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DISCOVERY OF A $z = 4.93$, X-RAY–SELECTED QUASAR BY THE *CHANDRA* MULTIWAVELENGTH PROJECT (ChaMP)

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ABSTRACT

We present X-ray and optical observations of CXOMP J213945.0−234655, a high-redshift ($z = 4.93$) quasar discovered through the *Chandra* Multiwavelength Project (ChaMP). This object is the most distant X-ray–selected quasar published, with a rest-frame X-ray luminosity of $L_X = 5.9 \times 10^{44}$ ergs s^{-1} (measured in the 0.3–2.5 keV band and corrected for Galactic absorption). CXOMP J213945.0−234655 is a g' dropout object (>26.2), with $r' = 22.87$ and $i' = 21.36$. The rest-frame X-ray–to–optical flux ratio is similar to quasars at lower redshifts and slightly X-ray bright relative to $z > 4$ optically selected quasars observed with *Chandra*. The ChaMP is beginning to acquire significant numbers of high-redshift quasars to investigate the X-ray luminosity function out to $z \sim 5$.

Subject headings: galaxies: active — galaxies: nuclei — quasars: general — quasars: individual (CXOMP J213945.0−234655) — X-rays: general

1. INTRODUCTION

The observed characteristics of known quasars are remarkably similar over a broad range of redshift. For example, X-ray studies utilizing the *ROSAT* database (Green et al. 1995; Kaspi, Brandt, & Schneider 2000) show little variation of the ratio of X-ray–to–optical flux for optically selected quasars. Also, the rest-frame UV spectra of quasars, including the broad Lyα, N v, and C iv emission lines, are nearly identical for a large range of redshift and present no evidence for subsolar metallicities even up to a $z \sim 6$ (Fan et al. 2001).

Even though the individual properties of quasars are similar, the comoving space density of quasars changes drastically with redshift. At high redshift ($z > 4$), a significant drop-off in the comoving space density of quasars seen in optical (e.g., Schmidt, Schneider, & Gunn 1995; Warren, Hewett, & Osmer 1994; Osmer 1982) and radio (Shaver et al. 1996) surveys hints at either the detection of the onset of accretion onto supermassive black holes or a missed high-redshift population, possibly due to obscuration. X-ray–selected quasars from *ROSAT* have been used to support the latter interpretation based on evidence for constant space densities beyond a redshift of 2 (Miyaji, Hasinger, & Schmidt 2000). Unfortunately, the *ROSAT* sample size is small, with only eight quasars beyond a redshift of 3.

Significant numbers of quasars with $z > 4$ are being amassed to investigate both their intrinsic properties and the evolutionary behavior of the quasar population. The Sloan Digital Sky Survey (SDSS) reports 123 optically selected quasars with $z > 4$ (Schneider et al. 2002; Anderson et al. 2001). However, optical surveys suffer from selection effects due to intrinsic obscuration and the intervening Lyα forest. Current X-ray surveys with *Chandra* and *XMM* do not have a strong selection effect based on redshift and can detect emission up to 10 keV (observed frame) to reveal hidden populations of active galactic nuclei (AGNs) including heavily obscured quasars (Norman et al. 2001; Stern et al. 2002). High-z objects can be detected through a larger intrinsic absorbing column of gas and dust because the observed-frame X-ray bandpass corresponds to higher energy, more penetrating X-rays at the source.[10] Therefore, optical and X-ray surveys will complement each other, providing a fair census of mass accretion onto black holes at high redshift.

Larger samples of X-ray observations of $z > 4$ quasars are needed since there are currently only 24 (Vignali et al. 2001), of which only three are X-ray–selected quasars. *Chandra* and *XMM-Newton* are beginning to probe faint flux levels for the first time to detect the high-z quasar population. Initial *Chandra* and *XMM-Newton* observations of optically selected quasars have shown a systematically lower X-ray flux relative to the optical at high redshift (Vignali et al. 2001; Brandt et al. 2001a).

In this Letter, we present the X-ray and optical properties of a newly discovered, X-ray–selected $z = 4.93$ quasar with the *Chandra X-Ray Observatory*. This quasar is the highest redshift object published[11] from an X-ray survey.

