RELATIVISTIC OUTFLOWS IN TWO QUASARS IN THE CHANDRA DEEP FIELD SOUTH

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ABSTRACT

In this paper we provide new 1 Ms Chandra ACIS spectra of two quasars in the Chandra Deep Field South (CDF-S) which had strong and extremely blueshifted X-ray emission/absorption line features in previous 1 Ms spectra, with outflowing bulk velocity $v \sim 0.65-0.84c$. In the new 1 Ms spectra, the relativistic blueshifted line feature is solidly confirmed in CXO CDFS J033225.3$-$274219 (CDFS 46, $z = 1.617$), and marginally visible in CXO CDFS J033260.0$-$274748 (CDFS 11, $z = 2.579$), probably due to the increased Chandra ACIS background in the new 1 Ms exposure. The data rule out the possibility (although very tiny already based on the old 1 Ms data) that the two sources were selected to be unusual due to noise spikes in the spectra. The only likely interpretation is extremely blueshifted iron absorption/absorption lines or an absorption edge due to relativistic outflow. We find that the rest-frame emission line center in CDFS 46 marginally decreased from 16.2 to 15.2 keV after 7 years. The line shift could be due to either a decreasing outflowing velocity or a lower ionization level. Including the two quasars reported in this paper, we collect a total of 7 quasars from the literature showing blueshifted emission or absorption line features with $v \geq 0.4c$ in X-ray spectra, and discuss their connection to jet and/or BAL (broad absorption line) outflows.

Subject headings: galaxies: active — quasars: emission lines — quasars: absorption lines — X-rays: galaxies — X-rays: individual (CXO CDFS J033225.3$-$274219, and CXO CDFS J033260.0$-$274748)

Online material: color figure

1. INTRODUCTION

It is well known that quasars interact with their environments through collimated jets and outflowing winds, which are required as the feedback (from the central supermassive black hole to the host galaxy) for the $M-\sigma_*$ relation (Gebhardt et al. 2000). The collimated jets and outflowing winds are also natural diagnostics for studying the gas flow patterns in the innermost regions of black holes, their source geometry, and energy generation mechanism (see, e.g., Cappi 2006). Intrinsic outflowing systems can be categorized by their outflowing velocities. Jets are often seen in radio-loud quasars with velocities very close to the speed of light (except for shock- and lobe-dominated sources, which interact with the surrounding medium and appear to be subrelativistic; e.g., Kellermann et al. 2004). The broad absorption lines (BALs) in the UV/optical band are blueshifted with velocities up to 0.2c in the spectra of 10%–20% of quasars. BAL outflows can be seen in the X-ray spectra at even higher velocities. Chartas et al. (2002, 2003, 2007a, 2007b) discovered very broad absorption lines with outflow velocities of 0.4–0.67c in three gravitational lensed radio-quiet BAL quasars (PG 1115+080, H 1413+117, and APM 08279+5255; see Table 1 for details), which are the only BALs reported with relativistic outflows ($v \geq 0.4c$) in their X-ray spectra.

Meanwhile, relativistic outflows with $v \sim 0.6-0.8c$ are also seen in the X-ray spectra of four non-BAL quasars. Yaoqob et al. (1998) reported a blueshifted O vi emission line in the ASCA spectrum of PKS 0637$-$752, with outflow velocity 0.77c. However, this line is invisible in the Chandra exposure obtained $\sim2$ yr later, which instead detected an extended X-ray jet in this core-dominated radio-loud quasar. Yaoqob et al. (1999) reported the detection of a blueshifted iron K emission line in the radio-loud quasar PKS 2149$-$306, with velocity 0.71c (see Table 1), in the ASCA spectrum. This feature is also visible in the follow-up XMM-Newton spectrum (see Fig. 2 of Page et al. 2005), and our independent analysis gives a confidence level of 99% in the XMM-Newton PN spectrum. With the 1 Ms Chandra exposure on the Chandra Deep Field South (CDF-S), Wang et al. (2003, 2005) reported the detection of strong blueshifted iron K line features, with $v \sim 0.65c$ and 0.84c, in CXO CDFS J033225.3$-$274219 (CDFS 46, $z = 1.617$, emission line, radio-loud) and CXO CDFS J033260.0$-$274748 (CDFS 11, $z = 2.579$, absorption line, radio-quiet), respectively. The blueshifted velocities of the three emission lines are far larger than could be produced by the rotational velocities of the accretion disk, and can only be due to outflow (see Wang et al. 2003).

