$ is the proportionality constant, $M_{\rm cold}$ is the total cold gas mass in the merger remnant, $Z_{\rm cold}$ is the metallicity of the cold gas, $r_{\rm e}$ is the effective radius of the merger remnant (bulge) and γ is a free parameter chosen to predict a consistent number of high-redshift galaxies with observations. As in Nagashima et al. (2005), we set $\gamma = 1$. Although Cole et al. (2000) assumed local extinction (Savage & Mathis 1979), $N_{\rm H}/E(B-V) = 5.8 \times 10^{21}\ \mathrm{cm^{-2}}$, we employ half of the value because we adopt the value of the chemical yield twice as large as that in Cole et al. (2000) in order to reproduce observed colour of elliptical galaxies (Nagashima et al. 2005). We employ the extinction curve by Calzetti et al. (2000), $R_V = 4.01$, and obtain $\tau_{B0} = 3.1 \times 10^{-9}$. The time evolution of $M_{\rm cold}$ and $Z_{\rm cold}$ after a major merger is also given in Nagashima et al. (2005).

An AGN must also be subject to the attenuation by the same dust that attenuates the merger remnant, since the AGN is embedded in the very centre of it. While we adopt a slab model for galaxies, we employ a screen model for AGNs. We also halve the optical depth obtained by equation (4) to compute the attenuation of AGNs because an AGN is located at the centre of its host bulge.

The other important physical parameter is the star formation time-scale for a starburst, $\tau_{\rm burst}$, since the cold gas is exhausted by this time-scale. We assume that this time-scale scales with the dynamical time-scale of a bulge as $\tau_{\rm burst} = 0.5 t_{\rm dyn}$. The proportionality constant

[1] E14 assumed that the AGN lifetime is proportional to the dynamical time-scale of the host *halo*. Although this modification does not affect the results in E14 qualitatively, the values of ϵ_B and $f_{\rm life}$ must be adjusted to obtain equivalent results to E14.

Downloaded from http://mnrasl.oxfordjournals.org/ at Hokkaido University on July 27, 2015

has been chosen to explain the colour of high-redshift starburst galaxies (Nagashima et al. 2005).

2.4 Models

In this Letter, we consider three models regarding the dust attenuation of AGNs and investigate quasar luminosity functions. In the first model, and the first model only, we ignore the dust attenuation. In this case, the luminosity of an AGN is fully specified by equation (2). This model is an analogue of the one presented in E14 and we call this model 'E14 model'. We note that this E14 model is different from the original E14 model in the treatment of dust attenuation; in the original E14 model, dust attenuation is effectively included since ϵ_B is treated as a free parameter.

In E14 model, we assume that the accretion on to an SMBH and a starburst begin immediately after the occurrence of a major merger. It may however take some time before the gas reaches to the galactic centre after a major merger. We hence consider the second model in which gas accretion on to an SMBH starts $\tau_{\rm delay} = \nu_{\rm delay} t_{\rm dyn}$ after a major merger; doing this must reduce the dust attenuation of AGNs. This delay is first introduced in this Letter. We refer to this model as 'delay model' and present the results of $\nu_{\rm delay} = 1$ and 3.

In the third model, we vary the dust covering factor (CF). We present the results of CF = 0.1, 0.5, 0.75, 0.9, while CF = 1 is assumed in E14 and delay models. We dub this model 'CF model'.

Quasars are required to be brighter than their host galaxies in our definition.

3 RESULTS

In order to focus on these effects, hereafter we show the luminosity functions of the quasars only at $z \sim 2$. Note that our model overpredicts the number of bright quasars in the *B*-band about an order of magnitude at $z < 0.5$. We leave this issue for future studies.

In Fig. 1, we present AGN luminosity functions in hard X-ray at $z \sim 2$. (red solid line). We presume that the dust attenuation is negligible in hard X-ray. Our result is broadly consistent with the observed luminosity function. Since, in our model, we only consider quasar-like AGNs, i.e. AGNs induced by major mergers, it is natural that our model underpredicts the number of faint AGNs. The brightest end is highly uncertain due to the cosmic variance.

