TYPE II QUASARS IN THE MOST LUMINOUS GALAXIES

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ABSTRACT

An X-ray investigation of Type II active nuclei hosted in the hyperluminous infrared galaxies (HLIGs) is presented. Two classical HLIGs discovered in the IRAS survey, IRAS 09104+4109 and IRAS F15307+3252, are found to share many properties: 1) The active nuclei are absorbed by Compton-thick obscuring matter, and powered by well-grown (billions solar mass) black holes; 2) The large infrared luminosity appears to be due to hot/warm dust heated by the hidden active nuclei; 3) Both galaxies resides in a rich environment and are very luminous. In comparison, the HLIGs might be fundamemntally different from the local lower luminosity counterparts, ultra-luminous infrared galaxies (ULIGs) in their formation. The rich environment suggests that it could be a necessary condition to form the most luminous quasars, and their relation to high redshift radio galaxies is discussed briefly.

Key words: LaTeX; ESA; X-rays.

1. INTRODUCTION

The hierarchical assembly in a cold dark matter halo and the apparent relation between massive black holes and their host galaxy spheroids predicts that most luminous quasars (or most massive black holes) would reside in a rich environment such as a galaxy cluster.

It is expected that the early growth of a massive black hole occurs in a dense gaseous environment where star formation is likely to take place at the same time. An active nucleus powered by such a black hole will therefore be observed as an obscured (or Type II) active nucleus. In this context, Type II quasars are part of the evolutionary phase of massive black holes, followed by the optical quasar phase after blowing away the obscuring material (e.g., Sanders etal 1988). On the other hand, as in the unification scheme for the two types of Seyfert galaxies (e.g., Antonucci & Miller 1985), the orientation effect may make a quasar nucleus to manifest itself as a Type II quasar if there are dense clouds in a toroidal form lying along the line of sight.

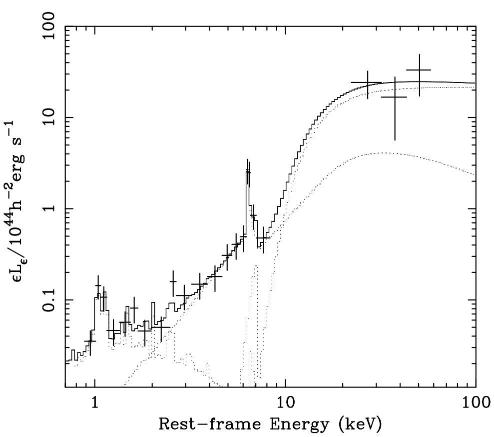

Figure 1. The energy distribution of IRAS 09104+4109 in the X-ray band derived from the Chandra and BeppoSAX observation. The unresolved nuclear component is plotted in the Chandra bandpass. The energy scale has been corrected for the galaxy redshift.

We take hyper-luminous infrared galaxies (HLIGs) with infrared luminosities in excess of $10^{13} L_\odot$ as a sub-class of the most luminous galaxies, and investigate the Type II quasars contained in them in relation with the galaxies themselves and their environments. The X-ray results on the two classical, IRAS-selected HLIGs, IRAS 09104+4109 ($z = 0.44$) and IRAS F15307+3252 ($z = 0.93$), and their remarkable similarities are discussed in detail. For calculating luminosities, we adopt the currently popular cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 0.27$ and $\Omega_\Lambda = 0.73$.

2. X-RAY DATA

2.1. IRAS 09104+4109

This HLIG has been known to be the central galaxy of a rich cluster at $z = 0.44$ since its discovery (Kleinmann

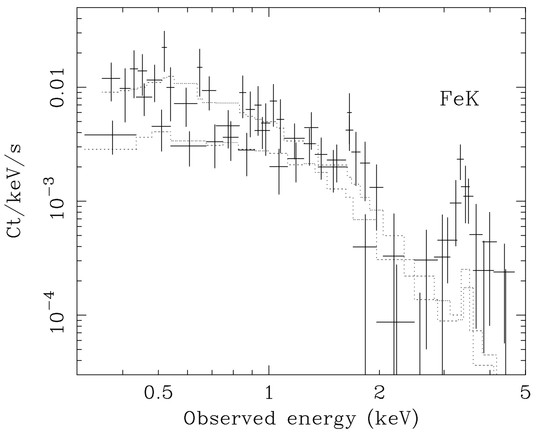

Figure 2. The X-ray spectrum of IRAS F15307+3252 obtained from the XMM-Newton EPIC cameras (the pn and MOS data are plotted separately). The soft X-ray emission is probably due to the extended cluster emission while the emission peaking in the 3–4 keV band is mostly due to Fe Kα.

