RELATIVISTIC OUTFLOW IN CXOCDFS J033260.0–274748

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ABSTRACT

In this Letter we report the detection of a strong and extremely blueshifted X-ray absorption feature in the 1 Ms Chandra spectrum of CXOCDFS J033260.0−274748, a quasar at z = 2.579 with \( L_{2-10 \text{ keV}} \sim 4 \times 10^{44} \) ergs s\(^{-1}\). The broad absorption feature at \(-6.3\) keV in the observed frame can be fitted either as an absorption edge at 20.9 keV or as a broad absorption line at 22.2 keV rest frame. The absorber has to be extremely ionized with an ionization parameter \( \xi \sim 10^4 \), and a high column density, \( N_H > 5 \times 10^{23} \) cm\(^{-2}\). We reject the possibility of a statistical or instrumental artifact. The most likely interpretation is an extremely blueshifted broad absorption line or absorption edge, due to H or He-like iron in a relativistic jetlike outflow with bulk velocity of \( \sim 0.7c\)–0.8c. Similar relativistic outflows have been reported in the X-ray spectra of several other AGNs in the past few years.

Subject headings: galaxies: active — quasars: individual (CXOCDFS J033260.0–274748) — X-rays: galaxies

1. INTRODUCTION

The 1 Ms exposure of Chandra Deep Field–South (CDF-S; e.g., Giacconi et al. 2002; Rosati et al. 2002b), along with the 2 Ms exposure of Chandra Deep Field–North (CDF-N; e.g., Brandt et al. 2001; Alexander et al. 2003) are the deepest X-ray images ever taken. With these two deep surveys, the origin of the cosmic X-ray background discovered by Giacconi et al. (1962), which has been a major goal of X-ray astronomy for almost four decades, is now almost completely resolved into individual sources. Most of these X-ray sources are extragalactic, harboring supermassive black holes. The major goal now is to study the properties of these X-ray sources and understand their physical nature.

Most recent Chandra and XMM-Newton observations have detected relativistic outflows with bulk velocity of \( v_{\text{out}} \sim 0.6c\)–0.7c in several active galactic nuclei (AGNs; Yaqoob et al. 1998, 1999; Wang et al. 2003), which are revealed by extremely blueshifted emission lines due to iron or other elements in the X-ray spectra. In this letter, we report the discovery of a strong and blueshifted X-ray absorption feature (suggesting an even higher \( v_{\text{out}} \sim 0.7c\)–0.8c) in one of the CDF-S sources, CXOCDFS J033260.0−274748 (hereafter CDFS 11).

2. THE DATA AND X-RAY SPECTRAL FITTING

The 1 Ms Chandra exposure on CDF-S was composed of 11 individual ACIS observations obtained from 1999 October to 2000 December. Giacconi et al. (2002) presented the detailed X-ray data reduction and the final X-ray catalog (see also Alexander et al. 2003). The source CDFS 11, \( \sim 7\)′ from the center of the field, was observed in all 11 exposures. Its X-ray radial intensity profile is consistent with that of a point source (Giacconi et al. 2002), and no other X-ray source was detected within 45″. The optical counterpart of CDFS 11 (\( R_{\text{opt}} = 21.8 \)) was selected using the deep optical image (\( R_{\text{opt}} < 26 \)), obtained with the FORS1 camera on the Antu telescope (UT1 at VLT). Giacconi et al. (2002) presented the R-band image cutout, overplotted with X-ray flux contours (see their Fig. 13). We can clearly see a single pointlike optical counterpart located right at the center of the X-ray contours, with no nearby optical source within 7″. The source was firmly classified as a quasar at \( z = 2.579 \) by the follow-up spectroscopy observations (see Fig. 6 of Szokoly et al. 2004). The X-ray to optical flux ratio log \( (f_{2-10 \text{ keV}}/f_{\text{opt}}) \) is 0.3, typical for AGNs (see, e.g., Hornschemeier et al. 2001). A weak, flat-spectrum radio counterpart has also been detected with the VLA with flux densities of \( 36 \pm 10 \) \( \mu \)Jy at 6 cm, and 33 \( \pm 11 \) at 22 cm (K. Kellermann et al. 2005, in preparation), making it radio quiet with radio-to-optical ratio \( f_{2-10 \text{ keV}}/f_{\text{opt}} \sim 6 \).

