A CLASSIC TYPE 2 QSO

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ABSTRACT

In the Chandra Deep Field–South 1 Ms exposure, we have found, at redshift 3.700 ± 0.005, the most distant type 2 active galactic nucleus ever detected. It is the source with the hardest X-ray spectrum with redshift \( z > 3 \). The optical spectrum has no detected continuum emission to a 3 \( \sigma \) detection limit of \( \sim 3 \times 10^{-19} \) ergs s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) and shows narrow lines of Ly\(\alpha\), C iv, N v, He ii, O vi, [O iii], and C iii]. Their FWHM line widths have a range of \( \sim 700–2300 \) km s\(^{-1}\) with an average of \( \sim 1500 \) km s\(^{-1}\). The emitting gas is metal-rich (\( Z \simeq 2.5–3 \) \( Z_\odot \)). In the X-ray spectrum of 130 counts in the 0.5–7 keV band, there is evidence for intrinsic absorption with \( N_H \gtrsim 10^{24} \) cm\(^{-2}\). An iron K\(\alpha\) line with rest-frame energy and equivalent width of \( \sim 6.4 \) keV and \( \sim 1 \) keV, respectively, in agreement with the obscuration scenario, is detected at a 2 \( \sigma \) level. If confirmed by our forthcoming XMM-Newton observations, this would be the highest redshift detection of Fe K\(\alpha\). Depending on the assumed cosmology and the X-ray transfer model, the 2–10 keV rest frame luminosity corrected for absorption is \( \sim 10^{45} \pm 0.5 \) ergs cm\(^{-2}\) s\(^{-1}\), which makes our source a classic example of the long-sought type 2 QSO. From standard population synthesis models, these sources are expected to account for a relevant fraction of the black hole–powered QSO distribution at high redshift.

Subject headings: quasars: emission lines — quasars: individual (CXOCDFS J033229.9–275106) — X-rays: galaxies

On-line material: color figures

1. INTRODUCTION

The unified model for active galactic nuclei (AGNs) is widely accepted. Briefly, the physics of black hole, accretion disk, jet, and obscuring torus is convolved with the geometry of the viewing angle and can explain most of the apparent disparate properties of active galaxies (Antonucci 1993). The use of the word “torus” here is generic for the obscuring region, since there are many variants of the geometry of the obscuring region, including a strict toroidal geometry and flaring disk models (Efstathiou & Rowan-Robinson 1995; Granato, Danese, & Franceschini 1997). Type 1 objects exhibit the straight physics of AGNs with no obscuration, and type 2 objects arise when the view is obscured by the torus. A crucial component that has long been sought is heavily obscured powerful quasars called type 2 QSOs. They have been predicted to have narrow permitted lines, powerful hard X-ray emission, and a high equivalent width Fe K\(\alpha\) line (Ghisellini, Haardt, & Matt 1994).

In the absence of a good standard case, doubt has been expressed at times about the whole type 2 QSO phenomenon (Halpern, Turner, & George 1999). The successful finding of an optically obscured central AGN in the starburst NGC 6240 (Vignati et al. 1999) made X-rays the obvious wavelength with which to uncover the type 2 QSO phenomenon. There have been few previous studies of candidate type 2 objects in the X-ray band. One was observed by ROSAT and ASCA (Almaini et al. 1995; Georgantopoulos et al. 1999). Two are underluminous objects from ASCA (Ohta et al. 1996) and Chandra (Fabian et al. 2000). Also, the hyperluminous infrared galaxy IRAS 09104+4109, observed with BeppoSAX (Franceschini et al. 2000) and recently with Chandra (Iwasawa, Fabian, & Ettori 2001), appears to be an example of a type 2 QSO at moderate redshift, \( z = 0.442 \). It is a cD galaxy in a rich cluster and is radio-loud with a radio jet. A recent candidate at high redshift (\( z = 3.288 \)) has been found in the deep Chandra exposure of the Lynx field (Stern et al. 2002).

Parallel with the X-ray work, imaging and spectropolarimetric studies on warm ultraluminous infrared galaxies (ULIRGs) indicate that all of them might contain buried QSOs (Tran, Cohen, & Villar-Martin 2000). In addition, high-redshift radio galaxies (H ZarGs) harbor obscured QSOs, and intensive studies are underway to understand the physics of the central regions of these objects (Vernet et al. 2001).

