DISCOVERY OF STRONG IRON Kα EMITTING COMPTON THICK QUASARS AT $z = 2.5$ AND 2.9

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Abstract

We report the detection of the 6.4 keV iron Kα emission line in two infrared-luminous, massive, star-forming BzK galaxies at $z = 2.578$ and $z = 2.90$ in the CDF-S. The Chandra 4 Ms spectra of BzK 4892 and BzK 8608 show a reflection-dominated continuum with strong iron lines, with rest-frame equivalent widths EW $\sim 2.3$ keV and 1.2 keV, respectively, demonstrating Compton thick (CT) obscuration of the central active galactic nucleus (AGN).

Highly obscured, deeply embedded active galactic nuclei (AGNs) might contribute significantly to the total accretion power in the universe (Marconi et al. 2004) and are required to account for the spectrum of the X-ray background (XRB; Gilli et al. 2007). In particular, AGNs obscured in the X-ray band by column densities larger than $N_H = 10^{24}$ cm$^{-2}$ (Compton thick AGN) represent 20%–25% of the AGN detected by INTEGRAL and SWIFT/BAT in the local universe (Malizia et al. 2009; Burlon et al. 2011).

The identification of highly obscured AGNs is particularly challenging since, because of the high column densities, the vast majority of their X-ray emission below rest frame 10 keV is absorbed, so that they are largely missed even in the deepest hard X-ray surveys available today. At high redshift the quest for such objects is mainly pursued by indirect evidence, by selecting galaxies with high ratios of mid-infrared to optical, or mid-infrared to X-ray fluxes, and by deriving average X-ray properties by stacking techniques (e.g., Daddi et al. 2007b, D07 hereafter; Fiore et al. 2008; Alexander et al. 2005, 2008; Treister et al. 2010; Georganopoulos et al. 2009; Donley et al. 2010). These studies have suggested that a substantial fraction of massive galaxies at $z > 1$ host highly obscured, intrinsically luminous AGNs.

Only a few tens of secure Compton thick (CT) AGNs are known so far in the local universe (Comastri et al. 2004; Della Ceca et al. 2008, and references therein), and only for a handful of them a quasar-like intrinsic hard X-ray luminosity has been inferred ($L_{2–10\text{keV}} > 10^{44}$ erg s$^{-1}$; Brait et al. 2004; Piconcelli et al. 2010). Their X-ray spectra are characterized by the presence of a strong iron Kα 6.4 keV fluorescent emission line, with large equivalent width EW $\gtrsim 1$ keV, on a flat reflection-dominated continuum (Matt et al. 2000). Not much evidence currently exists in the distant universe of AGNs showing prominent, high EW iron Kα line: an IRAS-selected hyperluminous galaxy at $z = 0.93$ (Iwasawa et al. 2005) and two possible detections in the CDF-S reported by Norman et al. (2002; a type 2 QSO at $z = 3.7$) and by Tozzi et al. (2006; a galaxy at $z = 1.53$), both confirmed by Comastri et al. (2011). In the following, we present the significant Chandra detection of the iron Kα emission line in two massive BzK galaxies at redshift $z = 2.578$ and $z = 2.90 \pm 0.10$ in GOODS-South, using the recently acquired 4 Ms data set. We used for this purpose the entire set of 52 observations for a total exposure time of 4 Ms, available at the Chandra Data Archive. We adopt a ΛCDM cosmology ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$) and a Chabrier stellar initial mass function.

1. INTRODUCTION

2. X-RAY PHOTOMETRIC AND SPECTRAL ANALYSIS

We have been investigating the properties of BzK-selected (Daddi et al. 2004), massive galaxies at redshift $1 < z < 3$ with faint or no X-ray emission, with the aim of constraining their obscured AGN activity. We have focused in particular on objects also showing a power-law emission in the near-IR rest frame, an independent indication for the presence of a luminous, obscured AGN. A large statistical sample of 750 X-ray undetected galaxies has been assembled in the COSMOS field, and their X-ray properties investigated through stacking. As a control sample, we also studied in detail a smaller sample of 26

http://cxc.harvard.edu/cda/Contrib/CDFS.html
similarly selected galaxies in GOODS-South, with less than 200 net counts in the 0.5–7 keV band in the CDF-S 4 Ms data that would remain thus undetected in the shallower COSMOS Chandra observations. While the general results of these studies will be reported elsewhere (C. Feruglio et al. 2011, in preparation), we concentrate here on two remarkable sources in our GOODS-S control sample, for which the available Chandra data allow the unambiguous detection of the iron Kα emission.