We extract the Chandra ACIS-I X-ray spectrum of CDFS 11 from a circle with radius of 7″, which is the 95% encircled-energy (EE) radius of the ACIS point-spread function at the source position. The local background was extracted from an annulus with outer radius of 19″ and inner radius of 9″. In Figure 1 we present the summed spectrum (source plus background) and the background evaluated in the outer annulus. The source is fairly bright in X-ray, with \( \sim 1040 \) net X-ray counts in the 0.5–2.0 keV band and \( \sim 350 \) in the 2.0–9.0 keV band, allowing us to perform X-ray spectroscopy. During the fit, we use the C-statistics (Cash 1979; Nousek & Shue 1989), which perform better than the \( \chi^2 \) analysis, particularly for spectra with low detected counts. We generate the X-ray telescope response and ACIS-I instrument response for each single Chandra observation and sum the response files, weighting them for the corresponding exposure times. The final time-weighted response files were used for spectral analysis. We use XSPEC version 11.2 to perform the spectral fitting. All the spectral fitting was done in the energy band 0.5–9.0 keV, and all the statistical errors quoted in this Letter are at the 90% confidence level for one interesting parameter.

We first fitted the spectrum with a simple power law plus a neutral absorber in the source frame. A Galactic neutral hydrogen...
were rebinned for display purposes. The spectrum was well fitted by a power law ($\Gamma$) with weak emission line. We tried different central values for the line energy from 4 to 6 keV, and found that an emission line can only improve the fit with a power-law continuum and a broad emission line. We add an absorption edge to our fit, which attenuates the continuum above $E_{\text{edge}} = \tau_\text{e}(E/E_{\text{edge}})^{-\Gamma}$. An absorption edge with $E_{\text{edge}} = 5.8$ keV and $\tau_\text{e} = 3.5$ significantly improves the fit ($\Delta C = -15$ with two extra free parameters; see Table 1). We also tried to model the absorption feature by a saturated absorption line model. The model notch of XSPEC was used by fixing the covering fraction at 0.99 to represent a heavily saturated absorption. The covering factor of the notch model was fixed to 0.99 to represent a heavily saturated absorption. The upper limit of the absorption depth was poorly constrained.

The X-ray spectrum of CDFS 11 was found to be variable with high probability ($>3 \sigma$; Paolillo et al. 2004). However, due to the limited number of X-ray photons over 5 keV, and the fact that the absorption feature is optically thick with black trough, we are unable to study the variability of the absorption itself, based on our data. Sometimes, a broad emission line might actually be mimicked by a strong absorption edge at higher energy (e.g., Reeves et al. 2004) and vice versa, especially in X-ray spectra with low S/N or low-energy resolution. To check if this is the case for CDFS 11, we fit the spectrum with a power-law continuum and a broad emission line. We tried different central values for the line energy from 4 to 6 keV, and found that an emission line can only improve the C-statistics by $\Delta C \leq -2$. This indicates that the absorption feature in CDFS 11 cannot be ascribed to the presence of a broad emission line.

3. DISCUSSION

We discuss here the possible origin of the significant broad absorption feature we detected in the X-ray spectrum of CDFS 11 with the 1 Ms Chandra ACIS exposure. The feature locates at energies $>20$ keV in the rest frame, with a confidence level of 99.98% according to F-test. We note that the confidence level given by F-test for an absorption feature might not be accurate (Protassov et al. 2002). Here we re-estimate the confidence level of the absorption feature via a simple approach. In the energy range 5.8–6.8 keV where the absorption feature is located, we detected a total of 11 photons (source + background), while the continuum model + background predict

![Fig. 1.—Summed (source plus background) X-ray spectrum of CDFS 11 and the expected background (squares with dotted error bars). The spectra were rebinned for display purposes.](image)

![Fig. 2.—Spectral data (rebinned for display purposes), best-fit continuum models, and the ratios of data to model for CDFS 11.](image)