From our multiwaveband studies of the 1 Ms exposure of the Chandra Deep Field–South (CDF-S; Giacconi et al. 2001, 2002; Tozzi et al. 2001; Rosati et al. 2002), we now discuss a classic X-ray–selected type 2 QSO: CXOCDFS J033229.9–275106 (hereafter CDF-S 202). We note in passing that in contrast to the radio studies mentioned above, CDF-S 202 is radio-quiet.
the ESO Imaging Survey (EIS) and reaches 23.6 in the limiting magnitude of 26. The near-infrared data come from data taken on the 2.2 m ESO telescope, which reaches a limiting flux of 21.8 in $K_s$.

We assume a cosmology in this paper with the parameters $H_0 = 60$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

## 2. IMAGING OBSERVATIONS

We have combined 11 individual Chandra pointings into a mosaic with a maximum of 942 ks of exposure time (hereafter the 1 Ms exposure). The limiting fluxes achieved are $5 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.5–2 keV band and $4.5 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ in the 2–10 keV band (Rosati et al. 2002). The details of the X-ray observations are given in Giacconi et al. (2001b). Among the sources with $z > 3$, CDF-S 202 is the one with the hardest X-ray spectrum. In the X-ray image from 0.5 to 7 keV, the source is $\sim 3'$ from the center, where the point response function has an FWHM of 1". The X-ray intensity profile is completely consistent with that of a point source at this resolution. There are no other X-ray sources detected within 30''.

The primary optical ID was made in deep $R$- and $I$-band images ($[R_{\text{Vega}}] \leq 26$) obtained using the Focal Reducer Spectrograph (FORS1) on the European Southern Observatory Very Large Telescope 8.2 m facility (ESO/VLT-ANTU). All magnitudes quoted in this paper are Vega magnitudes. CDF-S 202 has an $R$ magnitude of 23.53 and an $I$ magnitude of 22.65. We have additional photometric coverage of this object in the $U$, $V$, $B$, $J$, and $Ks$ bands (see Table 1). The $B$ band used here is from ESO Wide-Field Imager data taken on the 2.2 m ESO telescope, which reaches a limiting magnitude of 26. The near-infrared data come from the ESO Imaging Survey (EIS) and reaches 23.6 in $J$ and 21.8 in $Ks$. Of these five bands, our candidate type 2 QSO is detected significantly in $V$ and $Ks$ at 25.27 and 20.99, respectively. The $B$-band source is very faint, essentially at the limiting magnitude. The images in the $B$, $R$, $I$, $J$, and $Ks$ bands are given in Figure 1.

## 3. OPTICAL SPECTROSCOPY

### 3.1. Observations and Data Reduction

The optical spectrum was obtained with the multislit mode in the FORS1 on the ESO/VLT-ANTU on 2000 November 25. The FORS instrument is described in detail in Mitsch et al. (1994). The spectroscopy was obtained using the 1501+17 grism and no order separation filter, which allows maximum wavelength coverage but introduces second-order contamination. This grism gives a spectral resolution of $5.5 \, \text{Å}$ pixel$^{-1}$. The detector slit width was 1.0" (around 30 Å dispersed), chosen to maximize the signal-to-noise ratio (S/N) of the resulting spectra (i.e., including most of the light from the object, but minimizing the sky background). The final spectrum is composed of seven exposures with a total integration time of $\sim 3$ hr.

Data reduction was carried out using the IRAF package. This involved bias subtraction, flat-fielding, background subtraction, wavelength, and flux calibration. The background was subtracted by fitting a second-order polynomial to each column. The spectrum was extracted using an aperture width of 14 pixels, which was sufficient to include the total emission from the object.

Wavelength calibration was derived using the spectra from four arc lamps (He, HgCd, and two separate Ar lamps) taken on the same night. Line centers and shapes can only be determined to a few Å accuracy because of the finite slit width. In addition, the exact location of the object on the slit can introduce an additional few Å systematic shift in the spectrum. These limit the redshift to an accuracy of $\pm 0.005$. It is also important to note that the finite slit size and seeing introduces an artificial broadening of the lines. As the seeing is potentially wavelength-dependent, this effect can also be wavelength-dependent. We estimate this effect to be a few times 10 Å. Therefore, the line widths measured (see Table 2) should be considered upper limits.

The spectra were flux calibrated using very wide (5") slits using both a red and a blue photometric standard star for comparison. As the seeing is potentially wavelength-dependent, applying this flux calibration can introduce a wavelength-dependent slit loss (in addition to the varying slit loss introduced by the atmospheric refraction). Considering the relatively good seeing ($0.5$ FWHM at the beginning of the observation) and low air mass, this color effect is not very strong. Second-order contamination was removed from the spechot standard observations using two standards.