Both of the BzK galaxies under exam were selected from the D07 sample. BzK 4892 is a source with spectroscopic redshift z = 2.578 (Szokoly et al. 2004; Vanzella et al. 2006, based on multiple narrow emission lines), detected in the X-rays already in the 1 Ms Chandra data (Giacconi et al. 2001) as well as in the 2 Ms data (Luo et al. 2010). In the 4 Ms data set, it has 75 net counts in the 0.5–7 keV band and a hardness ratio of 0.58 (the hardness ratio is defined as HR = hard–soft/hard+soft, where S and H are the soft and hard band net counts detected by Chandra). BzK 8608 has a photometric redshift zphot = 2.94 (from D07; consistent with zphot = 2.88 from Santini et al. 2009). VLT+VIMOS spectroscopic observations (Popesso et al. 2009) show that there is no continuum emission in the blue, consistent with z ~ 3, but failed to yield a reliable redshift estimate. We tentatively detected in the VIMOS spectrum a low signal-to-noise feature at 6027 Å (a region clear from OH lines) that, if identified with C IV, would give z = 2.88. We note that the photometric redshift for BzK 8608 is reliable as the galaxy fulfills the U-band dropout criteria, corresponding to a Lyman continuum break (being undetected in the deep U-band imaging of Nonino et al. 2009; Figure 3). This source is not listed in the Chandra 2 Ms catalog (Luo et al. 2010), likely because of the presence of another nearby X-ray source (no. 193). In the 4 Ms data, BzK 8608 has 92 counts in the total band. It is not detected in the 0.3–1.5 band, and its hardness ratio is HR > 0.54 (3σ).

We extracted the Chandra spectra using a circular region of 1″3 and 3″ radius for BzK 4892 and BzK 8608 (off-axis ~ 7′4), respectively, estimating the background in an annulus around the source position. We experimented with different extraction radii, centering, and background estimates, taking care in all cases of excluding nearby detected sources (particularly important for BzK 8608), finding that the features found in the spectra were robust to the detail extraction method. The spectra for both galaxies show a flat continuum and prominent emission lines peaking at ~1.78 keV for BzK 4892 and ~1.64 keV for BzK 8608 (Figure 1).

We consider two spectral models to fit the data in XSPEC: (1) a reflection-dominated model, *pexrav + zgauss* and (2) a transmission (power-law) model, *wabs*(pow+zgauss). A narrow Gaussian component is used to model the emission lines. Given the limited photon statistic, the slope of the primary continuum has been fixed to Γ = 1.8 in both scenarios. Based on C-statistics, the emission line is detected with a significance of ≥3σ (ΔC = 17.5) for BzK 4892 and ≥3σ (ΔC = 7.5) for BzK 8608 (see also Figure 2) for the reflection-dominated model. In the case of a transmission model, the significance of the line remains above 4σ for BzK 4892 and just below 3σ for BzK 8608. To further evaluate the significance of the observed lines, we also performed 10̂5 simulations of the source continuum and background for both sources. The probability that the lines might be due to chance fluctuations is 3 × 10−5 and 2 × 10−4, respectively. The spectral fits are summarized in Table 1.

| Source ID | Model | Fe Kα Flux (10^{-17} erg cm^{-2} s^{-1}) | N_{H} | EW (keV) | C-stat/dof |
|-----------|-------|----------------------------------------|-------|---------|-----------|
| BzK 4892 | Abs   | 1.6 ± 0.5                              | 7.0^{+2.0}_{-2.0} | 2.1 ± 0.5 | 307/441   |
|           | Refl  | 2.0 ± 0.6                              | 2.3^{+0.6}_{-0.6} | 297/442  |
| BzK 8608 | Abs   | 3.6 ± 0.5                              | 7.0^{+2.0}_{-2.0} | 1.0 ± 0.3 | 411/440   |
|           | Refl  | 3.4 ± 0.8                              | 1.2 ± 0.4     | 418/442  |