![Table 1: Spectral Fits to CDFS 11](table)

| Model | Parameters | Value |
|-------|------------|-------|
| Continuum: $\Gamma$ | $1.7 \pm 0.1$ |
| $N_H$ | $0.13^{+0.01}_{-0.00} \times 10^{22}$ cm$^{-2}$ |
| $C/dof$ | 362/356 |
| Edge: $E_{\text{edge}}$ | 20.9$^{+0.3}_{-0.3}$ keV |
| $\tau_\text{e}$ | 3.5$^{+0.3}_{-0.2}$ |
| $C/dof$ | 347/354 |
| Notch: $E_c$ | 22.5$^{+0.3}_{-0.3}$ keV |
| Width | 3.0$^{+0.3}_{-0.3}$ keV |
| $C/dof$ | 345/354 |
| Absorbi | $\xi > 9000$ |
| $N_H$ | $\geq 500 \times 10^{22}$ cm$^{-2}$ |
| $C/dof$ | 344/353 |

The covering factor of the notch model was fixed to 0.99 to represent a heavily saturated absorption. The upper limit of the absorption depth was poorly constrained.
32 photons. The cumulative Poisson probability for such a deviation is $\sim 1.7 \times 10^{-3}$. Since the absorption feature was examined over the whole spectral band, which is 0.5–9.0 keV, the probability of detecting such a broad spurious absorption feature randomly in the spectrum is approximately $1.7 \times 10^{-3}(9.0-0.5) = 2.0 \times 10^{-4}$. This is consistent with the confidence level obtained with the F-test.

We also perform extensive Monte Carlo simulations to check the confidence level. First, we simulate 104 artificial spectra based on the best-fitting continuum model. We then search for spurious absorption lines in the artificial spectra by adding a notch component. All the three parameters of the notch model (central energy, width, and covering factor) are thawed. We did not fix the covering factor at 0.99 during the simulation because a shallower absorption line (i.e., with lower covering factor) can reach a comparable significance level at lower energy due to the higher S/N. To ensure an efficient search over the whole band, we perform the search in narrow energy bins (such as 0.5–1.5, 1.5–2.5 keV, etc.) with width comparable to that of the observed absorption feature, and count the total number of spectra in which we detected spurious absorption lines with $\Delta C < -17$. We found only six spectra with statistically significant broad (energy width $>0.5$ keV) spurious absorption lines. This indicates a confidence level of 99.94% for the broad absorption feature we detected. Note also that, while fitting the real spectra, we use only two free parameters of the notch model, while in the simulation, we use three. We remark that the confidence level would be higher (99.98%) if we searched for spurious features with $\Delta C < -19.6$ for three free parameters, instead of $\Delta C < -17$ for two.

We note that there is also weak evidence of the absorption feature in the 370 ks XMM-Newton spectrum (Streblyanska et al. 2004) of CDFS 11. The XMM-Newton spectrum is significantly steeper ($\Gamma = 2.3$) and was obtained about one year later. The statistical quality of the XMM-Newton spectrum around 6 keV is much lower due to the high background noise and the steeper continuum. By fitting the Chandra and XMM-Newton spectra simultaneously, we found an even higher confidence level of 99.97% for the absorption feature, based on F-test. However, due to the very limited statistical quality, we are unable to use the XMM-Newton spectrum independently to constrain the nature and possible time variability of the absorption feature.

We conclude that the confidence level of the absorption line we detected in CDFS 11 is $>99.98\%$. Even considering the number of all the CDF-S spectra we examined for interesting features ($\sim 30$ CDF-S spectra have X-ray photons $>500$, whose quality is high enough to make the search for broad line features possible), the absorption feature is still significant with a confidence level of 99.4%.

3.1. Instrumental Artifact?

Could such an unusual X-ray feature be due to any instrumental artifact or to some aspect of our analysis? We first consider improper background subtraction as a possible origin of the absorption feature. We check that we obtain consistent results when using background spectra extracted from different regions of the detector. We also note that the absorption feature is already significant in the spectrum without background subtraction. Finally, we do not see any bump at $\sim 6$ keV in the background spectrum either, suggesting that the significance level of the feature is not magnified by background subtraction. Therefore, we conclude that the absorption feature is not related to uncertainties in the background subtraction.