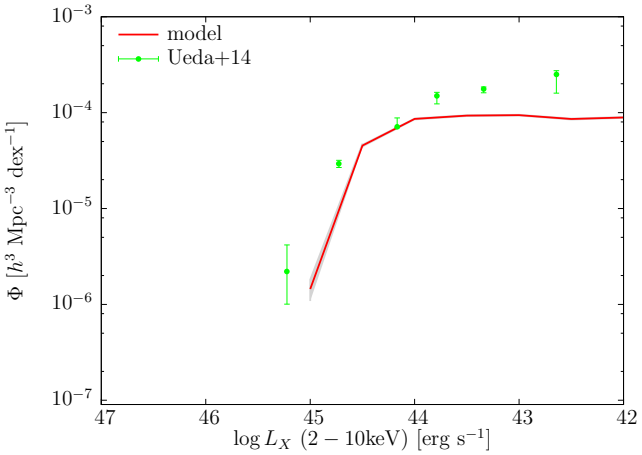

Figure 1. AGN luminosity functions in hard X-ray. We set $\epsilon_{\rm bol}$ and $f_{\rm life}$ so that the model reproduces the observed luminosity function obtained by Ueda et al. (2014, green points). Note that the model includes only AGNs that are triggered by major mergers. Hence, it is not surprising that it misses the less powerful Seyfert population. Red line shows the model result. The shaded region indicates 1σ error.

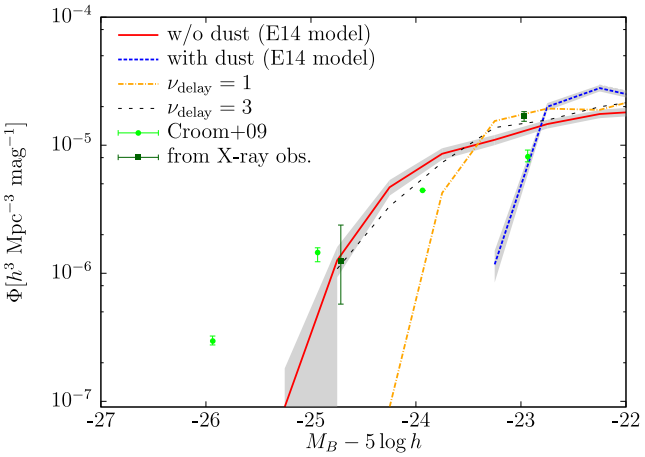

Figure 2. Quasar luminosity functions in the *B*-band at $z \sim 2$. The luminosity function of E14 model is indicated by the red solid line in which we ignore the dust attenuation. We also show the result by the same parameter set as E14 model but with the dust attenuation (blue dotted line). The shaded regions indicate 1σ error. The observational estimation is indicated by the green filled circles (Croom et al. 2009). The dark-green filled squares indicate the luminosity function that is converted from the hard X-ray luminosity function obtained by Ueda et al. (2014) using Marconi relations. These points are corresponding to the first and second brightest points in Fig. 1. We also show the results of delay model with $\nu_{\rm delay} = 1$ (orange dot dashed line) and with $\nu_{\rm delay} = 3$ (black dashed line).

In Fig. 2, we present quasar luminosity functions in the *B*-band at $z \sim 2$ predicted by E14 model (red solid line). We also show the luminosity function that is converted from the observed AGN luminosity function in hard X-ray obtained by Ueda et al. (2014) using Marconi relations (dark-green filled squares) together with an observed *B*-band luminosity function (Croom et al. 2009, green filled circles). These two luminosity functions are consistent. This suggests that if Marconi relations are appropriate, the dust attenuation of quasars in the *B*-band must be negligible because Marconi relation gives intrinsic *B*-band luminosity. We also plot the luminosity function by the same parameter set as E14 model but with the dust attenuation (blue dotted line). The dust distribution that we have assumed here is consistent with the dust model assumed for the host bulges. We find that the luminosity of the brightest quasar becomes fainter by about 2 mag and that is inconsistent with the observed quasar luminosity function. If we ignore the dust attenuation, we can roughly reproduce observed quasar luminosity function. Hence in order to reproduce the X-ray and *B*-band luminosity functions simultaneously, we should introduce some mechanisms that weaken the dust attenuation.

We now investigate effects of the delayed accretion on to SMBHs (delay model). In Fig. 2, we compare luminosity functions with $\nu_{\rm delay} = 0$ (E14 model), 1, and 3. We find that this effect is larger for the bright end. Thanks to the smaller amount of the cold gas due to star formation and feedback, the dust attenuation becomes weak. Since the red solid line (E14 model) and black dashed line ($\nu_{\rm delay} = 3$) in Fig. 2 are indistinguishable, we conclude that, in order to make the dust attenuation to be negligible, the gas accretion on to an SMBH has to wait $\sim 3 t_{\rm dyn}$ after a major merger.