These results are a component of the *Chandra* Multiwavelength Project (ChaMP; Wilkes et al. 2001). A primary aim of the ChaMP is to measure the intrinsic luminosity function of quasars and lower luminosity AGNs out to $z \sim 5$. The survey will provide a medium-depth, wide-area sample of serendipitous X-ray sources from archival *Chandra* fields in Cycles 1 and 2 covering ~14 deg^2. The broadband sensitivity between 0.3 and 8.0 keV enables the selection to be far less affected by absorption than previous optical, UV, or soft X-ray surveys. *Chandra*'s small point-spread function (~1″ resolution on-axis) and low background allow sources to be detected to fainter

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[10] The observed-frame, effective absorbing column is $N_H^{eff} \sim N_H/(1+z)^{2.6}$ (Wilman & Fabian 1999).

[11] A $z \sim 5.2$, X-ray–selected quasar detected in the Chandra Deep Field–North was presented at the 199th AAS meeting (Brandt et al. 2001c).

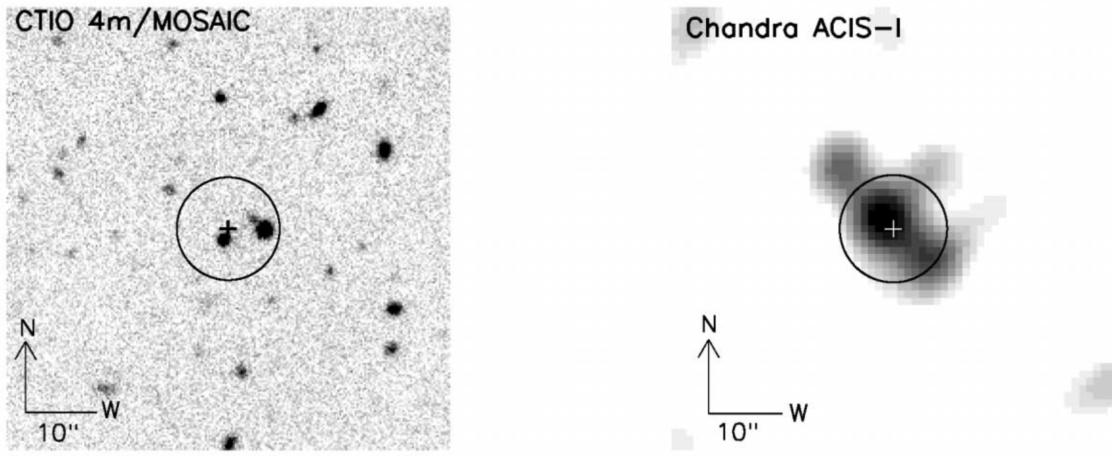

FIG. 1.—Optical (i') and X-ray (0.3–2.5 keV) imaging. To improve the visual clarity, in this figure we have smoothed the *Chandra* image with a Gaussian function ($\sigma = 1''.5$). The spatial distribution of the 17 X-ray counts at $9'.1$ off-axis is as expected from a point source. The circles show the region containing 50% of the encircled energy (radius $= 7''.3$) of the *Chandra* counts. The plus signs mark the centroid of the X-ray emission in both images.

flux levels, while the $\sim 1''$ X-ray astrometry greatly facilitates unambiguous optical identification of X-ray counterparts. The project will effectively bridge the gap between flux limits achieved with the Chandra Deep Field observations and those of past *ROSAT* surveys.

Throughout this Letter, we assume $H_0 = 50$ km s^{-1} Mpc^{-1} and a flat cosmology with $q_0 = 0.5$.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *X-Ray*

The X-ray source CXOMP J213945.0−234655 (sequence 800104) was observed on 1999 November 18 by *Chandra* (Weisskopf et al. 2000) with the Advanced CCD Imaging Spectrometer (ACIS-I; Nousek et al. 1998) in the field of the X-ray cluster MS 2137.3−2353 (PI: M. Wise). We have used data reprocessed (in 2001 April) at the *Chandra* X-ray Center (CXC).[12] We then ran a detection algorithm, XPIPE (D.-W. Kim et al. 2002, in preparation), which was specifically designed for the ChaMP to produce a uniform and high-quality source catalog.

