X-RAY INSIGHTS INTO INTERPRETING C IV BLUESHIFTS AND OPTICAL/ULTRAVIOLET CONTINUA

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ABSTRACT

We present 0.5–8.0 keV Chandra observations of six bright quasars that represent extrema in quasar emission-line properties—three quasars each with small and large blueshifts of the C IV emission line with respect to the systemic redshift of the quasars. Supplemented with seven archival Chandra observations of quasars that met our selection criteria, we investigate the origin of this emission-line phenomenon in the general context of the structure of quasars. We find that the quasars with the largest C IV blueshifts show evidence, from joint spectral fitting, for intrinsic X-ray absorption (N_H ~ 10^{22} cm^{-2}). Given the lack of accompanying C IV absorption, this gas is likely to be highly ionized and may be identified with the shielding gas in the disk-wind paradigm. Furthermore, we find evidence for a correlation of \alpha_{UV}, the ultraviolet spectral index, with the hardness of the X-ray continuum; an analysis of independent Bright Quasar Survey data from the literature supports this conclusion. This result points to intrinsically red quasars having systematically flatter hard X-ray continua without evidence for X-ray absorption. We speculate on the origins of these correlations of X-ray properties with both C IV blueshift and \alpha_{UV} and discuss the implications for models of quasar structure.

Key words: line: formation — line: profiles — quasars: emission lines — quasars: general — X-rays: galaxies

1. INTRODUCTION

Considering the dynamic range of black hole masses and luminosities, quasar emission-line phenomenology is remarkably consistent. At the same time, the physical drivers for the known range of emission-line properties (see Sulentic et al. 2000a for an extensive review) are poorly understood.

One of the reasons the emission-line region is not better understood is the general similarity of quasar spectra (Richards et al. 2001) and the lack of sufficient emission-line distinctions to test competing models. That said, there are a few well-known differences. For example, it is generally believed that the widths of the Balmer lines (and probably Mg ii) are related to the mass of a quasar’s central black hole (e.g., Vestergaard 2002)—although the presumed disk-like configuration of this gas means that the line widths will be affected by projection effects (see, e.g., Krolik 2001). There is also the observation that more luminous quasars tend to have C IV emission lines with smaller equivalent widths, otherwise known as the Baldwin (1977) effect. Recently, Baskin \& Laor (2004) have argued that the Baldwin effect and the dynamics of the broad emission line region (BELR) in general are driven by differences in the Eddington ratio, L/L_Edd, among quasars. Similarly, Boroson \& Green (1992) and others have proposed that L/L_Edd drives a third trend, the anticorrelation between the strengths of [O III] and Fe ii emission in the optical part of the spectrum. A fourth effect seen in quasar emission lines is emission-line blueshifting (e.g., Gaskell 1982; Wilkes 1984; Tytler \& Fan 1992), where higher ionization lines yield emission-line redshifts that are systematically too small—as if the lines had been shifted blueward.

Richards et al. (2002) recently presented a summary of the emission-line blueshift effect among a sample of 3814 quasars from the Sloan Digital Sky Survey (SDSS; York et al. 2000). They showed that these emission-line shifts are more ubiquitous than previously thought, with the average quasar having a C IV emission line that yields a redshift that is too small with respect to Mg ii by \approx 800 km s^{-1}. Furthermore, quasar composite spectra created from samples binned by C IV blueshift showed differences in their ultraviolet continua and other emission-line properties. Specifically, the composite spectrum of the largest-blueshift quasars had a significantly bluer than average ultraviolet continuum and weaker C IV emission, while the smallest-blueshift composite was notably redder with stronger C IV emission. Richards et al. (2002) showed that this difference resulted from the intrinsic continuum color of the quasars, rather than as an effect of reddening.

The distribution of C IV blueshifts ranges over 3000 km s^{-1}, making this effect an excellent candidate for further investigation into the structure of the BELR. Richards et al. (2002) hypothesized that the range of C IV blueshift and ultraviolet continuum color was a consequence of orientation. Orientation could be understood in one of two ways, either with respect to the accretion disk or with respect to the wind, which may have a range of opening angles (see, e.g., Fig. 7 in Elvis 2000 and Fig. 5 in Richards et al. 2004). In both cases, understanding the BELR might be aided by probing smaller scales. X-ray emission is believed to arise on physical scales comparable to and smaller than those of the optical/UV continuum. Therefore, not only are X-rays sensitive to physical conditions in the immediate vicinity of the black hole, they can also probe the line of sight to...
in Chandra observations have been supplemented with seven from the archive. We were awarded six observations in Cycle 4; these observations thus offer the potential to tie BELR phenomena (on scales of light-years) to fundamental properties of the accretion disk. For example, if the range of BELR phenomenology results purely from orientation effects, one might expect the intrinsic X-ray continuum properties to be unrelated.