![Fig. 1](image-url) — Optical and near-IR images with the X-ray brightness contours overlaid. Optical and near-IR images are 20" across; the X-ray contours correspond to 3, 5, 10, and 20 $\sigma$ levels above the background for the 2–7 keV image. [See the electronic edition of the Journal for a color version of this figure.]
with very different spectral shape. This made it possible to calibrate the true throughput of the system. Because of the very faint continuum of CDF-S 202, the second-order contamination was not removed from its spectra. This implies that the continuum shape would be incorrect (if we could detect it), but the emission-line features are correctly calibrated. Comparing the spectra obtained using each photometric standard, we estimate that our flux calibration is accurate to 5%. At present, we use known CTIO extinction curves until ESO extinction curves for Paranal become available to us.

### 3.2. Emission-Line Analysis

QSOs can be classified into type 2 and type 1 objects in a similar fashion to Seyfert galaxies, which are generally classified based on their relative emission-line widths using the scheme proposed by Weedman (1970, 1973) and Khachikian & Weedman (1971, 1974). In this scheme, Seyfert galaxies that show broad H α, He i, and He ii emission lines FWHM \(\sim(3-5) \times 10^3\) km s\(^{-1}\) are known as Seyfert 1 galaxies. These galaxies also display strong blue continua, and frequently complexes of broad Fe ii emission are also seen. Superposed on this spectrum are ”narrow” forbidden lines, which are thought to be formed in a much larger extended narrow-line region around the nucleus.

The forbidden lines in Seyfert 1 galaxies such as [O iii], [N ii], and [S ii] typically have FWHM of \(\sim5 \times 10^2\) km s\(^{-1}\). Galaxies with permitted and forbidden lines with approximately the same FWHM (typically \(\sim5 \times 10^2\) km s\(^{-1}\)) are called Seyfert 2 galaxies. The broad lines are absent in such objects and they display a flat, featureless continuum (e.g., Kinney et al. 1993; Heckman et al. 1995). Similarly, broad QSO emission lines typically have widths of 5000–5000 km s\(^{-1}\), while narrow QSO emission lines are a few hundred km s\(^{-1}\) (e.g., Peterson 1997; Forster et al. 2001).

To determine the emission-line fluxes and FWHM for CDF-S 202, the optical spectral line profiles were modeled by one Gaussian per line using the ngaussfits task in IRAF. This routine uses least-squares fitting implemented by a downhill simplex minimization algorithm. The resulting emission-line fluxes and FWHMs found for the emission lines in CDF-S 202 are given in Table 2. The final spectrum is shown in Figure 2. The permitted emission lines, O iv, Lyα, N v, C iv, and He ii, have S/N greater than 3 \(\sigma\) and are well identified, giving a redshift of \(z = 3.700 \pm 0.005\). The continuum is not detected to a 3 \(\sigma\) limit of \(\sim3 \times 10^{-19}\) ergs s\(^{-1}\) cm\(^{-2}\) A\(^{-1}\). This is consistent with the flat, featureless continuum seen in many type 2 objects such as NGC 3393 (e.g., Kinney et al. 1993; Heckman et al. 1995).

The emission-line widths of CDF-S 202 are given in Table 3. They have a rest-frame FWHM of between \(\sim700\) and \(2300\) km s\(^{-1}\). Note that these FWHMs are actually upper limits, as discussed in the previous section, and that the

### Table 2

**Optical Spectroscopy (Rest Frame)**

| Parameter | Lyα | N v | C iv | He ii |
|-----------|-----|-----|------|-------|
| F(10^{-18} ergs cm^{-2} s^{-1}) | 16.4 | 5.9 | 9.9 | 2.8 |
| FWHM (Å) | <5 | <7 | <9 | <4 |
| Velocity width (km s^{-1}) | <1130 | <1680 | <1680 | <680 |

* a Errors in emission-line fluxes are estimated to be 5%.

### Table 3

**X-Ray Data**

| Model | Transmission | Reflection |
|-------|--------------|------------|
|       | 1.8 | 1.8 |
| \(N_H (10^{22} \text{cm}^{-2})\) | 7.9^{+5.5}_{-3.3} | \(\geq 10^2\) |
| \(E_{\text{FeKα}}\) (rest-frame eV) | 823\(_{+131}^{-124}\) | 1186\(_{+119}^{-112}\) |
| \(F_{1.5-6\text{keV}} (10^{-16} \text{ergs cm}^{-2} \text{s}^{-1})\) | 2.21 \pm 0.33 | 2.25 \pm 0.33 |
| \(F_{2-10\text{keV}} (10^{-16} \text{ergs cm}^{-2} \text{s}^{-1})\) | 20.6 \pm 3.0 | 25.8 \pm 3.5 |

* a Assuming 6.4 and 0 keV for the rest-frame line energy and width, respectively.