CXOMP J213945.0−234655 is one of 72 sources detected using CIAO/WAVDETECT (Freeman et al. 2002) within the ACIS configuration (Fig. 1). The 41 ks observation yielded a net 16.7 ± 7.5 counts within the soft bandpass (0.3–2.5 keV) and no counts in the hard bandpass (2.5–8.0 keV). This corresponds to a Galactic absorption–corrected, observed frame X-ray flux of $f(0.3\text{–}2.5\ \text{keV}) = (2.82 \pm 1.26) \times 10^{-15}$ ergs cm^{-2} s^{-1} (Table 1).

The source-naming convention of the ChaMP (CXOMP Jhhmmss.s±ddmmss) is given with a prefix CXOMP (*Chandra X-ray Observatory* Multiwavelength Project) and affixed with the truncated J2000.0 position of the X-ray source after a mean field offset correction is applied, derived from the cross-correlation of optical and X-ray sources in each field.

TABLE 1
PROPERTIES OF CXOMP J213945.0−234655

Parameter	Value
$\alpha_{\rm J2000.0}$[a]	$21^{\rm h}39^{\rm m}44^{\rm s}.99$
$\delta_{\rm J2000.0}$[a]	$-23°46'56''.6$
z	4.930 ± 0.004
g^*	>26.2
r^*	22.87 ± 0.07
i^*	21.36 ± 0.10
X-ray counts[b]	16.7 ± 7.5
$f_{\rm X}$ ($\times 10^{-15}$ ergs s^{-1} cm^{-2})[b, c]	2.82 ± 1.26
$L_{\rm X}$ ($\times 10^{44}$ ergs s^{-1})[c, d]	5.89 ± 2.63
Hardness ratio[e]	<-0.54
$\alpha_{\rm ox}$	$1.52^{+0.08}_{-0.05}$
$AB_{1450(1+z)}$[f]	21.62

[a] Error $<0''.5$.
[b] Observed frame; 0.3–2.5 keV.
[c] Based on an assumed X-ray power-law spectrum ($S_E \propto E^{-\alpha}$; $\alpha = 1.0$); Galactic absorption–corrected ($N_{\rm H} = 3.55 \times 10^{20}$ cm^{-2}; Dickey & Lockman 1990).
[d] Rest frame; 0.3–2.5 keV.
[e] $(H - S)/(H + S)$. Soft band (S): 0.3–2.5 keV; hard band (H): 2.5–8.0 keV.
[f] Observed monochromatic, Galactic absorption–corrected, $AB_{1450(1+z)}$ magnitude (Fukugita et al. 1996) emitted at 1450 Å in the quasar's rest frame; based on an assumed optical power-law spectrum ($S_\nu \propto \nu^{-\alpha}$; $\alpha = 0.5$).

2.2. *Optical Imaging and Source Matching*

We obtained optical imaging of the field in three NOAO/Cerro Tololo Inter-American Observatory (CTIO) SDSS filters (g', r', and i'; Fukugita et al. 1996) with the CTIO 4 m/MOSAIC on 2000 October 29 as part of the ChaMP optical identification program (P. J. Green et al. 2002, in preparation). Integration time in each band ranged from 12 to 15 minutes during seeing of $1''.3$–$1''.8$ FWHM. Image reduction was performed with the IRAF(v2.11)/MSCRED package. We used SExtractor (Bertin & Arnouts 1996) to detect sources and measure (pixel) positions and magnitudes. Landolt standard stars were transformed to the SDSS photometric system (Fukugita et al. 1996) and used to calibrate the photometric solution. Following the convention of the early data release of the SDSS quasar catalog (Schneider et al. 2002), we present the optical photometry here as g^*, r^*, and i^* since the SDSS photometry system is not yet finalized and the CTIO filters are not a perfect match to the SDSS filters. The limiting magnitudes for a point source are given as the mean of 3 σ detections: $g^* = 26.18$, $r^* = 25.54$, $i^* = 25.11$.