Table 2

| Property               | BzK 4892 | BzK 8608 |
|------------------------|----------|----------|
| R.A.                   | 3:32:35.71 | 3:32:20.95 |
| Decl.                  | -27:49:16.1 | -27:55:46.3 |
| Redshift               | 2.578    | 2.90 ± 0.10 |
| HR                     | 0.58     | >0.54 (3σ) |
| SFR_{UV} (M_{⊙} yr^{-1}) | 70       | 70       |
| SFR_{radio} (M_{⊙} yr^{-1}) | 1100     | 300     |
| L(Kα) (erg s^{-1})     | 10^{42.1} | 10^{42.4} |
| L_{2–10 keV,abs} (erg s^{-1}) | 10^{42.5} | 10^{42.8} |
| L_{2–10 keV,Kα} (erg s^{-1}) | 10^{43.6–44.8} | 10^{43.9–45} |
| L_{2–10 keV,UV lines} (erg s^{-1}) | 10^{44} | 10^{45.5} |
| i (AB mag)             | 24.75    | 24.72    |
| IRAC 3.6 μm (AB mag)   | 20.81    | 21.29    |
| IRAC 4.5 μm (AB mag)   | 20.54    | 21.16    |
| IRAC 5.8 μm (AB mag)   | 20.1     | 20.84    |
| IRAC 8.0 μm (AB mag)   | 19.64    | 20.65    |
| MIPS 24 μm (mJy)       | 0.591 ± 0.07 | 0.045 ± 0.003 |
| MIPS 70 μm (mJy)       | 3.3 ± 1.8 | ...      |
| 850 μm (mJy)           | 3.3 ± 1.1 | ...      |
| 1.4 GHz (mJy)          | 80 ± 14  | 17.5 ± 6.5 |

为基础的二元X射线双星，如Donley et al. (2008)，由于光谱不相容（Persic & Raphaeli 2002）。

The fit with the transmission model gives N_{H} = (7 ± 2) × 10^{23} cm^{-2} for BzK 4892 and 7^{+3}_{-2} × 10^{23} cm^{-2} for BzK 8608, and is statistically indistinguishable from the fit with a reflection model. However, these N_{H} values are inconsistent with the measured EW ≥ 1 keV. Indeed, for N_{H} = 6 × 10^{23} cm^{-2}, an EW ~ 300 eV is predicted (Ikeda et al. 2009) and confirmed by observations (Guainazzi et al. 2005; Fukazawa et al. 2011). EW ≥ 1 keV are the hallmark of column densities larger than 10^{24} cm^{-2}. Therefore, in the following, we adopt as best fit the results from the reflection-dominated model for both sources (Table 2).

Figure 2 shows the Chandra images of BzK 4892 and BzK 8608 in three energy bands, including one centered on the iron lines. We note that BzK 8608 is not detected in the soft band.
Figure 1. Spectra of BzK 4892 (upper panels) and BzK 8608 (lower panels), fitted with a pure reflection model plus an iron Kα 6.4 keV line. The spectra are shown both in observed counts units (left panels) and in physical units (keV²; right panels). Each bin corresponds to a 2σ measurement. The red dotted line represents the average background extracted from the whole field, excluding sources (F. Fiore et al. 2011, in preparation).

3. DISCUSSION

3.1. Intrinsic Luminosities and Obscuration

The observed (obscured) hard X-ray luminosities are $L_{2-10\text{keV}} = 10^{42.5} \text{and} 10^{42.8} \text{erg s}^{-1}$ for BzK 4892 and BzK 8608, respectively. Given the large $N_H$ implied by the detection of high EW iron Kα lines, the X-ray emission is optically thick and we cannot directly estimate the intrinsic $L_{2-10 \text{keV}}$ using the X-ray data. In order to estimate the intrinsic luminosities of the AGN we used a variety of independent methods.