### Figure 2

Low-resolution optical spectrum of CDF-S 202 obtained with VLT UT1 FORS1. The emission features that the redshift determination is based on are marked. Wavelength calibration inaccuracies limit the accuracy of redshift determination to \(\pm 0.005\). Flux calibration of emission lines is good to 5% in the range displayed. Data were not corrected for slit loss, which we estimate to be around 30% and nearly achromatic.
We note that the absorption seen in CDF-S 202 of $N_H \gtrsim 10^{24}$ cm$^{-2}$ is common for type 2 objects (Maiolino et al. 1998; Risaliti, Maiolino, & Salvatii 1999) but not for type 1 objects (Reeves & Turner 2000). In addition, the flat, featureless continuum to a 3σ flux limit of $\sim 3 \times 10^{-19}$ ergs s$^{-1}$ cm$^{-2}$ supports a type 2 classification of CDF-S 202.

Figure 3 shows the N v/He ii versus N v/C iv diagram with models by Vernet et al. (2001) and Hamann & Ferland (1993). Hamann & Ferland (1993) showed that high-redshift quasars ($z > 2$) define a tight correlation, indicated by the dashed line in this figure. This correlation is predominantly a result of metallicity variations in which the higher redshift quasars have higher metallicities. This redshift-metallicity effect may be due to higher QSO or host galaxy masses at higher redshifts. From Figure 3, we can see that the N v/C iv and N v/He ii ratios for CDF-S 202 are strong, similar to those previously seen in type 1 QSOs and powerful radio galaxies at similar redshifts (Hamann & Ferland 1993; Vernet et al. 2001). The position of CDF-S 202 in this figure indicates emission-line ratios intermediate between HZRGs and broad emission-line regions of QSOs (BLR QSOs).

The solid line shown in Figure 3 gives the best-fit power-law photoionization model for HZRGs run by Vernet et al. for metallicities from 0.4 to 4 Z$_\odot$. Similarly, the Hamann & Ferland (1993) model for BLR QSOs is shown in dashes. From these models, CDF-S 202 appears to be a high-metallicity ($Z \sim 2.5$–3 Z$_\odot$) object at the high end of the metallicity range found in HZRGs by Vernet et al. although an independent metallicity diagnostic is required to verify this.

The He ii/C iv ratio is $\sim$0.3. Heckman et al. (1995) note that this ratio is typically 0.1 in Seyfert 1 galaxies compared with 0.9 for Seyfert 2 galaxies. Narrow-line radio galaxies (the radio-loud analogs to Seyfert 2 galaxies) also show strong He ii/C iv ratios ($\sim$0.9; McCarthy 1993), while spectra of high-z quasars resemble the Seyfert 1 galaxies with He ii/C iv $\sim$ 0.15 (Francis et al. 1991). The He ii/C iv ratio for CDF-S 202 is intermediate between the type 1 and type 2 values. However, CDF-S 202 is more likely a type 2 QSO rather than an intermediate QSO, since its emission-line velocity widths are relatively narrow, and heavy obscuration is confirmed from the X-rays.

4. X-RAY SPECTROSCOPY

The X-ray spectrum of CDF-S 202 and the relative background spectrum were extracted from the X-ray image using the standard CIAO v2 software. The source spectrum was extracted in a circle with radius $R = 5''$, while the background spectrum was extracted in an annulus between $R + 2''$ and $R + 12''$ around the source position. We verified that changing the source extraction radius does not affect our results significantly. With the same software, we produced response matrix functions at the CDF-S 202 position. The X-ray spectrum of CDF-S 202 was then analyzed using XSPEC v11.0. The data were rebinned to have at least 10 counts per bin (source+background) in order to validate the use of the $\chi^2$ statistics. Hereafter, errors are quoted at the 90% confidence level for one interesting parameter ($\Delta \chi^2 = 2.71$). The fit with a simple power law absorbed by the Galactic hydrogen gives a very flat slope ($\Gamma = 0.51 \pm 0.27$) suggesting heavy absorption. We then considered two possible scenarios. First, we assumed that the X-ray emission is transmitted through an absorber that cuts off the spectrum at low energies. Usually, the absorber is identified with the putative obscuring torus expected from unified schemes, although its geometry could be different. Second, we assumed that the X-rays are reflected. The obscuring material is then optically thick to Compton scattering with no transmitted X-rays observed in the Chandra band up to $7(1+z) \sim 33$ keV, implying $N_H \gtrsim 10^{25}$ cm$^{-2}$. In this case, the X-rays are reflected by the inner edge of the torus (or any cold cloud off the line of sight). Generally, for large equivalent widths of the Fe Kα line, the reflection model is favored (Ghisellini et al. 1994).