et al 1988). Extended thermal X-ray emission due to the intracluster medium (ICM) has been imaged by ROSAT (Fabian & Crawford 1995) and the Chandra X-ray Observatory (Iwasawa et al 2001). The ICM has a virial temperature of $kT \simeq 7$ keV with a cooling core of which temperature drops to 2-3 keV towards the cluster centre. The bolometric luminosity of the cluster medium 3×10^{45} erg s^{-1} makes IRAS 09104+4109 one of the most luminous clusters (Allen 2000). The point-like active nucleus is hard in X-ray colour and resolved only with Chandra. The spectrum of the nucleus is characterized by a strong Fe Kα emission at 6.4 keV, and together with the hard X-ray detection with the BeppoSAX PDS (Franceschini et al 1999), indicates a Compton thick nucleus (Fig. 1). The absorption-corrected 2–10 keV luminosity is estimated to be $\times10^{45}$ erg s^{-1}. With a bolometric correction appropriate for quasars (e.g., Elvis et al 1994), the obscured active nucleus is likely to power most of the bolometric luminosity of this galaxy.

2.2. IRAS F15307+3252

The first X-ray detection from this more distant (z = 0.926; Cutri et al 1994) galaxy was made with XMM-Newton (Iwasawa et al 2005, and the details are therein) following no detection with the previous X-ray telescopes (Fabian et al 1996; Ogasaka et al 1997). While the data collected from total exposure times of 21 ks and 33 ks from the EPIC pn and MOS detectors, respectively, from three observations are still noisy, they show clear detection of soft X-ray emission up to 2 keV and strong Fe Kα emission, redshifted to the 3–4 keV band (Fig. 2). The photometric study combining the both EPIC cameras shows a drop-out in the 2–3 keV band and 4σ detection in the observed 5–10 keV band (Fig. 3). The Fe K line infers reflection from cold matter.

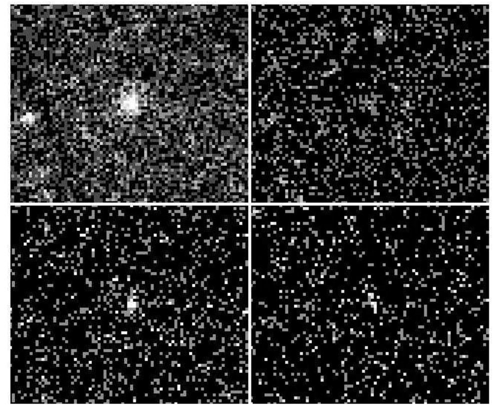

Figure 3. The X-ray images of IRAS F15307+3252 in the four energy bands, clockwise from upper left: 0.5–2, 2–3, 5–10 and 3–4 keV. The size of the each image is 5×4.5 arcmin^2.

In the absence of any transmitted emission from the central source, the central source is hidden behind an absorber with a column density larger than 10^{24} cm^{-2}. For the luminosity of the hidden source, we estimate the X-ray luminosity required to produce the Fe K luminosity $\approx 4 \times 10^{43}$ erg s^{-1} through reflection from cold slab extending over 2π in solid angle. The value is $\geq 1 \times 10^{45}$ erg s^{-1}, which infers the bolometric luminosity of the active nucleus being at least a few times of 10^{46} erg s^{-1}. This estimate suggests that a significant fraction of the total luminosity can be attributed to the hidden active nucleus.