To investigate this avenue, we undertook an exploratory Chandra (Weisskopf et al. 2002) survey to study the X-ray properties of extreme examples of the C IV blueshift distribution. We were awarded six observations in Cycle 4; these observations have been supplemented with seven from the archive. In § 2, we present the target selection process and describe the initial Chandra data analysis. We study the trends in these data in § 3. The results from joint spectral fitting of the Chandra spectra and the connection to optical/UV emission-line and continuum properties are presented in § 4. In § 5, we summarize the results from our X-ray analysis and introduce comparison data from the literature on objects from the Bright Quasar Survey (BQS; Schmidt & Green 1983). In § 6, we discuss the physical origins of our observed correlations and comment on the relation between the C IV and Mg II emission lines in the SDSS spectra. The velocity offsets between the C IV and Mg II emission-line redshifts were computed, and the quasars were divided into four broad blueshift bins from small to large C IV blueshift. From the smallest- and the largest-blueshift bins, we requested time for exploratory Chandra Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) observations, giving priority to the optically brightest quasars with small Galactic N H. The sample was vetted to exclude broad absorption line (BAL) quasars and quasars detected in the 20 cm FIRST survey (Becker et al. 1995). In Cycle 4 we were awarded time to observe six quasars for this program.

In addition to the six targets in our primary program, we also included seven additional targets from the Chandra archive to increase the sample size. These archival data were found by cross-correlating the complete list of SDSS Data Release 1 (DR1) quasars (Schneider et al. 2003) with the same redshift range as the primary sample with observations publicly available from the Chandra ACIS archive as of 2004 March. Of these, only J2348+00577 was an observation target (Green et al. 2002); the rest were serendipitous. The target list and optical properties of all of the quasars in this program are presented in Table 1. The optical properties include Δv (the C IV blueshift), Δ(g−i) (the observed g−i minus the median of the DR1 g−i distribution at the redshift of the quasar; Richards et al. 2001), and α UV (the spectral index of a power-law continuum fit to the optical spectra between rest-frame 1450 and 2200 Å). The optical spectra are shown in Figures 1 and 2. A catalog of the Chandra observations is presented in Table 2. The additional archival targets are listed below the primary sample in the data tables.

All archival targets were checked to exclude radio-detected and BAL quasars. The archival quasar, J0200−0845, was

### Table 1

| Name (SDSS) | z_em | i | M_i | Δv/| Δ(g−i) | α_{UV} | E(B−V) | N_H | Sample
|---|---|---|---|---|---|---|---|---|---|
| J003131.44+004320.2 | 1.732 | 18.425 | 26.62 | 64.268 | 0.122±0.038 | -0.24 | 0.024 | 2.41 | S/II |
| J173716.5+582839.4 | 1.775 | 18.509 | 26.49 | 63.60 | 0.047±0.023 | -0.15 | 0.042 | 3.51 | S/II |
| J234815.98+005721.4 | 2.160 | 18.611 | 26.93 | 61.173 | -0.115±0.043 | -0.14 | 0.025 | 3.81 | M/IND |
| J011309.06+153553.5 | 1.809 | 18.739 | 27.28 | 70.123 | -0.142±0.029 | 0.03 | 0.070 | 4.38 | M/IND |
| J245400.99+007244.8 | 1.687 | 18.157 | 26.83 | 72.155 | 0.228±0.028 | -0.58 | 0.024 | 1.73 | NA/NA |
| J143841.95+034110.3 | 1.740 | 18.754 | 27.27 | 78.386 | 0.313±0.022 | -1.20 | 0.043 | 2.62 | M/IND |
| J204306.63+150250.6 | 1.936 | 18.395 | 26.88 | 124.136 | -0.099±0.030 | -0.84 | 0.026 | 1.88 | L/III |
| J020022.01−084512.1 | 1.942 | 18.283 | 27.02 | 33.18 | 0.398±0.033 | ... | 0.024 | 2.12 | NA |

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7 This quasar is a member of a wide quasar binary (Q2345+007AB; Weedman et al. 1982); the fainter member of the pair is not included in our study, as it has no SDSS spectrum.
See http://space.mit.edu/CXC/analysis/ACIS_Contam/ACIS_Contam.html.

Chandra processed using the standard exposure times ranging from 3.5 to 5.6 ks. The data were profile of the back-illuminated S3 CCD of ACIS in faint mode with and 2003 August 26. Each target was observed at the aim point each of small and large blueshifts) between 2002 November 20 and 2003 August 26. Each target was observed at the aim point of the back-illuminated S3 CCD of ACIS in faint mode with exposure times ranging from 3.5 to 5.6 ks. The data were processed using the standard Chandra X-Ray Center aspect solution and grade filtering, from which the level 2 event file was taken.