Following Iwasawa et al. (2005), a lower limit to the X-ray luminosity can be obtained in the expectation that in typical conditions the luminosity of the iron Kα line is at most 3% of the 2–10 keV luminosity. For BzK 4892 $L_{\text{Kα}} = 1.25 \times 10^{42} \text{erg s}^{-1}$ would imply an intrinsic 2–10 keV luminosity of $4 \times 10^{43} \text{erg s}^{-1}$. The relation $L_{\text{Kα}}/L_{2-10\text{keV}}$ of Levenson et al. (2006) implies a higher luminosity, $L_{2-10\text{keV}}\sim 10^{44.8} \text{erg s}^{-1}$. An alternative estimate is obtained from the 6.0 μm luminosity. The 24 μm flux of 591 μJy implies $L_{6.0\mu\text{m}} = 10^{45.5} \text{erg s}^{-1}$ (the mid-IR spectral energy distribution (SED) of Mrk 231 is used for the small K-correction). While 24 μm at $z = 2.578$ might be contaminated by polycyclic aromatic hydrocarbon features, we find similar results if we use the 16 μm flux of 209 μJy (Teplitz et al. 2011) for which no contamination is expected (4.5 μm rest frame). This would suggest $L_{2-10\text{keV}} = 10^{45.2\pm0.5} \text{erg s}^{-1}$ using the Lutz et al. (2004) correlation and a lower $L_{2-10\text{keV}} = 10^{44.4\pm0.5} \text{erg s}^{-1}$ using Lanzuisi et al. (2009). A third estimate can be derived from the luminosity of the UV–optical emission lines. The VLT/FORS1-2 optical spectrum of BzK 4892 shows prominent Lyα, C iv, He ii, and C iii] narrow emission lines (Szokoly et al. 2004; Vanzella et al. 2006). Using the observed ratios between the line and the intrinsic 2–10 keV emission from Mulchaey et al. (1994), we infer $L_{2-10\text{keV}} = 10^{44.5\pm0.5} \text{erg s}^{-1}$. Using the Netzer et al. (2006) conversion for UV–optical line luminosities would give larger X-ray luminosities by ~0.5 dex or $L_{2-10\text{keV}} = 10^{45.0\pm0.5} \text{erg s}^{-1}$. All in all, it appears that the 2–10 keV luminosity of BzK 4892 is in the QSO range, well in excess of $10^{44} \text{erg s}^{-1}$ and more likely of $10^{45.5}-10^{45} \text{erg s}^{-1}$. The implied column density is at the level of $N_H \sim 10^{24.5}-10^{25} \text{cm}^{-2}$. 

3
For BzK 8608, we measure $L(\text{K}\alpha) = 2.5 \times 10^{42}$ erg s$^{-1}$. This converts to $L_{2–10\text{ keV}} \sim 10^{43.9}$ erg s$^{-1}$ (Iwasawa et al. 2005) or $\sim 10^{42}$ erg s$^{-1}$ adopting Levenson et al. (2006). This galaxy is about 10 times fainter in the mid-IR than BzK 4892, which implies a lower $L_{6.0\mu m}$. Using the Lutz et al. (2004) relation, this in turn suggests $L_{2–10\text{ keV}} = 10^{44}$ erg s$^{-1}$. We cannot obtain an independent estimate from the UV–optical emission lines given that no lines were detected in the VIMOS spectrum. The intrinsic 2–10 keV luminosity of BzK 8608 is likely $\approx 10^{44}$ erg s$^{-1}$. The implied column density is likely in the range $N_{\text{H}} \sim (1–5) \times 10^{24}$ cm$^{-2}$, hence this object might be a borderline CT AGN. We note that both sources have estimated intrinsic 2–10 keV luminosities in the QSO regime.