An unexpected but possibly important finding is an extension of the soft X-ray emission. The image at energies below 2 keV is significantly broader than the point spread function and its intrinsic extension is 21 ± 5 arcsec in FWHM, corresponding to 85 kpc in radius at the distance of the galaxy. Fitting a thermal emission model to the spectrum below 2 keV gives a temperature of $2.1^{+0.6}_{-0.4}$ keV. The bolometric luminosity of this component is estimated to be 1×10^{44} erg s^{-1}. These values lie on the L-TX relation of galaxy clusters (e.g., Fukazawa et al 2004). Combinied with the large source extent, the soft X-ray emission may well be due to ICM of a poor cluster. The optical image of the region around the HLIG shows some evidence of galaxy overdensity (Fig. 4).

3. DISCUSSION

3.1. Common properties

The previous optical spectropolarimetry have already revealed a hidden broad-line regions both in IRAS 09104+4109 and IRAS F15307+3252 (Hines et al 1995). The hidden active nuclei are found to be both Compton thick by the X-ray observations, and they are likely to dominate the energetics of these HLIGs. Their black hole

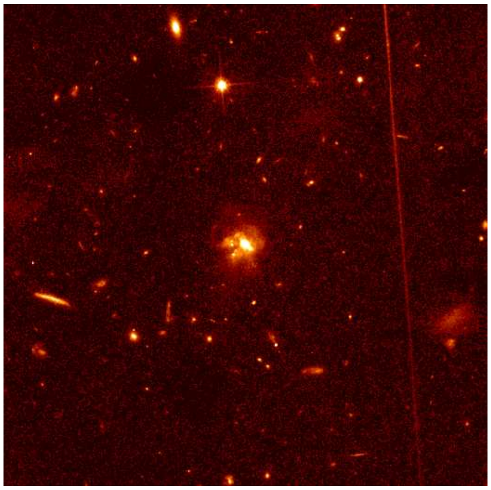

Figure 4. The HST/ACS image of the 1×1 arcmin^2 region around IRAS F15307+3252, taken through the F814W filter (rest-frame blue). North is up and east to the left. A chain of small galaxies 11–15 arcsec ($\sim$ 100 kpc at $z = 0.93$) lies to the sourth of the IRAS galaxy, which is reminiscent of Markarian's chain of galaxies in the Virgo cluster.

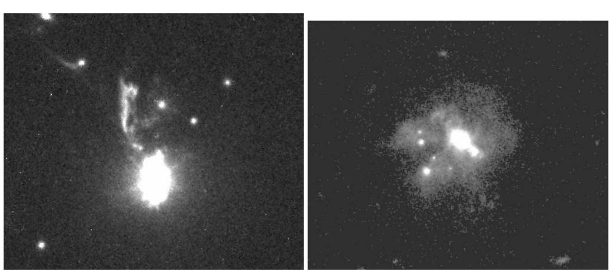

Figure 5. Left: The HST WFPC2 image of IRAS 09104+4109 with the F814W filter. Right: The HST ACS image of IRAS F15307+3252 (zoom-up of Fig 4).

masses are estimated to be $3 \times 10^9 M_{\odot}$ and $1.3 \times 10^9 M_{\odot}$, respectively, using the MgII widths seen in the polarized light and the UV luminosities (McLure & Jarvis 2002). They are efficiently accreting at a large fraction of the Eddington limit. The radio sources are moderately powerful in both galaxies and most likely associated with the active nuclei (Kleinmann et al 1988; Hines & Wills 1993; Drake et al 2003).

The optical images of the two galaxies show well-developed spheroids of a giant elliptical with evidence of minor mergers which lead to the somewhat disturbed morphology (Fig. 5). They are quite luminous in optical (e.g., $M_{\rm I} = -26.4$ for F15307, Farrah et al 2002) compared to the average quasar hosts. There is little evidence for a large reservoir of cold gas, as suggested by no detection of CO (Evans et al 1998; Yun & Scoville 1998) and no detection with SCUBA (Deane & Trentham 2001). This means that a gaseous/dusty condition envisaged for forming galaxies such as high-z SCUBA sources does not apply, and the large X-ray absorbing column and the high accretion onto the black holes are supplied by the gas at small radii in the nuclear region rather than cold gas distributed on the galactic scale. Such cold gas has perhaps been exhausted already after forming stars and/or been expelled by mechanical outflow from the central active nucleus. Cold dust with a temperature around 40 K, typically found in star-forming local ULIGs, are not present in large amount in these galaxies (Deane & Trentham 2001). The dust reradiation responsible for the luminous infrared emission is predominantly due to hot dust, presumably heated by the hidden active nucleus, which peaks in the mid infrared band.