Both aperture photometry and the CIAO 3.08 wavelet detection tool “wavdetect” (Freeman et al. 2002) were used in the soft (0.5–2.0 keV), hard (2.0–8.0 keV), and full (0.5–8.0 keV) bands to determine the measured counts for a point source in each band. The lower limit of 0.5 keV was chosen to match the well-calibrated part of the response; above 8.0 keV, the effective area of the Chandra mirrors drops considerably and the back-illuminated S3 CCD of ACIS in faint mode with exposure times ranging from 3.5 to 5.6 ks. The data were processed using the standard Chandra X-Ray Center aspect solution and grade filtering, from which the level 2 event file was taken.

For each new target, the appropriate Galactic column density included in the model. The ARF contains the energy-dependent effective area and quantum efficiency of the telescope, filter, and detector system. Each ARF was modified using the tool "contamfit" to take into account the time-dependent degradation of the ACIS low-energy effective area, likely due to

omitted from subsequent analysis because it is a radio-loud BAL quasar. We include it in the data tables to present the X-ray data for the record.

2.2. X-Ray Analysis

Chandra observed the six extreme C iv blueshift targets (three each of small and large blueshifts) between 2002 November 20 and 2003 August 26. Each target was observed at the aim point of the back-illuminated S3 CCD of ACIS in faint mode with exposure times ranging from 3.5 to 5.6 ks. The data were processed using the standard Chandra X-Ray Center aspect solution and grade filtering, from which the level 2 event file was taken.

For each new target, the appropriate Galactic column density included in the model. The ARF contains the energy-dependent effective area and quantum efficiency of the telescope, filter, and detector system. Each ARF was modified using the tool "contamfit" to take into account the time-dependent degradation of the ACIS low-energy effective area, likely due to

entire data set. For the mean flux of our sample (∼7 × 10⁻¹⁴ ergs cm⁻² s⁻¹), the source density from blank-field number counts is (1.5–3.9) × 10⁻¹⁰ sources arcsec⁻² (see, e.g., Bauer et al. 2004), and so the chance of a misidentification is negligible.

For the off-axis archival observations, the wavdetect photometry was found to be unreliable, particularly in the hard band, and so aperture photometry was used for the subsequent calculations for these quasars. For the on-axis observations, the background was in all cases negligible (<1 count in the source region). For the off-axis observations, the source counts are background-subtracted. The background was determined from a source-free elliptical or circular annulus around the source aperture and normalized to the area of the source region. In all cases backgrounds were still low; the largest background contributed ≤6% of the net full-band counts within the source aperture (for J1204+0150).

For each target, to provide a coarse quantitative measure of the spectral shape we calculated the hardness ratio, defined as

\[
HR = \frac{N_{\text{soft}}}{N_{\text{hard}}},
\]

where

\[
N_{\text{soft}} = \frac{N_{\text{soft}}}{N_{\text{hard}}} = \frac{N_{1\text{keV}}}{N_{\text{hard}}}
\]

and

\[
N_{1\text{keV}} = \int_{1\text{keV}}^{\text{max}} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}.
\]

From spectral fitting of ASCA and other data, Γ is found to average 2.0 ± 0.25 for radio-quiet quasars (e.g., George et al. 2000; Reeves & Turner 2000). To transform the observed HR into Γ, the X-ray spectral modeling tool XSPEC (Arnaud 1996) was used to simulate the response of the instrument. The simulation procedures followed were slightly different for the new and archival observations because the archival data were taken from different CCDs, requiring a unique response for each observation.

For each new target, the appropriate Galactic column density (see Table 1) and modified auxiliary response file (ARF) were included in the model. The ARF contains the energy-dependent effective area and quantum efficiency of the telescope, filter, and detector system. Each ARF was modified using the tool “contamfit” to take into account the time-dependent degradation of the ACIS low-energy effective area, likely due to