[12] CXCDS version R4CU5UPD14.1, along with ACIS calibration data from the *Chandra* CALDB 2.0b.

As evident from Figure 1, there are three optical sources detected down to a limiting i^* magnitude of 25.1 within the 50% encircled energy radius of the X-ray centroid. The two primary candidates, based on optical brightness, have offsets between the optical and X-ray positions of 1″.87 and 4″.94. To determine whether either of these sources are the likely counterpart to the X-ray detection, we have determined errors associated with the X-ray astrometric solution.

D.-W. Kim et al. (2002, in preparation) have carried out extensive simulations of point sources generated using the SAOSAC ray-trace program[13] and detected using CIAO/WAVDETECT. For weak sources of ∼20 counts between 8′ and 10′, off-axis from the aim point, the reported X-ray centroid position is correct within 1″.8, corresponding to a 1 σ confidence contour. Therefore, the nearby optical source ($\Delta r = 1''.9$) is the likely counterpart to the X-ray detection. The (J2000.0) position of the optical counterpart as measured from the r' image referenced to the Guide Star Catalog II[14] is $\alpha = 21^{\rm h}39^{\rm m}44^{\rm s}.99$, $\delta = -23°46'56''.6$.

2.3. *Optical Spectroscopy*

We obtained a low-resolution optical spectrum of CXOMP J213945.0−234655 (Fig. 2) with the CTIO 4 m/HYDRA multifiber spectrograph on 2001 October 15. Spectra of 17 of 22 optical counterparts to X-ray sources with a magnitude $r^* < 21$ were acquired in a 3 hr integration within the *Chandra* field. The spectrograph has 2″ diameter fibers and was configured with a 527 line $\rm mm^{-1}$ grating that provided ∼2800 Å of spectral coverage with a resolution of ∼4 Å. The sky background was measured using 81 fibers not assigned to the *Chandra* X-ray detections within the 1° field spectrograph. We processed the data using the IRAF(v2.11)/HYDRA reduction package.

An additional spectrum of the high-redshift quasar (Fig. 2) and the optically brighter source 4″.9 west of the *Chandra* X-ray position were obtained on the following evening with the ESO New Technology Telescope (NTT) 3.5 m to verify the intriguing Hydra spectrum and obtain greater wavelength coverage. A 300 line $\rm mm^{-1}$ grating was implemented with a wavelength coverage of 4000 Å and a resolution of ∼11 Å. Because of poor weather conditions at the end of the evening, flux calibration was done using the standard star LTT 2415 observed the following night. From the NTT spectrum, we classify the brighter object as an M3 dwarf with no sign of emission lines, confirming the quasar as the optical counterpart of the X-ray source.

We measured a mean redshift $z = 4.930 \pm 0.004$ from the Lyβ+O VI, C II, Si IV+O IV], and C IV emission lines in the NTT spectrum. Using this redshift, the Lyα line centroid is shifted by ≈4 Å redward from the expected rest wavelength, probably as a result of significant H I absorption. This is similar to the mean shift of Lyα observed in a sample of 33 high-redshift quasars by Schneider, Schmidt, & Gunn (1991).

The spectrum obtained at the NTT was used to measure the rest-frame equivalent widths of Lyβ/O VI (30 ± 7 Å), Lyα+N V (73 ± 5 Å), and C IV (40 ± 8 Å). For comparison, we also measured Lyα+N V for 10 high-redshift quasars in the range $4.8 < z < 5.1$ from the SDSS spectra of Anderson et al. (2001). This subsample has a similar mean redshift (4.91), but with an average $i^* = 19.7$ is 4.5 times more optically luminous than CXOMP J213945.0−234655. Nevertheless, the mean rest-frame equivalent width of Lyα+N V in the SDSS subsample is consistent at 79 Å, with an rms dispersion of 27 Å. The poor signal-to-noise ratio of the SDSS spectra and the strong Lyα forest prevent meaningful comparison of other line strengths.

[13] See http://hea-www.harvard.edu/MST.

[14] The Guide Star Catalog II is a joint project of the Space Telescope Science Institute and the Osservatorio Astronomico di Torino.