In this paper, we report on a new Chandra 1 Ms observation\textsuperscript{2} of the two CDF-S sources with relativistic outflows. Their multiband properties are described in detail in Wang et al. (2003, 2005). The X-ray data and spectral fitting are reported in § 2, and the nature of the blueshifted features are discussed in § 3. Throughout the paper we assume a cosmological model with $H_0 = 70$ km s\textsuperscript{$-1$} Mpc\textsuperscript{$-1$}, $\Omega_m = 0.3$, and $\Omega_L = 0.7$.

2. THE DATA AND X-RAY SPECTRAL FITTING

The newly released 1 Ms Chandra exposure on the CDF-S consisted of 12 individual ACIS observations obtained from September to November 2007. Each observation was filtered to include only standard ASCA event grades. Cosmic ray afterglows and ACIS hot pixels and bad pixels were removed, and high background intervals were subtracted. All exposures were then added to produce a combined event file with net exposure of 954 ks. The two sources CDFS 46 and CDFS 11, $\sim6'$ and $\sim7'$ from the center of the field, respectively, were covered by all 12 exposures. The X-ray count rates of CDFS 46 and CDFS 11 extracted from 12 exposures were examined, and no significant fluctuations ($>3\sigma$) were seen.

\textsuperscript{2} Data have been released for the new Chandra Deep Field South (CDF-S; e.g., Gioia et al. 2002; Rosati et al. 2002) 1 Ms exposure (from 2007 September to November); see http://cxc.harvard.edu/cda/whatsnew.html#CDFS2000-2007.
We extract the Chandra ACIS-I X-ray spectra for CDFS 46 and CDFS 11 from the 95% encircled-energy radius $r_S$ of the ACIS point-spread function at each source’s position; the background spectra are extracted from the annulus at the same position, with inner and outer radii of $1.2r_S$ and $2.4r_S$. The X-ray telescope response and CCD ACIS-I instrument response were generated for each single Chandra observation, and then summed together with corresponding exposure times as a weighting factor. The final time-weighted response files were used for spectral analysis. The net counts of CDFS 46 and CDFS 11 are 375 and 963 in the 0.5–2.0 keV band, and 170 and 451 in the 2.0–9.0 keV band. During the fit, we use the C-statistics (Cash 1979; Nousek & Shue 1989), which perform better than the $\chi^2$ analysis for spectra with low detected counts. We use XSPEC version 12.0 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 paper are at the 90% confidence level for one interesting parameter.

The spectra of both CDFS 46 and CDFS 11 were binned to have at least one count per bin, and were first fitted with a simple power law plus a neutral absorber in the quasar frame. A Galactic neutral hydrogen absorption column of $8 \times 10^{19}$ cm$^{-2}$ (Dickey & Lockman 1990) was also included. The fitting results for CDFS 46 are presented in Table 2.

In Figure 1 we plot the Chandra spectra for CDFS 46, using the old 1 Ms, new 1 Ms, and combined 2 Ms exposures. In the new 1 Ms exposure, the emission-line feature at around 6 keV (observed frame) is obvious. A single Gaussian was added to our continuum model. With three more free parameters ($E_c$, $\sigma$, and $I$), the fit was significantly improved ($\Delta C = 18.2$), indicating a confidence level of 99.99% based on the $F$-test. However, compared to the old 1 Ms exposure, we find a marginal shift of the rest-frame line center, from $16.2^{+0.4}_{-0.4}$ keV to $15.2^{+0.3}_{-0.2}$ keV (see Fig. 2).

The absorption feature at around 7 keV in CDFS 11 is also marginally visible in the new 1 Ms exposure (see Fig. 3). We added an absorption edge to our continuum model, but it did not improve the fit significantly ($\Delta C \sim -2$). We also tried to model the absorption feature with a saturated absorption line model. The notch model of XSPEC was used by fixing the covering fraction at 0.99 to represent a blank absorption trough. The fit was slightly better, with $\Delta C = -4.9$ for two extra free parameters, yielding a confidence level of 93% based on the $F$-test. Note in the old 1 Ms spectra, this feature was detected with a level of...
99.98%. This difference is likely due to the significantly higher ACIS background in the new 1 Ms exposure.