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9 See http://space.mit.edu/CXC/analysis/ACIS_Ccontam/ACIS_Ccontam.html.
the accumulation of a layer of hydrocarbon contaminant on
the optical blocking filters (Marshall et al. 2004). The ARF is
modified by multiplying the original by a time- and energy-
dependent function derived from the empirically determined
optical depth of the contaminant. The redistribution matrix file
(RMF) maps the energy of an incident X-ray into the space of
the observed charge distribution of the detector. The ARF and
RMF, both required to simulate the instrument response, were
generated using the CIAO 3.0 tools mkarf and mkrmf. The
detector response to incident power-law spectra with varying
\( \gamma \) was then simulated. The hardness ratio and errors were
compared with the modeled HR to determine the \( \Gamma_{HR} \) (with errors)
that would generate the observed HR. For reference, a typical
radio-quiet quasar with no intrinsic absorption and a photon index
\( \Gamma = 2.0 \) would be observed to have \( HR \approx -0.63 \) on-axis. The
modeled full-band count rate was normalized to the observed
full-band count rate to obtain the power-law normalization, \( N_1 \) keV.
With \( N_1 \) keV and \( \Gamma_{HR} \), the 0.5–8.0 keV flux, \( F_X \), and the flux
density at rest-frame 2 keV, \( f_{2,\text{keV}} \), were calculated. The errors
quoted for these two values are the Poisson errors (Gehrels 1986)
from the full-band counts. Lastly, \( \alpha_{\text{dr}} = 0.384 \log \left( \frac{f_{2,\text{keV}}}{f_{2,5000}} \right) \)
and its associated uncertainties were calculated, where the fac-
tor 0.384 is the logarithm of the ratio of the frequencies at
which the flux densities are measured and \( f_{2,5000} \) is the average flux
density within the rest-frame range 2500 ± 25 Å in the SDSS
optical spectrum. For reference, the SDSS spectrophotometric
calibration has a typical uncertainty of 4% (rms) in the \( r \) band
(Azajjan et al. 2004). The uncertainty on \( \alpha_{\text{dr}} \) is given by
\[ \sigma_{\alpha_{\text{dr}}} = 0.4084\left( \frac{\sigma_{f_{2,\text{keV}}}}{f_{2,\text{keV}}} \right) + \left( \frac{\sigma_{f_{2,5000}}}{f_{2,5000}} \right)^2 \right)^{1/2}, \]
where \( \sigma_{f_{2,\text{keV}}} \) is just the Poisson uncertainty\(^{10} \) but \( \sigma_{f_{2,5000}} \) includes the estimated
effects of variability. We use a formula from Ivezić et al. (2004)
to calculate the characteristic variation in magnitudes at 2500 Å
for each quasar’s absolute magnitude, \( M_r \), and for the rest-frame
\( \Delta \nu \) (in days) between the SDSS spectral and X-ray imaging
epochs: \( \sigma_{m_{\text{spec}}} = (1 + 0.24M_r/\Delta \nu/2500)^{0.3} \) which is then
converted to the flux uncertainty \( \sigma_{f_{\text{spec}}} \) and used to calculate \( \sigma_{f_{\text{spec}}} \).

For the archival data, the same procedure was followed with
the exception that the ARFs and RMFs were generated for
each observation using the CIAO 3.0 script psextract. This
process also takes into account the time-dependent change in
the ARFs. The source extraction regions were the same as the
apertures used for aperture photometry. The X-ray properties and
the MJDs of the SDSS optical spectra used are all presented in
Table 3.

2.3. Notes on UV Absorption and Individual Quasars

Some of our objects have intervening or associated ultraviolet
absorbers. If the former are damped Ly\( \alpha \) absorbers (DLAs),
they may produce some appreciable X-ray absorption. We use
the criteria of Rao & Turnshek (2000) to determine which
intervening absorbers have a 50% chance of being a DLA, with
\( N_1 > 2 \times 10^{20} \) cm\(^{-2} \). J006–0015 and J1438+0341 have inter-
vening candidate DLA systems, the latter at a redshift that
places Al in absorption atop the C iv emission line (see Figs. 1–
2). J1245–0027 has an associated C iv absorber that may be
intrinsic, as the absorption appears saturated even though the
flux does not decrease to zero. J1737+5825 may have a weak
associated C iv absorber. None of these narrow intervening or
associated absorption systems is likely to have column densities of
gas or dust large enough to significantly affect the colors or X-ray
properties of our targets.

2.3.1. J0156+0053 (\( z = 1.652 \))

The ultraviolet spectrum of this quasar shows unusually
strong, narrow He ii and O iii emission lines, as well as the
reddest \( \Delta (g-i) \) and the next-to-smallest blueshift in the sample.

\(^{10}\) Using the ACIS archival observations of more than 15 ks exposure time,
we have verified that X-ray variability on ~5 ks timescales does not contribute
any significant excess variance to the measured X-ray flux.
In addition, it has the smallest inferred \( \Gamma \) (Tables 2 and 3). This quasar clearly has extreme properties in both the ultraviolet and X-ray regimes.

2.3.2. \( J0200-0845 \) (\( z = 1.942 \))

We initially identified archival quasar observations based only on the overlap between the SDSS DR1 quasar catalog and the Chandra archive. Subsequent checking revealed \( J0200-0845 \) to be a radio-loud BAL quasar with radio-loudness parameter \( R_l = 1.66 \) (Ivezić et al. 2002). Given the known connection between both radio loudness (e.g., Reeves & Turner 2000) and the presence of broadband ultraviolet absorption lines (e.g., Gallagher et al. 1999) to broadband X-ray properties, this object is not appropriate for our study and has been excluded from all correlation analysis and X-ray spectral fitting. Furthermore, intrinsic UV absorption may mask the blue shift measured by the SDSS pipeline inaccurate, and the \( \Delta(g-i) \) could be affected by reddening. We have included this object in the data tables to present the X-ray properties for the record.