3.2. Bolometric Luminosities and Star Formation Rates

The ratio of the bolometric to the 2–10 keV luminosity, $L_{\text{bol}}/L_{2–10\text{ keV}}$, is typically of the order 30–50 for quasars (Marconi et al. 2004). Assuming such a bolometric correction, we estimate $L_{\text{bol}} \sim 10^{46.2} \pm 0.5$ erg s$^{-1}$ for BzK 4892 and $\sim 10^{45.5} \pm 0.5$ erg s$^{-1}$ for BzK 8608. These very high luminosities, if expressed in solar units, correspond to $L_{\text{bol}} \sim 10^{12.4} \pm 0.5 L_{\odot}$ and $\sim 10^{11.9} \pm 0.5 L_{\odot}$. When powered by star formation, similar luminosities require star formation rates (SFRs) in the host galaxies at the level of 100–1000 $M_{\odot}$ yr$^{-1}$. It is interesting thus to compare these estimates to the inferred SFR for the two BzK galaxies, in order to compare the relative AGN and SFR contributions.

From the stellar SED (UV to the near-IR rest frame; Figure 3), we estimate SFR $\sim 70 M_{\odot}$ yr$^{-1}$ for BzK 4892, corrected for dust reddening based on the observed UV slope (see D07 for more details). It is quite possible though that also the stellar UV emission might be optically thick. If we interpret its mid-IR emission (591 $\mu$mJy at 24 $\mu$m) as due to star formation this would imply a whopping SFR $\sim 10^{4} M_{\odot}$ yr$^{-1}$, demonstrating that the mid-IR is likely completely dominated by the AGN (this object is among the most extreme mid-IR excess galaxies in the sample of D07). The SED fit with a star-forming galaxy template (Figure 3) shows an excess emission already at 5.8 $\mu$m (observed frame) probably due to the AGN contribution. The SED in the IRAC bands is indeed showing a steep power law, extending all the way to 24 $\mu$m. Due to its faint optical counterpart ($i \sim 25$ AB), BzK 4892 has high mid-infrared to optical flux ratio, $F(24)/F(i) \sim 2000$, and therefore is also classified as a dust-obscured galaxy (Dey et al. 2008). It is an extreme object also in the Fiore et al. (2008) sample. Alonso-Herrero et al. (2006) report a 70 $\mu$m flux of 3.3 $\pm$ 1.8 mJy for this galaxy, which is also likely affected by the AGN emission. On the other hand, the galaxy is seen at 1.4 GHz with a flux of 80 $\mu$Jy in the Very Large Array (VLA) data of Miller et al. (2008). If this measured flux is due to star formation, the radio–IR correlation would imply SFR $\sim 1100 M_{\odot}$ yr$^{-1}$. Inspecting the publicly available Apex+LABOCA 870 $\mu$m map of GOODS-S (Weiss et al. 2009), we find a $3\sigma$ signal at the position of BzK 4892 of 3.3 mJy, which would also convert into a similar SFR, $\sim 500 M_{\odot}$ yr$^{-1}$.

Even for the most luminous quasars it is generally found that the far-IR emission in the submillimeter bands is due to star formation. If this is the case also for BzK 4892, our results suggest that the galaxy is witnessing also very powerful star formation activity at the level of 500–1000 $M_{\odot}$ yr$^{-1}$. Only 5%–10% of this is seen directly in the UV, implying that also the UV emission from stars is optically thick, similarly to local ultraluminous infrared galaxies (e.g., Goldader et al. 2002; da Cunha et al. 2010) and to what is expected to be found in major mergers. However, we note that the radio and 870 $\mu$m derived SFRs would formally imply $L_{\text{bol}} \sim 10^{46.0–6.5}$ erg s$^{-1}$, comparable to what inferred for the obscured AGN. Hence,
the AGN is likely contributing an important fraction of the total $L_{bol}$. The morphology of the galaxy from $HST$+ACS imaging is suggestive of a merger, showing two distinct clumps in the UV in the rest frame. When smoothing, after excluding the two bright knots, we detect significant faint low-level emission in the summed $i+z$ band, extended over a diameter of about 0.75 (6 kpc). Overall, this is consistent with the size of a massive galaxy at $z \sim 2$, and we cannot exclude that the two UV knots might be just luminous H II regions inside a big disk galaxy.