We considered the transmission model first and fitted the spectrum with an absorbed power law (see Table 3). The best-fit photon index ($\Gamma = 1.847$) is poorly constrained, therefore we fixed it to be $\Gamma = 1.8$, a standard value for AGNs, deriving a column density of $N_H = 6.7_{-2.4}^{+2.4} \times 10^{23}$ cm$^{-2}$. A residual excess around 1.4 keV suggested the presence of an iron Kα line at 6.4 keV rest frame [6.4 keV/(1 + 3.700) $\sim$ 1.4 keV]; therefore, we added a narrow Gaussian line to the model, fixing the line energy to 6.4 keV and the line width to 0 keV. The addition of the iron line changes the $\chi^2$/dof value from 11.6/16 to 9.5/15; the fitted column density slightly increases to $N_H = 7.9_{-2.3}^{+2.5} \times 10^{23}$ cm$^{-2}$. Although the iron line detection is not significant (less than 2 σ level according to a F-test for one additional free parameter), we will leave the line in the transmission model for comparison with the reflection model. The line equivalent width in the observed frame is $EW_{Kα} = 175_{-175}^{+360}$ eV, corresponding to $EW_{Kα} = 823_{-823}^{+1694}$ eV in the rest frame. The 2–10 keV rest-frame luminosity is calculated to be $4.4 \times 10^{43}$ ergs s$^{-1}$. When correcting for absorption, the intrinsic 2–10 keV rest-frame luminosity is $3.3 \times 10^{44}$ ergs s$^{-1}$. In Figure 4, we show the fit to the X-ray spectrum together with the best-fit transmission model.

We then considered a pure reflection model using the pexrae model in XSPEC with $\Gamma$ fixed to 1.8 and adding at the $\sim$6.4 keV rest frame a narrow Gaussian line with $\sigma_{Kα} = 0$ keV. The description of the data is as good as in the transmission model ($\chi^2$/dof = 10/15; see Fig. 5). With this...
model, the line is detected at greater than the 2 \( \sigma \) level according to an \( F \)-test for one additional free parameter (\( \Delta \chi^2 = 4.6 \) with respect to the same reflection model without the line). The rest-frame line energy and equivalent width are \( E_{K\alpha} = 6.43 \pm 0.34 \) keV and \( EW_{K\alpha} = 1186^{+1195}_{-322} \) eV, respectively. The line equivalent width is then in full agreement with the expectations from Compton thick sources (Ghisellini et al. 1994). Assuming a reflection efficiency of 3\% (see, e.g., Krolik, Madau, & Zycki 1994; Maiolino et al. 1998; and \$ 3.1 in Gilli, Risaliti, & Salvati 1999), the 2–10 keV rest-frame intrinsic luminosity of the source is \( 1.4 \times 10^{45} \) ergs s\(^{-1}\).

In principle, one could look at the source variability to estimate which scenario is favored. Indeed, short-term variability, on timescales of a few tens of kiloseconds, indicates that the observed radiation is transmitted rather than reprocessed by a parsec-scale reflecting material. Unfortunately, analysis of short-term variability is not possible given our photon statistics. Also, long-term variability (the data were collected in a 14 month period) is poorly constrained.

We note also in passing the blip in the X-ray spectrum at 3.2 keV, corresponding to a rest-frame energy \( \sim 15 \) keV. This is not a statistically significant line in the spectrum, but we point out that such features have been found twice previously in ASCA observations of other AGNs and may be associated with Doppler-boosted Fe K\( \alpha \) (Yaqoob et al. 1999).

5. Discussion and Implications

How common are type 2 QSOs, and how can more be detected? This object stood out in a hardness ratio–redshift plot of the currently cataloged sources in CDF-S as the highest redshift source with the hardest spectrum. One would expect to observe the red \( (R-Ks \gtrsim 4) \) colors of the host galaxy (see, e.g., Fig. 7 in Lehmann et al. 2001). In this case, at \( z = 3.700 \), the \( R-Ks \) color of \( \sim 2.5 \) does not reflect the galactic continuum, but rather the chance superposition of emission lines into the broadband filters. For CDF-S 202, the \( R \) band contains both Ly\( \alpha \) and C iv, while the \( Ks \) band contains the weaker H\( \beta \), H\( \delta \), and He ii. Since the CDF-S 202 optical continuum is not detected, we used the NGC 1068 template redshifted to \( z = 3.7 \) to verify the effect of line subtraction to the optical-infrared colors, assuming that the NGC 1068 spectrum is identical to that of CDF-S 202. We found that \( R-Ks = 3.92 \) when lines are subtracted, which is comparable with the Lehmann et al. findings.