2.3.3. \( J1151+0038 \) (LBQS 1148+0055; \( z = 1.884 \))

Visual inspection of the Chandra data revealed two X-ray point sources within \( 4'' \) of the SDSS optical position of this quasar. The fainter X-ray source is coincident with the optical position of a lower luminosity quasar, LBQS 1148+0055B, with a discordant redshift (\( z = 1.409 \); Hewett et al. 1998). This source is spatially resolved from J1151+0038 and does not contaminate the X-ray analysis. LBQS 1148+0055B is not included separately in our study, because it has no SDSS spectrum.

3. TRENDS WITH BLUESHIFT AND OBSERVED-FRAME COLOR

It has been shown that \( \alpha_{ox} \) is correlated with UV luminosity (e.g., Green et al. 1995; Vignali et al. 2003 and references therein). We chose to remove that correlation and look for trends as a function of \( \Delta \alpha_{ox} = \alpha_{ox} - \alpha_{ox}(L_{2500}) \), where \( \alpha_{ox}(L_{2500}) \) is the expected \( \alpha_{ox} \) for the observed luminosity, \( L_{2500} \), of the quasar, taken from equation (4) of Vignali et al. (2003). The value of \( \Delta \alpha_{ox} \) reveals an excess or deficit of X-ray emission relative to the UV luminosity; negative values of \( \Delta \alpha_{ox} \) indicate a deficit of X-ray emission. For reference, the range of \( L_{2500} \) in our sample is approximately 1 dex (Table 3). We find no correlation of \( \Delta \alpha_{ox} \) with \( \Gamma_{IR} \), with C iv blueshift (Fig. 3a), or with \( \Delta(g-i) \) color (Fig. 3b). We use \( \Gamma_{IR} \) rather than HR to remove any systematic effects introduced by differences of the ACIS response as a function of position on the detector or observation date. We use \( \Delta(g-i) \) rather than simply \( g-i \) because the observed \( g-i \) color of a typical quasar varies with redshift. The parameter \( \Delta(g-i) \) is the observed \( g-i \) minus the median of the DR1 \( g-i \) distribution at the redshift of the quasar (Richards et al. 2001). The three line segments in Figure 3b show how absorption and reddening by neutral gas and dust with column densities \( N_H \) of \( 7.8 \times 10^{20} \), \( 2 \times 10^{21} \), and \( 3.5 \times 10^{21} \) cm\(^{-2} \) at \( z \approx 2 \) would affect \( \alpha_{ox} \) and \( \Delta(g-i) \), using the SMC dust-to-gas ratio of Bouchet et al. (1985). Richards et al. (2003) have argued that quasars have an intrinsic distribution of \( -0.3 < \Delta(g-i) < 0.3 \) and that quasars with \( \Delta(g-i) \approx 0.3 \) are dominated by objects reddened by SMC-like dust (see also Hopkins et al. 2004) rather than by intrinsically red objects. As can be seen in Figure 3b, gas with SMC-like dust would have a much larger effect on the \( \Delta(g-i) \) color than on \( \Delta \alpha_{ox} \).

To investigate potential statistically significant trends, we calculated both Spearman’s \( \rho \) and Kendall’s \( \tau \), two nonparametric measures of the probability of significant correlations, for \( \Delta \alpha_{ox} \) and \( \Gamma_{IR} \) versus blueshift (Figs. 3a and 3c) and \( \Delta \alpha_{ox} \) and \( \Gamma_{IR} \) versus \( \Delta(g-i) \). The only marginally significant trend we detect is an inverse correlation of \( \Gamma_{IR} \) with \( \Delta(g-i) \) whereby redder objects tend to have harder 0.5–8.0 keV X-ray spectra.
method (Akritas & Bershady 1996). The BCES estimator takes into account errors in both parameters, as well as intrinsic scatter, in calculating the best-fitting slope, intercept, and 1 σ errors in each. The best-fitting line for the correlation between $\Gamma_{HR}$ and $\alpha_{uv}$ is plotted in Figure 3d, as well as lines bracketing the 1 σ errors in the slope and intercept.

4. JOINT X-RAY SPECTRAL FITTING

Given the uncertain interpretation of $\Gamma_{HR}$, which is a coarse spectral parameterization, we proceed to joint spectral fitting. This technique enables utilization of all of the spectral information available in these exploratory Chandra observations to determine the average properties of a sample. The model fit in each case is a power-law continuum with both Galactic and intrinsic neutral absorption. For each quasar, the Galactic $N_H$ and $z$ are fixed to the appropriate values, the values for neutral, intrinsic $N_H$ and $\Gamma$ are tied to the other quasars in the sample, and the values of $N_{1\,keV}$ are free to vary for each quasar.

Each spectrum was extracted from the source cell used for aperture photometry, and an ARF and RMF were generated using the CIAO 3.0 script psextract, which appropriately modifies the ARF to take into account the low-energy quantum efficiency degradation. Because of the low number of counts in each spectrum, the data were fitted by minimizing the C-statistic (Cash 1979), an option for low-count spectra within XSPEC. For this type of fitting, the data are not binned and background spectra are not subtracted, in order to maintain the Poisson nature of the data. Errors given in the text are for 90% confidence for two parameters of interest, $\Delta C = 4.61$, unless otherwise indicated.