3. DISCUSSION

Wang et al. (2003, 2005) have ruled out the possibilities that the unusual X-ray features in CDFS 46 and CDFS 11 could be due to any instrumental artifact, or to improper background subtraction. These conclusions hold for the new 1 Ms exposure, and are even stronger, since it is even more unlikely that either of these artifacts could affect both exposures obtained 7 years apart. Statistical fitting results show that the confidence level of the unusual features in both CDFS 46 and CDFS 11 is lower in the new 1 Ms exposure than reported with the old 1 Ms exposure. This is actually expected, because of the increase of the Chandra ACIS background with time.\(^3\) Note that the blueshifted absorption feature in CDFS 11 is only marginally visible in the new 1 Ms spectrum, and we are unable to tell whether it varies based on current data. Except for providing marginal confirmation of the reality of the unusual absorption feature in CDFS 11 with new 1 Ms spectra, we do not discuss its nature further than in Wang et al. (2005). In this paper we focus on CDFS 46.

Wang et al. (2003) has interpreted the X-ray emission line in CDFS 46 as a relativistic blueshifted iron K line intrinsic to the quasar at \(z = 1.617\) (see below for further discussion). We note that Basu (2006) proposed a different scenario to interpret the optical and X-ray spectrum of CDFS 46. He suggested that all the optical and X-ray emission lines are blueshifted, as the result of an ejection. However, we find this scenario unlikely, for several reasons. First, all the emission lines have been identified as having negative redshift, i.e., the observed optical emission lines are infrared lines in the rest frame. However, such extremely unusual galaxies with high blueshifts have never been reported. Furthermore, the identification of three optical emission lines yields a redshift/blueshift scatter of 2.8%, significantly larger than the 0.8% we obtained. The scatter (corresponding to 8400 km s\(^{-1}\)) is even larger than the full width of the broadest emission line identified in CDFS 46 (see Fig. 6 of Szokoly et al. 2004). Finally, the statistical fitting results show that the confidence level of the unusual features in both CDFS 46 and CDFS 11 is lower in the new 1 Ms exposure than reported with the old 1 Ms exposure. This is actually expected, because of the increase of the Chandra ACIS background with time.\(^3\)

\(^3\) The ACIS background rates remained relatively constant from the year 2000 until the end of 2003, and started to increase in 2004 at the rate of 10% per year, independent of any variability induced by the solar cycle. (See § 6.16.2 of the Proposers’ Observatory Guide v. 10, http://cxc.harvard.edu/proposer/POG/.)
strong X-ray emission line was classified as S Kα, which is supposed to be rather weak, and has never been detected before.

It is interesting to note that in the GOODS-S ACS images, a nearby fainter galaxy (i = 24.7) is detected 1.1′′ to the southwest of the quasar CDFS 46. We note that the possibility of having a random galaxy brighter than i = 24.7 within 1.1′′ of a certain known galaxy in GOODS-S is only 4%, suggesting that the two galaxies are likely at the same redshift. VLT/FORS spectroscopy observations have classified the nearby fainter galaxy as an emission-line galaxy at redshift 1.609, based on the detection of [O ii] λ3727 and photometric measurements (Vanzella et al. 2008). This is within 0.5% of the redshift of CDFS 46 (z = 1.617). This provides further evidence that the redshift measurement of CDFS 46 is reliable. CDFS 11 is not covered by GOODS ACS images.

3.1. The Nature of the Outflow

Wang et al. (2003) has listed several possible explanations for the unusual strong emission line in CDFS 46, including an iron emission line from a relativistic outflow intrinsic to the quasar, a strong iron absorption edge due to a cold relativistic outflow, or an intervening low-redshift (z ∼ 0.034) type 2 active galactic nucleus (AGN). In the high spatial resolution GOODS ACS images, only CDFS 46 at z = 1.617 and a nearby galaxy at z = 1.609 (1.1′′ apart) are visible within 3.5″ radius. Also, although a strong Fe Kα line from neutral iron at 6.4 keV is not unusual in type 2 AGNs, variations in the line central energy are not expected, yet these are found in CDFS 46. These facts firmly rule out an intervening low-redshift type 2 AGN.