Both observed and corrected (i.e., line-subtracted) magnitudes are shown in Figure 6, along with the X-ray spectrum and the radio upper limit \( (F_\nu < 100 \mu Jy, F_\nu \) is the flux density at 20 cm) derived from VLA observations (K. Kellerman 2001, private communication; see Table 4). To put our data into perspective, they have been shifted to the rest frame and compared with the spectral energy distribution (SED) the nearby galaxy NGC 6240 (Hasinger 2000), which has no AGN signatures in its optical spectrum but shows clearly a buried AGN emerging at higher X-ray energies (Vignati et al. 1999).

The inferred metallicity for this object is \( \gtrsim Z_\odot \) typical of high-redshift AGNs but on the high side. In fact, looking at our diagnostic diagram, CDF-S 202 has a higher metallicity than any of the high-z radio galaxies of Vernet et al. (2001) and Hamann & Ferland (1993). Indeed, it has been found that there is a metallicity evolution such that for redshift \( z > 3 \) radio galaxies, the metallicity is less than 2 \( Z_\odot \) (de Breuck et al. 2000). This relatively high metallicity is consistent with a high star formation rate during these early epochs as the bulge and central black hole are formed.

\[ q_0 = 0 \] gives luminosities higher by a factor of \( \sim 3 \).

We note that assuming \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 0 \) gives luminosities higher by a factor of \( \sim 3 \).
Assume now that the Fe Kα line arises in the obscuring cloud. We will now estimate various quantities of the obscuring region using either standard parameters or, where possible, parameters inferred from our data. To simplify the calculation, we assume that the obscuring cloud is spherical. From other studies (Gilli, Salvati, & Hasinger 2001) we find that the type 2 to type 1 ratio is ~10 at high redshift, therefore it is a reasonable assumption that the obscuring torus is an almost totally enclosing cloud.

We define the ionization parameter, \( U \), in the usual manner as

\[
U = \frac{L_x}{n r^2}
\]

(1)
in an obscuring material of density \( n \) at distance \( r \) from the source. For standard values, \( U = 10^2 \) ergs cm s\(^{-1} \) (Matt, Fabian, & Ross 1996).

For the inferred absorbing column \( N \) of the spherical uniform cloud, we find

\[
N = n r.
\]

(2)

For a typical inferred absorbing column, we use a value of \( N = 10^{24.5} \) cm\(^{-2} \), which is consistent with canonical estimates expected for type 2 QSOs and also with our inferred column densities in § 4.

It follows directly that the radius of the cloud is

\[
r = \frac{L_x}{NU} \sim 1 \text{ pc} \times \frac{L_x}{10^{45} \text{ ergs s}^{-1}} \frac{10^2 \text{ ergs cm}^{-2} \text{ s}^{-1}}{U} \times \frac{10^{24.5} \text{ cm}^{-2}}{N},
\]

(3)

and the density of the cloud is

\[
n = \frac{N^2 U}{L_x}.
\]

(4)
The mass estimate of the obscuring cloud, \( M_{\text{cloud}} \), is

\[
M_{\text{cloud}} = \frac{4\pi \mu m_H n r^3}{3} = \frac{4\pi}{3} \mu m_H \frac{L_x^2}{NU^2},
\]

(5)

where \( \mu \) is the mean molecular weight of the obscuring material. We then estimate the mass in the obscuring region \( M_{\text{cloud}} \) to be

\[
M_{\text{cloud}} \sim 1 \times 10^5 \, M_\odot \frac{L_x}{10^{45} \text{ ergs s}^{-1}} \times \frac{10^2 \text{ ergs cm}^{-2} \text{ s}^{-1}}{U} \frac{10^{24.5} \text{ cm}^{-2}}{N_H}.
\]

(6)

We assume now that the velocity dispersion outside the obscuring cloud can still be dominated by influence of the black hole. This will not always be the case, but here the numbers are sufficiently interesting and consistent to analyze the problem further. Then, the velocity dispersion, \( \sigma_{\text{cloud}} \), just outside the obscuring region is given by

\[
\sigma_{\text{cloud}}^2 = \frac{G M_{\text{BH}}}{r},
\]