4.1. Average X-Ray Spectral Properties of Blueshift Samples

We first fit the new data for the large-blueshift ($\Delta v_b > 1100\, \text{km s}^{-1}$) and small-blueshift ($\Delta v_b < 500\, \text{km s}^{-1}$) quasar samples separately. This approach yields the average spectral properties of these representatives of the extreme ends of the blueshift distribution. The total 0.5–8.0 keV counts in the large- and small-blueshift samples were 129 and 180, respectively.

For the large-blueshift group (sample 1), the best-fitting photon index, $\Gamma = 2.0 \pm 0.6$, is consistent with the average of a sample of typical radio-quiet quasars ($2.0 \pm 0.3$; e.g., George

![Fig. 4.—Chandra spectra of the combined large-blueshift (circles) and small-blueshift (crosses) samples. Both data sets have been fitted with a power-law model above observed-frame 1 keV, and the models (histograms) have been extrapolated back to 0.5 keV. The residuals (bottom) indicate that while a power-law model with $\Gamma \sim 1.4$ is an adequate fit to the small-blueshift sample, a power-law model with $\Gamma \sim 2.2$ overpredicts the counts between 0.5 and 1.0 keV for the large-blueshift sample. These negative residuals are the signature of intrinsic absorption.](image-url)
et al. 2000), while for the small-blueshift group (sample 2), the best-fitting photon index was noticeably flatter: \( \Gamma = 1.4 \pm 0.3 \). We consider this latter result uncertain, as J0156+0053, with 89 counts and \( \Gamma_{HR} = 1.1 \pm 0.2 \), contributes half of the signal to the joint spectral fitting for the small-blueshift group and appears to drive the low value for \( \Gamma \). Nevertheless, a flatter \( \Gamma \) for the small-blueshift sample is consistent with the measured values for \( \Gamma_{HR} \). While the small-blueshift quasars have best-fitting intrinsic column densities consistent with zero, the large-blueshift quasar spectra indicate that intrinsic absorption is present with \( N_H = 1.6^{+1.9}_{-1.5} \times 10^{22} \) cm\(^{-2} \). With the sample data quality and the observed-frame 0.5–8.0 keV ACIS bandpass, our joint spectral fitting is not sensitive to the ionization state of the gas, and ionized gas would have higher column densities.

The binned spectra presented in Figure 4 illustrate the difference between a flat power-law continuum and a steeper power-law continuum with absorption. Two composite spectra were created, one each of the large-blueshift and small-blueshift samples, by adding together the unbinned spectra in each sample. Three ARFs were combined by weighting by the 0.5–8.0 keV counts in each spectrum, to create a composite ARF. The same weighting scheme was used to make composite RMFs. The data were grouped to have at least 5 counts per bin. The data below 1 keV observed-frame were ignored, and both spectra were fitted independently with power-law models. This procedure sets both \( N_{1 \text{keV}} \) and \( \Gamma \) of the hard-band continuum and is insensitive to \( N_H \lesssim 3 \times 10^{22} \) cm\(^{-2} \) at these redshifts. Finally, the power-law models were extrapolated to 0.5 keV for comparison with the 0.5–1 keV data. As can be seen in the residuals panel in Figure 4, while a \( \Gamma \approx 1.4 \) power-law model fits the soft-band small-blueshift composite spectrum quite well, a \( \Gamma \approx 2.2 \) power-law model significantly overpredicts the soft-band counts from the large-blueshift composite spectrum. These negative residuals are a clear signature of intrinsic absorption. For reference, uncertainties in the contaminant model applied to correct the ARFs for the low-energy quantum efficiency degradation are estimated to be \( \pm 5\% \) in the 0.5–1.0 keV range,\(^\text{11} \) much less than these large negative residuals. Furthermore, any errors in the contaminant model would not affect the large-blueshift sample preferentially, as the observations contributing to each sample span roughly the same time.

To confirm these trends, we included the archival spectra in the joint spectral fitting and created a third, “moderate” blueshift group with \( \Delta \chi^2 = 500–1100 \) km s\(^{-1} \). We excluded the archival quasar J1245–0027 because of the large uncertainty in its blueshift (see Table 1). The same procedure was followed, with the large (sample 3), small (sample 4), and moderate (sample 5) blueshift groups. The addition of the archival quasars significantly increased the total 0.5–8.0 keV counts in the large- and small-blueshift samples, to 266 and 260, respectively. Once again, best-fitting parameters for the large-blueshift sample included a steeper photon index, \( \Gamma = 2.0^{+0.3}_{-0.2} \), and significant intrinsic absorption, \( N_H = 1.5^{+2.4}_{-0.3} \times 10^{22} \) cm\(^{-2} \). The small-blueshift sample also showed consistent results, with a harder X-ray continuum, \( \Gamma = 1.6^{+0.3}_{-0.2} \). At 90% confidence, intrinsic absorption is constrained to be less than 0.63 \times 10^{22} \) cm\(^{-2} \). The upper limit is set primarily by the low-energy cutoff (0.5 keV observed-frame) of the ACIS bandpass.