P09104+4109 has been considered peculiar among luminous infrared galaxies, being the central galaxy of a rich cluster, since local ULIGs do not usually reside in a rich environment (Sanders & Mirabel 1996). However, if the possible poor cluster around F15307+3252 suggested by the extended X-ray emission is confirmed, the two earliest examples of HLIGs are found to be in a cluster environment. This means that they are located in a massive dark matter halo, the masses of which are estimated to be in the range of $10^14M_{\odot}$ to $10^15M_{\odot}$ from the temperature-mass relation for clusters (e.g., Finoguenov et al 2001). The galaxies probably grew by the accretion of other galaxies in the respective dark matter halos, and they seem to have a well-grown black hole emitting at the quasar luminosity, as discussed above. In the absense of large amount of cold gas, the classification of Type II quasars is likely to be due to the orientation effect and the central sources are expected to be identical to normal (but powerful) quasars (e.g., Hines et al 1995).

Many pieces of evidence point to that the most massive ($\geq 10^9 M_{\odot}$) black holes are formed early ($z \geq 3$, Merloni 2004) probably behind heavy obscuration of dense gas. Both quasar activity and star formation in the universe peak at around $z = 2$ (e.g., Hasinger et al 2005), but the assembly of cluster central galaxies through hierarchical merging continues afterward. Since star formation induced by minor galaxy mergers does not appear to contribute significantly to the final mass of the central galaxies (e.g., Concelice et al 2001), it is expected in those systems that cold gas has been exhausted by vigorous star formation by $z \sim 2$ and the black hole has grown fully (to the mass of $\sim 10^9 M_\odot$) even before. Therefore, for the two HLIGs with $z \leq 1$ we studied, the observed common properties are in agreement with the above scenario.

At least these two HLIGs differ significantly from local ULIGs in all apsects of the massive black holes, galaxies, and environments, and they are probably fundamentally different in formation process. As seen in these cases, massive dark matter halo may be one of the necessary condition to produce the most luminous quasars (and also giant ellipticals). As previously suggested by, e.g., Genzel et al (2001), the local ULIGs will not evolve into such extremely luminous objects.

3.2. Relation to high-z radio galaxies

Radio galaxies found at high redshift are considered to be a sign post of massive dark matter concentration. Two radio galaxies at $z > 3$, B2 0902+34 ($z = 3.4$) and 4C+41.17 ($z = 3.8$), which are found to be HLIGs (Huges, Dunlop & Rawlkings 1997; Rowan-Robinson 2000), have been detected in X-ray (Fabian et al 2002; Scharf et al 2003). They are, of course, powerful radio sources. While no clear galaxy overdensity is observed, large rotation measure is observed in both objects. Since strong Faraday rotation is often associated with nearby, strong cooling flow clusters (e.g., Carilli 1995), they might be in a proto-cluster. Unlike P09104+4109 and F15307+3252 at lower redshift, evidence for large amount of cold gas have been reported for both galaxies. At this high redshift, the central black hole may be still in its growth phase, and its activity is of great interest. As shown in Table 1, while they show similar infrared luminosities, observed X-ray luminosities of their nuclei are vastly different: the active nucleus of B2 0902+34 shows strong absorption in the X-ray spectrum, but the quasar luminosity in the X-ray band suggests that a efficiently accreting $10^9 M_\odot$ black hole is already in place in this object (Fabian et al 2002). The weak X-ray nucleus in 4C+41.17 indicates that, if a similarly massive black hole is present, the accretion mode must be radiatively inefficient, most likely dominated by jets. Besides the black hole growth, as proposed by Churazov et al (2005) as in the galactic black hole sources, switching between the two different accretion modes may be occuring in the course of black hole evolution, for which a statistical study will be required to investigate it quantitatively.

ACKNOWLEDGMENTS

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Table 1. Infrared-Hyperluminous radio galaxies. ∗The absorption-corrected nuclear luminosities.

Galaxy	z	log $L_{\rm IR}$	log $L_{\rm X}^*$
B20902+34	3.4	46.74	45.60
4C+41.17	3.8	46.97	43.95

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