Finally, we have tested the CF model in Fig. 3. We find that the shape of the quasar luminosity functions vary according to the CF,

Downloaded from http://mnrasl.oxfordjournals.org/ at Hokkaido University on July 27, 2015

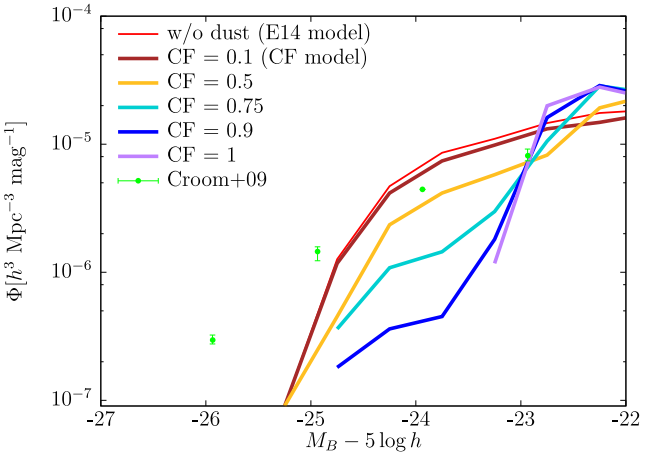

Figure 3. Quasar luminosity functions of the CF model. The red solid line shows the quasar luminosity function without dust attenuation. Other five thick lines show that of with CF = 0.1 (brown solid line), 0.5 (orange solid line), 0.75 (cyan solid line), 0.9 (blue solid line) and 1 (purple solid line); the smaller CF corresponds to the brighter bright end.

and that the dust attenuation can be negligible if CF ∼0.1. The dust distribution therefore plays an important role for dust attenuation as mentioned in Cattaneo et al. (2005a).

4 SUMMARY AND DISCUSSION

We have analysed the quasars obtained by an SA galaxy formation model of E14, which naturally explains the antihierarchical evolution of the AGNs, to study the dust attenuation of the quasars self-consistently with galaxy formation.

We find that bright quasars suffer significant dust attenuation, ∼2 mag in the *B* band, if the accretion on to a central black hole occurs simultaneously with a starburst. Hence, we should introduce some mechanisms which weaken the dust attenuation in order for our model to reproduced observed quasar luminosity functions, both in the *B*-band and X-ray.

The dust attenuation is weakened if the accretion on to an SMBH starts sometime after a major merger since the amount of the cold gas and hence the dust in the host bulge is reduced by star formation and feedback. We take this process into account for the first time in SA galaxy formation models. We find that the delay must be at least $\sim 3t_{\rm dyn}$ in order for the dust attenuation to be completely negligible. This result suggests that the SMBH growth might significantly lag behind the peak star formation activity in the host.

The dust distribution that we have assumed in E14 and delay models is consistent with the dust model assumed for the host bulges. It is however possible that the dust attenuates the light only along certain lines of sight. We find that if CF ∼ 0.1, the dust attenuation becomes negligible. The dust CF may play an important role for dust attenuation of AGNs in late-type galaxies (Rigby et al. 2006). We however consider gas rich major mergers as a trigger of AGN activities, and therefore CF ∼ 1 might be plausible (Cattaneo et al. 2005a).

AGN feedback, in particular the so-called quasar mode feedback (e.g. Di Matteo, Springel & Hernquist 2005; Hopkins et al. 2005), may also affect the dust attenuation by blowing away the cold gas from a bulge (Hopkins et al. 2005). Including this effect however changes galaxy properties as well, and thus we have to weaken the stellar feedback to obtain the equivalent results for galaxies. We hence speculate that inclusion of this feedback will not change our results much.

We conclude that the attenuation by the dust in the host galaxies is so large that we cannot ignore it for modelling quasars. We have not considered nuclear dust in this Letter, which might be more important than the dust in the host galaxies because of its higher column density. The role of the AGN feedback is likely to be more important for the nuclear dust than the galactic one (Hopkins et al. 2005). To consider the nuclear dust, we however have to model the nuclei more in detail and we leave it for future studies.