The contours for samples 3–5 are presented in Figure 5, and the results from the joint spectral fitting of samples 1–5 are listed in Table 4. The moderate-blueshift group, sample 5, has only three quasars but, with the total number counts equal to 1139, has significantly higher signal-to-noise ratio than the other two samples. While the best-fitting photon index for this

![Figure 5](image-url)  
**Fig. 5.**—Confidence contours of photon index \( \Gamma \) vs. intrinsic \( N_H \) from joint spectral fitting for the new plus archival large (thick solid curves; sample 3), moderate (thin solid curves; sample 5), and small (dotted curves; sample 4) blueshift samples as defined in Table 4. The contours are for 68% (\( \Delta C = 2.30 \)) and 90% (\( \Delta C = 4.61 \)) confidence.

| Sample \(^a\) | \( \Gamma \) \(^b\) | \( N_H \) \(^c\) | C-Statistic/\( \nu \) | Total Counts |
|-------------|-------------|-------------|----------------|-----------|
| 1. Large: new (3) | 2.00 \( ^{+0.61}_{-0.62} \) | 1.56 \( ^{+1.37}_{-1.53} \) | 426.8/1536 | 129 |
| 2. Small: new (3) | 1.42 \( ^{+0.35}_{-0.26} \) | 0.00 \( ^{+0.36}_{-0.00} \) | 553.2/1536 | 180 |
| 3. Large: new (3) + archival (1) | 1.98 \( ^{+0.29}_{-0.29} \) | 1.47 \( ^{+0.27}_{-0.27} \) | 648.2/2048 | 266 |
| 4. Small: new (3) + archival (2) | 1.64 \( ^{+0.20}_{-0.20} \) | 0.00 \( ^{+0.36}_{-0.00} \) | 801.8/2560 | 260 |
| 5. Moderate: archival (3) | 1.98 \( ^{+0.31}_{-0.13} \) | 0.27 \( ^{+0.27}_{-0.27} \) | 996.9/1536 | 1139 |

\(^a\) The samples are described in more detail in § 4.2. The numbers in parentheses refer to the number of quasars in each sample.

\(^b\) The errors quoted are for 90% confidence (\( \Delta C = 4.61 \) for two parameters of interest). Both \( \Gamma \) and \( N_H \) are tied together to determine the average parameter values for each sample. The redshift and Galactic \( N_H \) for each quasar are fixed to the appropriate values (see Table 1).

\(^c\) See http://asc.harvard.edu/cal/ACIS/Cal...prod/qeDeg/index.html.
sample, $\Gamma = 2.0^{+0.3}_{-0.1}$, is consistent with sample 3, the best-fitting intrinsic $N_{\text{H}}$ is consistent with zero. This suggests that samples 3 and 5 have consistent intrinsic hard-band X-ray continua, while the quasars in sample 4 may have harder (flatter) X-ray continua. To investigate this possible trend in more depth, we pursued joint spectral fitting analysis further.

### 4.2. Blueshift or Color?

In Figure 6, we present both the histogram of C iv blueshifts for the $z = 1.54-2.20$ SDSS Data Release 2 (Abazajian et al. 2004) quasars (updated from Fig. 1 in Richards et al. 2002) and the plot of $\Delta(g-i)$ versus C iv blueshift for these objects. As noted by Richards et al. (2002), quasar composite spectra made by binning in blueshift indicate that color differences correlate with blueshift: large-blueshift quasars tend to have bluer $\Delta(g-i)$ colors, while small-blueshift quasars tend to have redder optical/UV continua. However, the two-dimensional structure in the $\Delta(g-i)$-blueshift distribution indicates that these properties are not simply related. Though large-blueshift quasars are much more likely to have blue $\Delta(g-i)$ colors, quasars with blueshifts less than the median value of $\sim 800$ km s$^{-1}$ span the entire color range.

In an attempt to disentangle the connection between X-ray spectral differences and blueshift, we extended the joint spectral fitting by binning the quasars into finer blueshift bins. The three moderate-blueshift quasars (J0113+1535, J1438+0341, and J2348+0057) each had enough counts to be fitted independently. The other quasars were grouped into the smallest samples (from two to four objects; see Table 1) that would enable reasonable constraints to be set on $\Gamma$ and intrinsic $N_{\text{H}}$ from joint spectral fitting of an absorbed power-law model. The results from this analysis are presented in Figure 7.