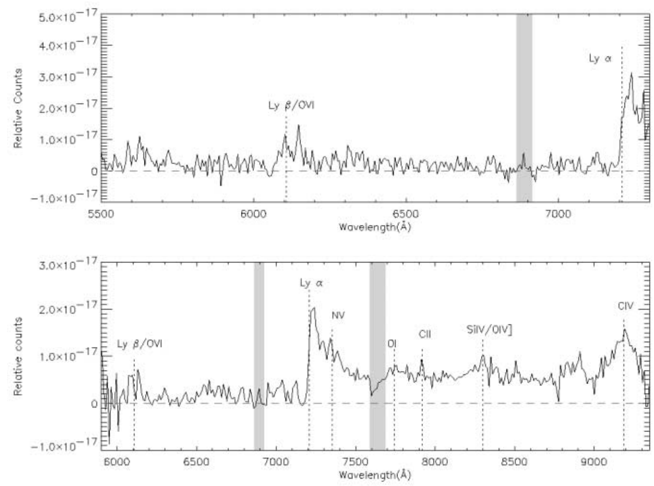

FIG. 2.—Optical spectroscopy of CXOMP J213945.0−234655. The top spectrum is the discovery observation taken with the CTIO 4 m/HYDRA on 2001 October 15. The spectrum has been binned to produce a resolution of 16.4 Å. The bottom panel is a follow-up observation with the NTT on the next evening to detect spectral features redward of Lyα (11 Å resolution). Dashed lines indicate the expected positions of emission lines at a redshift of 4.93. Shaded regions mark the uncorrected telluric O_2 absorption band regions.

3. RESULTS

To compare the broadband spectral energy distribution of CXOMP J213945.0−234655 to other X-ray–detected quasars, we have calculated $\alpha_{\rm ox}$ (Tananbaum et al. 1979), the slope of a hypothetical power law between the X-ray and optical flux. The rest-frame, monochromatic luminosity at 2 keV corresponding to the derived X-ray flux is $\log l_{2\,\rm keV} = 26.76$ ergs $\rm s^{-1}$ $\rm Hz^{-1}$. Assuming $\alpha = 0.5$ for the optical continuum power-law slope, we derive the rest-frame, monochromatic optical luminosity at 2500 Å from the i^* magnitude to be $\log l_{2500\,Å} = 30.73$ ergs $\rm s^{-1}$ $\rm Hz^{-1}$. We thus find $\alpha_{\rm ox} = 1.52^{+0.08}_{-0.05}$. Table 1 lists the measured X-ray and optical properties of CXOMP J213945.0−234655.

We compare the X-ray–to–optical flux ratio of CXOMP J213945.0−234655 to other $z > 4$ quasars by plotting the observed-frame, Galactic absorption–corrected 0.5–2.0 keV X-ray flux versus the $\rm AB_{1450(1+z)}$ magnitude (Fig. 3). The plotted lines represent the locus of points for a hypothetical quasar with a wide range of luminosities and an $\alpha_{\rm ox} = 1.6 \pm 0.15$ (Green et al. 1995), representative of the mean for quasars selected from the Large Bright Quasar Survey and detected in the *ROSAT* All-Sky Survey. The $\alpha_{\rm ox}$ of CXOMP J213945.0−234655 is comparable with low-redshift quasars in contrast to the X-ray faint *Chandra* detections of optically selected quasars at $z > 4$ (Vignali et al. 2001). The X-ray weakness of the latter may be due to intrinsic absorption by large amounts of gas in the quasars' host galaxies.