Could the absorption feature be an artifact of calibration uncertainty in the ACIS instrumental response function? As far as we know, no such artifact (i.e., an absorption feature at $6.3$ keV) has been reported. We examined the spectra of nearby X-ray sources, but we found no evidence of an absorption feature at $6.3$ keV among them. Tozzi et al. (2005) presented the X-ray spectra of CDF-S sources using updated Chandra calibration files (with CIAO3.0.1 and CALDB2.26 instead of the CIAO2.0.1 and CALDB2.0 adopted in Giacconi et al. [2002] and in this Letter). We repeated the fitting using the updated spectrum and obtained consistent results for both the continuum and the absorption feature. This confirms that the absorption feature is not due to improper data calibration. Note that Wang et al. (2003) reported a puzzling strong emission line at $\sim 6.3$ keV in the observed frame in CXCDFS J033225.3–274219 (CDFS 46). The two unusual features (the emission feature in CDFS 46, and the absorption feature in CDFS 11 reported in this Letter), which are located at similar energies in the observing frame, could suggest a common origin related to instrumental effects. However, there are strong evidences against this: since the total exposure was composed of 11 individual observations with different roll angles, photons from each source fall into different positions on different chips during different observations. It is unlikely that an unknown instrumental artifact (if any) would affect photons from all 11 exposures. Furthermore, the two sources are around 9' apart, and fall into different chips during the observations. We conclude that the similar energy of the two features is just a coincidence.

3.2. The Nature of the Absorber

Among the heavy elements, iron is the only one that can produce such a strong absorption feature at high energies. However, the rest-frame energy of the absorption ($>20$ keV) is too high for static iron in the rest frame, since the highest energy transition is the K-shell edge of H-like ion at 9.28 keV. Therefore, we consider two possibilities: that the absorber is located either at a much lower redshift along the line of sight or in a relativistic outflow intrinsic to the quasar.

The continuum fitting yields a marginal intrinsic absorption with $N_{\text{H}} \sim 10^{21} \text{cm}^{-2}$, which is too small to account for the strong absorption feature at $\sim 6.3$ keV. We cannot locate other absorption features in the spectrum at lower energy (due to relatively lower ionized ions, such as the O viii absorption edge at 0.87 keV). This suggests that the absorber has to be extremely ionized, with almost all abundant elements fully ionized, and the absorption is dominated by H or He-like iron atoms. Adopting the photon ionization absorption model $\text{absor}$ (Magdziarz & Zdziarski 1995) to fit the spectrum, we obtain an ionization parameter $\xi > 9000$ and $N_{\text{H}} > 3 \times 10^{24} \text{cm}^{-2}$ (Table 1). Note that the upper limits of $\xi$ and $N_{\text{H}}$ are poorly constrained, since the two parameters are degenerate. Assuming $\xi = 10,000$, we obtain $N_{\text{H}} = 5 \times 10^{24} \text{cm}^{-2}$. We assume a temperature of $10^6$ K and solar abundance for the absorber. We note that an intrinsic absorption at the level of $N_{\text{H}} = 5 \times 10^{24} \text{cm}^{-2}$ (well within the Compton-thick regime) would strongly attenuate the continuum photons. However, if the iron in the absorber is overabundant by a factor of 10 with respect to the solar value, we obtain $N_{\text{H}} = 5 \times 10^{23} \text{cm}^{-2}$.

The absorption feature can also be fitted by a broad saturated

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$\xi = L \sin R^2$, where $L$ is the integrated incident luminosity between 5 eV and 300 keV, $n$ is the density of the material, and $R$ is the distance of the material from the illuminating source (Done et al. 1992).
absorption line. The most likely responsible lines are Fe xxv Kα (6.70 keV) and/or Fe xxvi Kα (6.97 keV). Assuming an average depth of the absorption line τ = 2, and a factor of 10 overabundance for iron, we obtain N_H = 5 × 10^{23} cm^{-2}. We point out that for such an absorber, we also expect Fe xxv Kβ (7.85 keV), Fe xxvi Kβ (8.26 keV) absorption lines, and strong Fe xxv (8.83 keV), Fe xxvi (9.28 keV) absorption edges. Given the few counts we measure above 7 keV, we cannot check the existence of these features. Future X-ray missions with higher sensitivity can help us to unveil the nature of the absorber by showing us the spectral properties at energies >7 keV and the absorption profile with higher S/N.