(7)

where \( M_{\text{BH}} \) is the mass of the black hole. It follows directly that

\[
\sigma_{\text{cloud}} = \frac{G M_{\text{BH}}}{L_x} (NU).
\]

(8)

We further rewrite the black hole mass in terms of the Eddington luminosity given by

\[
M_{\text{BH}} = \frac{\sigma_T}{4\pi G c m_H} L_{\text{Edd}},
\]

(9)

and then

\[
\sigma_{\text{cloud}}^2 = \frac{\sigma_T}{4\pi G c m_H} \frac{L_{\text{Edd}}}{L_x} (NU).
\]

(10)

Now we can estimate that the velocity dispersion just outside the obscuring region is

\[
\sigma_{\text{cloud}} \lesssim 2500 \, \text{ km s}^{-1} \left( \frac{L/L_{\text{Edd}}}{10^2} \right)^{1/2} \times \left( \frac{U}{10^3 \text{ ergs cm}^{-1} \text{ s}^{-1}} \right)^{1/2} \left( \frac{N}{10^{24.5} \text{ cm}^{-2}} \right)^{1/2}.
\]

(11)

We have assumed here that the black hole is generating X-rays with an efficiency of 1% relative to the Eddington luminosity, which we justify as follows. As discussed by Elvis et al. (1994), the ratio of X-ray luminosity to bolometric luminosity, \( L_{\text{bol}}/L_{\text{Edd}} \), is 10%. Here, we assume \( L_{\text{bol}}/L_{\text{Edd}} \) is...
also 10%. The inferred mass of the black hole is then

\[ M_{\text{BH}} \sim 8 \times 10^8 M_\odot \frac{10^{-2}}{L_X/L_{\text{bol}}} \frac{L_X}{10^{45} \text{ ergs s}^{-1}}. \]  

(12)

This explains the rather large width of the narrow lines that originate outside the obscuring region. That such a dense cloud closely covers the nucleus in high-redshift type 2 objects is to be expected, since in the galaxy-formation process large amounts of gas are present in the bulge-forming black hole growing epoch. The encapsulation of the nucleus probably increases with redshift.

We now discuss our analysis and analyze the energetics of the line emission. Following the standard scenario, we assume that (1) the ratio of UV to X-ray luminosity is 10 (Elvis et al. 1994); (2) 10% of the UV continuum escapes, consistent with the ratio of type 2 to type 1 ~10 at high redshift; (3) 10% of the continuum flux is reradiated isotropically into lines; and (4) the covering factor of the narrow-line region is 10%. We find that the line flux should be

\[ 10^{-2} L_X. \] 

The actual line flux is \[ L_{\text{line}} \sim 2 \times 10^{43} \text{ ergs s}^{-1}, \] roughly consistent with the above model. In a similar calculation, we use the observationally derived relation

\[ L_{\text{Ly} \alpha} \sim 10^{-2} L_{\text{bol}} \] 

(Vanden Berk et al. 2001; T. Heckman 2001, private communication), where \( L_{\text{bol}} \) is the bolometric luminosity of the QSO and \( L_{\text{Ly} \alpha} \) is the narrow-line luminosity in \( \text{Ly} \alpha \). We then find that CDF-S 202 has an inferred luminosity from the \( \text{Ly} \alpha \) line of \( L_{\text{bol}} = 2 \times 10^{46} \text{ ergs s}^{-1} \). In addition, the X-ray luminosity inferred from the line strength and the observationally determined value

\[ L_X/L_{\text{bol}} = 0.1 \] 

Elvis et al. 1994) is \[ L_X = 2 \times 10^{46} \text{ ergs s}^{-1}. \] This constructs a consistent picture of CDF-S as an enshrouded type 2 QSO.

In general, for observations to support such an analysis of type 2 QSOs physics as given above, we would like to study in the future a significantly lower redshift sample of X-ray–selected type 2 QSOs to attempt to infer the depth of the potential well via the rotation curve and the central stellar velocity dispersion using, say, Space Telescope Imaging Spectrograph observations. Imaging observations of such objects in CDF-S with the Hubble Space Telescope (HST) can give important morphological constraints (see Schreier et al. 2001) and possibly an estimate of the bulge mass, which can also be used to estimate the black hole mass (Magorrian et al. 1998; Gebhardt et al. 2000). In addition, deep Chandra and XMM-Newton observations of high-redshift narrow-line radio galaxies (NLRGs) can give insight into the physics of type 2 QSOs. In unified models, NLRGs are the radio-loud equivalent of type 2 QSOs. It has been proposed by Ridgway et al. (2001) that a few percent of the Lyman break galaxy population (Steidel et al. 1999) may be type 2 QSOs. X-ray studies of a well-selected subsample of these Lyman break systems are also indicated.