As Wang et al. (2003) stated, the emission-line feature could also be statistically fitted by a blueshifted strong Fe absorption edge due to cold outflow. Spectral fitting to the 2 Ms spectrum shows that a heavy absorption (with N_H = 3.2 ± 0.3 × 10^{24} cm^{-2}), covering 99.92% ± 0.04% of the direct continuum, is required. Statistically, we cannot rule out this model based on the 2 Ms exposure; however, we point out that, in addition to a Compton-thick cold outflow with a velocity of 0.65c, such a model could only work under more extreme conditions: the intrinsic X-ray luminosity of CDFS 46 would need to be ≥500 times larger (L_{2-10 keV} ∼ 3.0 × 10^{46} erg s^{-1}), which is way too luminous for its radio and optical emission; the leaking X-ray emission (or scattered X-ray emission) could not exceed 0.12%; and the cold outflow would need to slow down from 0.69c to 0.65c after 2.7 yr (in the quasar rest frame), and to be located at a large distance from the unusual strong central continuum, to avoid to be ionized, or else we would see strong soft X-ray emission that is free from absorption by an ionized absorber. Assuming a density of 10^{11} cm^{-3}, which is typical of the broad-line region in AGNs, we obtained a distance r > 2 × 10^{16} cm from the central emission. Assuming that the outflow cloud has a round or square shape, the outflow rate is then M = 4πf_c r^2 n_e m_p v_{wind} ∼ (4πf_c)^2 2.1 × 10^{-4} M_☉ yr^{-1}, which is higher than the Eddington accretion rate M_{Edd} = 2.2 M_☉ yr^{-1} of a 10^8 M_☉ black hole, even for a very small covering factor of the outflow, f_c ∼ 10^{-4}.

Therefore, the line feature we detected is most plausibly a blueshifted iron line arising from a relativistic outflow intrinsic to the quasar.

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4 The redshift of CDFS 46 was identified based on the detection of C iv, C iii], and Mg ii emission lines; see Wang et al. (2003) and Szokoly et al. (2004).

5 The intrinsic X-ray to optical ratio α_{ox} obtained with this model is 0.2.

6 The velocity of 0.74c in Wang et al. (2003; p. L90, right column, 5th line) should be corrected to 0.69c: there is a mistake in the calculation from Doppler factor to velocity.
the quasar. The Doppler factor of 2.2 (for H-like Fe \( \text{xxvi} \) \( \text{K} \alpha \), 6.97 keV) implies bulk velocity of \( \sim 0.65c \) (head-on) that must be responsible for the blueshift and relativistic boosting intensity. Assuming a lower ionization state would yield higher velocity, up to 0.7c (for the neutral Fe \( \text{K} \alpha \) line). If the line is due to fluorescent emission or recombination emission from plasma ionized by the X-ray continuum, the continuum must illuminate the outflow from the sides to produce a strong line with equivalent width above several keV. In this case, the equivalent width of the line could be boosted by a factor of \( DF^\text{3+} \), where DF is the Doppler factor for the bulk motion, and \( \Gamma \) is the photon index of the X-ray continuum.

If the outflow is not ionized by the central X-ray emission, considering that the recombination timescale for Fe \( \text{xxv} \) is \( t_{\text{recomb}} \sim 3 \times 10^6 Z^{-2} T_7^{1/2} n_e^{-1} \) s (Allen 1973; where \( T_7 \) is the temperature in units of 10\(^7\) K, and \( n_e \) is the electron density in units of 10\(^7\) cm\(^{-3}\)), typically in the range between \( 4.4 \times 10^3 \) and 4.4 s (Chartas et al. 2002), there must be some mechanism (such as magnetic driving) which keeps heating the relativistic outflow. Migliari et al. (2002) reported the discovery of blueshifted and very strong iron emission lines (with velocity of 0.26c and equivalent width of 13 keV; S. Migliari 2003, private communication) from extended X-ray emission in the X-ray binary system SS 433. Their discovery implied the presence of large-scale reheating of baryons, which may also be the source of the extreme blueshifted iron line in CDFS 46.

We note that the new HETG observation of SS 433 also shows relativistic red- and blueshifted lines from the central part, indicating two side relativistic jets (Marshall et al. 2002; Lopez et al. 2006). Taking the velocity of the outflow as 0.70c, the distance that the outflow traveled during the 7 yr observation gap is \( \sim 0.6 \) pc = \( 1.8 \times 10^{18} \) cm (in the quasar rest frame), which is \( \sim 5 \) times the dust sublimation radius (\( R_d = 0.4L_4^{1/2} \approx 0.13 \) pc, where \( L_4 \) is the intrinsic 0.5–10 keV luminosity in units of \( 10^{44} \) erg s\(^{-1}\)). The distance is too large for an adiabatic cooling process except if there is reheating (Migliari et al. 2002).