If the absorption is due to a foreground absorber, the absorber has to be located at a much lower redshift ν_0 ≈ 0.5 (if due to H or He-like ion absorption edges) or ν_0 ≈ 0.1 (if due to an H or He-like iron-resonant absorption line). The absorber must be extremely ionized, with N_H > 5 × 10^{23} cm^{-2}. Note that the foreground absorber is unlikely to be photoionized; otherwise, we should have seen the extra photon ionization source. Thus it has to be extremely hot, with a temperature of ≈ 10^9 K, to reach the required ionization stage. Such a high temperature and N_H is very unusual for intervening systems. The only possible candidate is the hot intracluster medium found in clusters of galaxies (see Rosati et al. 2002a and references therein).

However, for a cluster with K, we expect an X-ray absorption feature (ν_0 ≈ 0.17), similar to that of the outflow in PDS 456 (ν_0 ≈ 0.17c; Reeves et al. 2003). However, because of the extremely high outflow speed in this case, the kinetic energy carried by the relativistic material outflow would be 2 × 10^{32} erg s^{-1}, requiring an accretion rate of at least 200 M_☉ yr^{-1}, with an assumed energy production efficiency ε = 0.1 that entirely goes into the outflow. Such an accretion rate is far beyond the Eddington limit even for a supermassive black hole of 10^8 M_☉ (∼ 3 M_☉ yr^{-1}). To keep the rate of kinetic energy outflow lower than that released by Eddington accretion, a more reasonable outflow rate would be at least 100 times smaller (<0.1 M_☉ yr^{-1}).

We conclude that the X-ray absorption feature we detected in CDFS 11 cannot be due to intervening systems along the line of sight. Finally, we consider a relativistic outflow intrinsic to the quasar, with a speed of ≈ 0.7c (Doppler factor ν_0 = 2.3) or ν_0 = 0.83c (DF = 3.2 for absorption line), to produce the observed blueshift of the absorption feature. Note that similar blueshifted features have been reported in the X-ray spectra of three AGNs: a highly blueshifted O viii emission line in PKS 0637−75 with DF = 2.7−2.8 (Yaqoob et al. 1998); a blueshifted Fe K emission line (DF = 2.4−2.6) in QSO PKS 2149+360 (Yaqoob et al. 1999); and a strong blueshifted Fe K emission line (DF = 2.3−2.5) in CXC/CDF S J0323.5−274219 (Wang et al. 2003). The good agreements of the blueshift factors from different sources strongly suggest a close origin of the relativistic outflow, and strengthen the statistical significance of these features.

Taking log ν_0 = 4 and N_H = 5 × 10^{23} cm^{-2}, we estimate the distance of the absorber from the central source R by assuming the thickness of the absorber ΔR ≈ 0.1R. We obtain R ≈ 6 × 10^{16} cm. Following Reeves et al. (2003), we estimate the rate of relativistic outflow. The outflow rate (Q_{out}) can be calculated as Q_{out} = Ω ν_{out} m_p L_X/ν_0. Assuming that the outflow subtends a solid angle of 0.1 sr, we obtain an outflow rate of ≈ 10^{27} g s^{-1} or 10 M_☉ yr^{-1}, similar to that of the outflow in PDS 456 (ν_{out} ≈ 0.17c; Reeves et al. 2003). However, because of the extremely high outflow speed in this case, the kinetic energy carried by the relativistic material outflow would be 2 × 10^{32} erg s^{-1}, requiring an accretion rate of at least 200 M_☉ yr^{-1}, with an assumed energy production efficiency ε = 0.1 that entirely goes into the outflow. Such an accretion rate is far beyond the Eddington limit even for a supermassive black hole of 10^8 M_☉ (∼ 3 M_☉ yr^{-1}). To keep the rate of kinetic energy outflow lower than that released by Eddington accretion, a more reasonable outflow rate would be at least 100 times smaller (<0.1 M_☉ yr^{-1}).

We conclude that the X-ray absorption feature in CDFS 11 is due to an ionized jetlike outflow intrinsic to the quasar, with a bulk velocity of ≈ 0.7c−0.8c. Similar outflows have been reported in the X-ray spectra of several other AGNs. Future X-ray missions with higher intensities can help us understand the nature of the outflows by providing X-ray spectra with higher S/N.

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