X-ray and optical observations of CXOMP J213945.0−234655 show no direct evidence of significant obscuration. The optical color ($r^*-i^* = 1.51 \pm 0.12$) is consistent with optically selected quasars. We measured the mean color r^*-i^* from 15 SDSS quasars (Anderson et al. 2001) with $4.7 < z < 5.2$ to be 1.69 with rms dispersion of 0.30. The upper limit to the X-ray hardness ratio (<-0.54) hints at an unobscured X-ray spectrum,

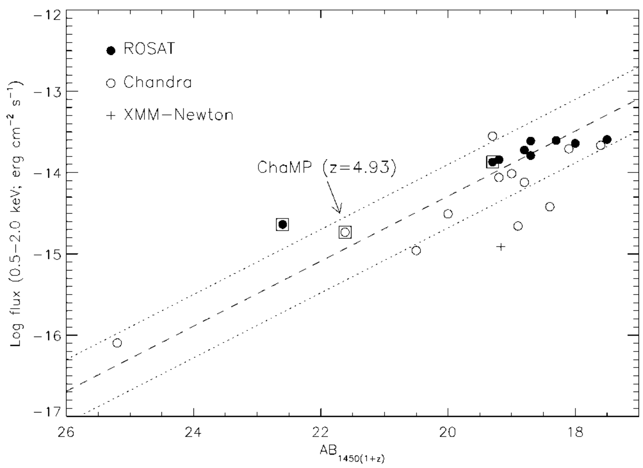

FIG. 3.—X-ray–to–optical flux correlation for $z > 4$ AGNs (adapted from Vignali et al. 2001). The primary symbols represent the X-ray observatory used. Squares mark X-ray–selected AGNs. The faintest source shown is a radio-selected Seyfert galaxy at $z = 4.424$ (Brandt et al. 2001b). The dashed lines display the relation for AGNs with $\alpha_{ox} = 1.6 \pm 0.15$ at $z = 4.9$ (Green et al. 1995).

although a moderately absorbed component, if present, would be redshifted out of the *Chandra* bandpass.

X-ray–selected samples may be less biased against absorbers (both intrinsic and line of sight) than are optically selected samples, an advantage expected to be especially important at high redshifts. From our flux-calibrated NTT spectrum, we measure $D_A = (f_{cont} - f_{obs})/f_{cont}$, the flux decrement caused by the Lyα forest (Oke & Korycansky 1982) relative to an extrapolated power-law continuum[15] in the region between rest-frame limits 1050−1170 Å. The value we measure of $D_A = 0.79 \pm 0.02$ is between the $\bar{z} \sim 4$ measurement of 0.54 from Rauch et al. (1997) and the $z \sim 6$ measurements of $D_A \sim 0.9$ from four SDSS quasars in Becker et al. (2001). While CXOMP J213945.0−234655 thus appears consistent with the handful of bracketing measurements of optically selected quasars (see also Riediger, Petitjean, & Mücket 1998), more high-redshift X-ray–selected quasars are needed to test possible biases caused by absorption.

CXOMP J213945.0−234655 exemplifies the potential for the ChaMP project to detect quasars with fluxes at the faint end of the f_X-f_{opt} parameter space (Fig. 3). This will allow the ChaMP to acquire significant numbers of high-redshift quasars. From the first year of spectroscopic follow-up of *Chandra* X-ray sources to $i' \lesssim 21$, we currently have 22 newly identified quasars with $z > 2$ and eight with $z > 3$, approximately two to three such objects per field. Nearly 5% of ChaMP sources identified to date are $z > 3$ quasars.

[15] As in Fan et al. (2001), we measure the observed flux f_{obs} relative to a $f_\lambda \propto \lambda^{-1.5}$ power-law continuum normalized to the observed flux in the region 1270 ± 10 Å in the rest frame. We derive uncertainties by measuring against continua with slopes in the range $-0.5 < \alpha \leq 1.5$.

4. CONCLUSION

We present the discovery of CXOMP J213945.0−234655, at $z = 4.93$ the most distant X-ray–selected object published to date. With a measured optical–to–X-ray flux ratio $\alpha_{ox} = 1.52$, CXOMP J213945.0−234655 is similar to low-redshift quasars, in contrast to several optically selected $z > 4$ quasars previously detected by *Chandra*.

This detection highlights the importance of wide-area, intermediate-depth surveys like the ChaMP for studies of the high-redshift quasar population ($z \sim 3$–5). The ChaMP[16] has begun to amass a sample of high-redshift, X-ray–selected quasars with the goal of measuring the cosmic evolution of accretion-powered sources relatively unhampered by the absorption and reddening that affects optical surveys.

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[16] See http://hea-www.harvard.edu/CHAMP.

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