The marginal change in the observed line central energy could be due to either a slowdown of the outflow (from 0.69c to 0.65c for H-like Fe \( \text{K} \alpha \) line), or a change of the ionization state, for example, from H-like Fe \( \text{K} \alpha \) dominated to He-like Fe \( \text{K} \alpha \) dominated (see Table 3). In the former case, we would expect weaker emission lines due to the weaker boosting effect, which is consistent with observations (see Fig. 1 and Table 3). In the later case, the line could get either stronger or weaker, depending on the exact ionization state. We note that Chartas et al. (2007a) discovered 0.92 yr and 5.9 day (rest-frame) variability of the outflowing absorbing gas, with velocities of \( \sim 0.1c \) (0.05c) and \( \sim 0.4c \) (0.36c) due to He-like Fe \( \text{K} \alpha \) (H-like Fe \( \text{K} \alpha \)) resonant absorption, in the large gravitational lensed BAL quasar PG 1115+80.

### 3.2. Why So Rare?

Our two quasars are among the several AGNs which show X-ray outflows with velocities \( \geq 0.4c \) (see Table 1). Considering the large number of X-ray spectra obtained for quasars with advanced X-ray telescopes such as \( \text{XMM-Newton} \) and \( \text{Chandra} \), why do only a few sources show relativistic outflowing features in their X-ray spectra? We attribute this to the orientation and observational selection effect. Broad absorption line outflows in quasars, with velocities up to 0.1c, are believed to have a sky coverage of 20%. We propose that the relativistic outflows, with velocities of \( \geq 0.4c \), have a similar or smaller sky coverage, and thus can only be detected in a small fraction of quasars.

The instrumental bandpass, such as \( \text{Chandra} \) 0.3–10 keV and \( \text{XMM-Newton} \) 0.3–12 keV, also limits the detection of relativistic outflowing features to a certain redshift range. Assuming a Doppler factor \( \geq 2 \) (or a bulk velocity of \( \geq 0.6c \)), only a H-like Fe K\( \alpha \) line at redshift above 1.0 can be detected below 7 keV in the observed frame (where \( \text{Chandra} \) and XMM-Newton are sufficiently sensitive to detect enough counts). Furthermore, to confirm an emission or absorption line feature in an X-ray spectrum requires high number of detected photons (more than several hundred); thus, they can only be detected in luminous sources or by long exposures.

### 3.3. Connection with Jet or BAL Outflows in AGNs

We have stated above that the strong blueshifted emission line could possibly be due to line emission from collimated jets. It is interesting to note that all three sources with blueshifted emission lines in Table 1 are radio-loud, suggesting that the blueshifted emission lines and jets are somehow connected.

Historically, in addition to jets, the most common examples of AGN outflows have been found in broad absorption line quasars (BAL QSOs), which show absorption troughs in UV and optical lines with velocities up to tens of thousands of km s\(^{-1}\) (as large as 0.2c; e.g., Rodriguez Hidalgo et al. 2007). The disk wind model is one of the most popular models of BAL outflows (see Proga 2007); in this model the presence of X-ray-shielding gas is required to prevent the gas from overionizing and attenuating the X-ray continuum, as observed (with \( N_{\text{H}} \geq 10^{23} \text{cm}^{-2}\); Gallagher & Everett 2007). We propose that the innermost region of the X-ray-shielding gas could be outflowing at a higher velocity (such as 0.6–0.7c), and more ionized, thus producing not photoelectric but He-like and H-like iron absorption to the central X-ray continuum. Actually, Chartas et al. (2002, 2003, 2007a, 2007b) have identified blueshifted X-ray absorption features in BAL QSOs at higher velocities and higher ionization levels (see Table 1). An iron absorption line is produced when our line of sight is covered by the innermost shielding gas, and an emission line is observed when our line of sight is not covered but is close to the outflowing direction (see Fig. 4). Note that the most recent simulation work of Sim et al. (2008) shows a similar and clear pattern that outflows can produce both iron absorption and emission features, depending on the viewing angle. Taking into account the relativistic boosting effect, the blueshifted Fe K emission line can be seen at a significant level. The innermost region of the X-ray shielding gas might have a different sky coverage from the broad absorption line region, so the presence of X-ray absorption or emission line features does not necessarily mean the presence of broad absorption line in the optical/UV band. However, it is worth looking for possible blueshifted optical/UV features in CDFS 46 and CDFS 11, which will require optical spectra of much higher quality. A search for blueshifted X-ray features in high-S/N X-ray spectra of BAL QSOs would also be helpful.

Finally, we note that BAL outflows could be aligned with jets, at least in some BAL QSOs, and these might be physically connected.
This suggests that both mechanisms (jet or BAL outflow) could also work simultaneously to produce blueshifted emission/absorption lines with $v > 0.4c$ in the X-ray spectra of quasars.

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