The photometric information is of lower quality for $BzK$ 8608 due to its overall faintness. The SFR inferred from the UV is also $70 \ M_\odot \ yr^{-1}$. This object is also a mid-IR excess source in D07 sample (by a less extreme factor of six), with $L_{25} = 45 \ \mu Jy$ ($\sim 1/10$ of $BzK$ 4892), although it is not a dust obscured galaxy. The SED (Figure 3) might also be consistent with pure stellar emission, but a deviation from the star formation template is observed at the 8$\mu$m band. This galaxy is not detected at 70 $\mu$m and 870 $\mu$m, suggesting a lower AGN luminosity and/or SFR. Inspecting the VLA 1.4 GHz data (Miller et al. 2008), we detect a faint 3$\sigma$ source at its position with a flux of $17.5 \pm 6.5 \ \mu Jy$. This corresponds to a luminosity $3 \times 10^{22} \ L_\odot$ and SFR $\sim 300 \ M_\odot \ yr^{-1}$. If the radio signal is real and not due to AGN, also in this case the stellar emission appears to be heavily obscured, i.e., optically thick in the UV, as expected for very active starbursts and mergers. The $HST$+ACS imaging of this galaxy (Figure 3) is not particularly telling.

For both galaxies we derive similar estimates of the stellar masses, at the level of $5 \times 10^{10} \ M_\odot$. Our results thus support the picture that the luminous, CT AGNs that we discovered are hosted by fairly massive galaxies at $z \sim 2.5$–3, which at the same time also host vigorous star formation activity heavily obscured by dust. This is relevant in the AGN–host galaxy co-evolution scenario, in which a phase of rapid, heavily obscured black hole growth accompanied by intense obscured star formation is predicted (Silk & Rees 1998; Fabian 1999; Granato et al. 2004).

3.3. Implications for Compton Thick Nuclear Activity at High Redshift

We derive a crude value of the volume density of CT AGN with high EW iron Kα emission, based on our two detections. We conservatively use the full redshift range explored by the $BzK$ selection ($z = 1.4$–3), finding a space density of $3 \times 10^{-6} \ Mpc^{-3}$. This is consistent with the predictions of the Gilli et al. (2007) XRB synthesis model, for CT AGN with $L_{2–10 \ keV} > 10^{44} \ erg \ s^{-1}$. However, we note that our sampling of $L_{2–10 \ keV} > 10^{44} \ erg \ s^{-1}$ AGNs with CT absorption at $1.4 < z < 3$ might be substantially incomplete due to selection effects, and the luminosity of at least one of the $BzK$ galaxies in this Letter might be substantially higher than the adopted $10^{44} \ erg \ s^{-1}$ limit.

We emphasize that the sources presented here have X-ray spectra that are the high-luminosity analogous of those of local prototype CT AGNs. This discovery represents one of the first clear-cut evidence for this class of objects at high redshift. Our results confirm that indeed there is a population of CT QSO among massive, star-forming, dust obscured galaxies, as suggested by several studies (D07; Fiore et al. 2008; Treister et al. 2010; Alexander et al. 2008; Lanzuisi et al. 2009) and as predicted by models of merger-driven AGN/galaxy co-evolution (Silk & Rees 1998; Fabian 1999; Di Matteo et al. 2005). Indeed, these luminous CT quasars appear to be hosted by galaxies with optically thick UV emission, which are a relative small minority among $BzK$ s (Daddi et al. 2007a) and imply the presence of a dense starburst usually connected with mergers. This seems to agree with evolutionary scenarios, where mergers induce both rapid accretion onto supermassive black hole and intense star formation activity.

The two sources presented here have high intrinsic X-ray and bolometric luminosity, and bright iron Kα line, allowing their identification. They might represent just the tip of the iceberg of a much larger population of highly obscured AGNs with somewhat lower intrinsic luminosity, whose iron lines...
are still remaining hardly detectable even in the deepest hard X-ray surveys. For example, the Gilli et al. (2007) model predicts a \( \sim 10^\times \) higher space density of CT sources with \( \int L_{\text{2–10 keV}} > 10^{43} \text{ erg s}^{-1} \). Detecting iron lines in galaxies with such luminosities might be challenging with current facilities, even if they have similar EW as in \( BzK_{4892} \) and \( BzK_{8608} \).

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