ACKNOWLEDGEMENTS

We appreciate the detailed review and useful suggestions of anonymous referee that have improved our paper. We would like to thank T. Nagao, M. Akiyama, T. Kawaguchi, Y. Matsuoka, M. Brown and Y. Toba for helpful comments on observational data. We also thank K. Wada, T. Kozasa, K. Ohsuga, T. Oogi and K. Hiura for useful discussion. TO has been financially supported by Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Young Scientists (B: 24740112). MN has been supported by the Grant-in-Aid (No. 25287049) from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. TI has been supported by MEXT HPCI STRATEGIC PROGRAM and MEXT/JSPS KAKENHI (No. 24740115). RM has been supported by the Grant-in-Aid for JSPS Fellows.

REFERENCES

Barger A. J., Cowie L. L., Mushotzky R. F., Yang Y., Wang W.-H., Steffen A. T., Capak P., 2005, AJ, 129, 578
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Cattaneo A., 2001, MNRAS, 324, 128
Cattaneo A., Combes F., Colombi S., Bertin E., Melchior A.-L., 2005a, MNRAS, 359, 1237
Cattaneo A., Blaizot J., Devriendt J., Guiderdoni B., 2005b, MNRAS, 364, 407
Cole S., Lacey C. G., Baugh C. M., Frenk C. S., 2000, MNRAS, 319, 168
Croom S. M., Smith R. J., Boyle B. J., Shanks T., Loaring N. S., Miller L., Lewis I. J., 2001, MNRAS, 322, L29
Croom S. M. et al., 2009, MNRAS, 399, 1755
Di Matteo T., Springel V., Hernquist L., 2005, Nature, 433, 604
Enoki M., Nagashima M., Gouda N., 2003, PASJ, 55, 133
Enoki M., Ishiyama T., Kobayashi M. A. R., Nagashima M., 2014, ApJ, 794, 69 (E14)
Fanidakis N. et al., 2012, MNRAS, 419, 2797
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Gaskell C. M., Benker A. J., 2007, preprint (arXiv:0711.1013)
Häring N., Rix H.-W., 2004, ApJ, 604, L89
Hasinger G., 2008, A&A, 490, 905
Hirschmann M., Somerville R. S., Naab T., Burkert A., 2012, MNRAS, 426, 237
Hopkins P. F., Hernquist L., Cox T. J., Di Matteo T., Martini P., Robertson B., Springel V., 2005, ApJ, 630, 705
Ishiyama T., Enoki M., Kobayashi M. A. R., Makiya R., Nagashima M., Oogi T., 2014, preprint (arXiv:1412.2860)
Kauffmann G., Haehnelt M., 2000, MNRAS, 311, 576
Komatsu E. et al., 2011, ApJS, 192, 18
Lacy M., Petric A. O., Sajina A., Canalizo G., Storrie-Lombardi L. J., Armus L., Fadda D., Marleau F. R., 2007, AJ, 133, 186
Lagos C. D. P., Cora S. A., Padilla N. D., 2008, MNRAS, 388, 587
McConnell N. J., Ma C.-P., 2013, ApJ, 764, 184
Magorrian J. et al., 1998, AJ, 115, 2285

Downloaded from http://mnrasl.oxfordjournals.org/ at Hokkaido University on July 27, 2015

Marconi A., Risaliti G., Gilli R., Hunt L. K., Maiolino R., Salvati M., 2004, MNRAS, 351, 169
Marulli F., Bonoli S., Branchini E., Moscardini L., Springel V., 2008, MNRAS, 385, 1846
Monaco P., Fontanot F., Taffoni G., 2007, MNRAS, 375, 1189
Nagashima M., Yahagi H., Enoki M., Yoshii Y., Gouda N., 2005, ApJ, 634, 26
Rigby J. R., Rieke G. H., Donley J. L., Alonso-Herrero A., Pérez-González P. G., 2006, ApJ, 645, 115
Sanders D. B., Soifer B. T., Elias J. H., Neugebauer G., Matthews K., 1988, ApJ, 328, L35
Savage B. D., Mathis J. S., 1979, ARA&A, 17, 73
Szokoly G. P. et al., 2004, ApJS, 155, 271
Ueda Y., Akiyama M., Ohta K., Miyaji T., 2003, ApJ, 598, 886
Ueda Y., Akiyama M., Hasinger G., Miyaji T., Watson M. G., 2014, ApJ, 786, 104

This paper has been typeset from a TEX/LATEX file prepared by the author.

Downloaded from http://mnrasl.oxfordjournals.org/ at Hokkaido University on July 27, 2015