It is expected from models that the radiation absorbed in the cold obscuring torus will be reradiated in the far-IR. IRAS 09014+4109 is such an object. Interestingly, it is the only hyperluminous infrared galaxy to be detected as an obscured AGN (Iwasawa et al. 2001). Deep IR imaging and spectroscopy are essential to constrain the contribution of type 2 QSOs to the IR background. Current thinking is that the AGN contribution may approach that due to star formation if sufficient type 2 QSOs contribute. For these powerful buried QSOs at high redshift, the type 2 to type 1 ratio is unknown but may continue to increase with redshift, giving a major contribution to the IR background. In a related issue, these type 2 QSOs may be powerful submillimeter sources. We already know that a fraction of optically identified Submillimeter Common-User Bolometric Array (SCUBA) sources are AGNs (Barger et al. 1999; Smail et al. 1999), although the bulk of the submillimeter population is not likely to be powered by AGNs, as suggested by the non-detections of SCUBA sources with Chandra (Hornschemeier et al. 2000). However, we must await the Atacama Large Millimeter Array (ALMA) to study them in detail in the CDF-S.

Depending on the assumed cosmology and X-ray transmission or reflection scenario, the intrinsic 2–10 keV rest-frame luminosity of CDF-S 202 varies from \( \sim 3 \times 10^{44} \) to \( \sim 3 \times 10^{45} \) ergs s\(^{-1}\). Even assuming the lowest luminosity value, CDF-S 202 is a powerful obscured AGN beyond the knee, or break in the slope, of the AGN X-ray luminosity function at \( L_{\text{x}} = 10^{43.7} \text{ ergs s}^{-1} \) (Miyaji, Hasinger, & Schmidt 2000). Above this break luminosity, \( L_{\text{x}} \), the X-ray–selected AGNs are QSOs. Let us now discuss the implications of CDF-S 202 for the origin of the X-ray background (Comastri et al. 1995). Based on the population synthesis models described by Gilli et al. (2001), obscured AGNs with \( L_{2–10} > 3 \times 10^{44} \text{ ergs s}^{-1} \) and \( N_H > 10^{22} \text{ cm}^{-2} \) should make a significant part (~30%) of the hard X-ray background. About 70% of them should be observed at \( z > 3 \), while 15% are expected at higher redshifts, assuming that the AGN space density decreases above \( z \sim 3 \), as found in optical and radio surveys (Schmidt, Schneider, & Gunn 1995; Fan et al. 2001; Shaver et al. 1999). On the same assumption, we expect eight obscured QSOs with intrinsic luminosity \( L_{2–10} > 3 \times 10^{44} \text{ ergs s}^{-1}, N_H > 10^{22} \text{ cm}^{-2}, \) and \( z > 3 \) to be observed in the 1 Ms CDF-S. We will have to await further analysis of these objects in CDF-S to understand the contribution of the type 2 QSO population relative to the other sources that make up the X-ray background.

6. CONCLUSIONS AND FUTURE WORK

We conclude that in the Chandra Deep Field–South 1 Ms exposure, we have found a type 2 QSO at redshift 3.700 (CDF-S 202). There is no generally accepted definition of a type 2 QSO. We suggest that CDF-S 202 defines the class of X-ray–selected QSOs, which is luminosity \((10^{45.0 \pm 0.5} \text{ ergs s}^{-1})\) in the 2–10 keV band), X-ray spectrum, narrow permitted lines (\((\sim 1500 \text{ km s}^{-1})\), and undetected continuum (to a limit of \((\sim 3 \times 10^{-19} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ A}^{-1})\)). There are several other candidates in the field that have hard spectra and high redshift. Clearly, in type 2 QSOs, the Fe K\(_\alpha\) feature can be used in conjunction with deep optical and IR faint-object spectroscopy to determine redshifts. CDF-S 202 has the highest redshift Fe K\(_\alpha\) line spectrum yet observed (Reeves et al. 2001).

We have discussed the implications for the X-ray background, the infrared background, the origin of the UV continuum in type 2 objects, and the relation of the growth of the black holes to bulge and galaxy formation. Currently, we aim to both increase the sample and observe CDF-S 202 fur-

\(^{10}\) Gilli et al. (2001) adopted \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 1, \) and \( \Omega_{\Lambda} = 0. \) Here, we quote their predictions correcting for the different cosmology adopted in this paper.
ther with IR spectroscopy and imaging, HST, millimeter facilities, and XMM-Newton.

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