Figures 7a and 3d indicate that both large-blueshift and blue quasars tend to have larger X-ray photon indices. However, only the second trend is statistically significant. Therefore, $\alpha_{\text{UV}}$, rather than blueshift, appears to be linked to the steepness of the hard-band X-ray continuum. Figure 7b clearly supports the significant detection of intrinsic absorption in the large-blueshift quasars.

### 5. SUMMARY OF X-RAY ANALYSIS AND COMPARISON WITH BQS QUASARS

With a modest amount of Chandra exposure, we have derived some insight into the connection between X-ray and UV spectral properties of luminous quasars. From joint spectral fitting, we have found that the quasars with large blueshifts ($\Delta v > 1100$ km s$^{-1}$) in our sample show significant evidence for intrinsic absorption with $N_{\text{H}} \sim 10^{22}$ cm$^{-2}$ (assuming neutral gas with solar abundances). For this sample, unlike with samples of low-$z$ or BAL quasars, $\Gamma_{\text{abs}}$ is not a sensitive absorption indicator. The combination of column density ($N_{\text{H}} \sim 10^{22}$ cm$^{-2}$)
and redshift pushes the energy cutoff from absorption to observed-frame ~0.8 keV (see Fig. 4). The effective area of ACIS S3 peaks between 1 and 2 keV, after the spectrum has recovered. The low-energy curvature of the power-law spectrum from absorption is thus only evident with the additional energy resolution utilized in joint spectral fitting. These same factors—bandpass, redshift, and column density—also make \( \alpha_{\text{ox}} \) a weak indicator of intrinsic absorption for this sample, unlike for the \textit{ROSAT} survey of low-redshift BQS quasars by Brandt et al. (2000). For that sample, \( \alpha_{\text{ox}} \leq 2.0 \) was a strong predictor of comparable column densities of X-ray absorption (Gallagher et al. 2001).

Unfortunately, the BQS sample cannot be used effectively to study X-ray absorption in large-blueshift quasars. Of luminous \( (M_V < -24) \), radio-quiet BQS quasars with measured blueshifts (Baskin & Laor 2005), only two would qualify for our large-blueshift sample with \( \Delta v_b \geq 1100 \text{ km s}^{-1} \). The first, PG 1259+593 \( (\Delta v_b = 3304 \text{ km s}^{-1}) \), was not detected with \textit{ROSAT}; and Brandt et al. (2000) measured an upper limit on \( \alpha_{\text{ox}} \) of \(-1.79\), which is (at least) moderately X-ray–weak. For the second, PG 1543+489 \( (\Delta v_b = 2032 \text{ km s}^{-1}) \), George et al. (2000) find their preferred spectral model for the \textit{ASCA} data to include intrinsic absorption \( (N_H = 0.7 \times 10^{21} \text{ cm}^{-2} \) for neutral gas) that may be ionized. Though the X-ray properties of these two quasars suggest that both may harbor intrinsic absorbers, the quality of the existing X-ray data is not sufficient for such a claim.

Our second result is that \( \Gamma_{\text{HR}} \) correlates with \( \alpha_{\text{UV}} \). This might be expected if smaller values \( \Gamma_{\text{HR}} \) were tracing intrinsic absorption. Instead, the results from joint spectral fitting indicate that the \( \Gamma_{\text{HR}}-\alpha_{\text{UV}} \) trend seen in Figure 3d is not driven by absorption: instead, the bluest quasars with the largest \( \Gamma_{\text{HR}} \) values show evidence for absorption. The correlation indicates an inherent difference in the actual X-ray photon index as a function of color, with redder quasars having harder X-ray spectra.

Given that our sample is small and the statistical errors in the X-ray spectral properties are large, we investigated the connection between optical/UV continuum color and \( \Gamma \) further with additional data from Porquet et al. (2004, hereafter P04). P04 systematically analyzed BQS X-ray spectra from the \textit{XMM-Newton} archive. Many of these quasars also have measurements of their optical/UV continuum slopes, \( \alpha_{\text{p}} \), from power-law fits to narrowband optical photometry by Neugebauer et al. (1987). For comparison with our results, P04 sample was stripped of all radio-loud quasars and all quasars more than 2 mag less luminous than PG 0953+414, the most luminous radio-quiet quasar in the sample \( (M_V = -25.65 \); see Table 1 of P04), because both radio loudness and luminosity might influence X-ray properties. The resulting range of optical luminosity matches that of our sample, though our sample is significantly more luminous overall (see col. [4] of Table 1). Of the 16 remaining quasars, 14 had measurements of \( \alpha_{\text{p}} \).

In Figure 8, we plot the observed-frame 2–5 keV \( \Gamma \) measured by P04 versus \( \alpha_{\text{p}} \), from Neugebauer et al. (1987). Many of these quasars have additional hard-band \( \Gamma \) measurements from spectroscopic data sets to different data (see the Appendix of P04 and references therein), and we plot these as well (circles). Several quasars (PG 1202+281, 1307+085, 1352+183, and 1613+658) show significant differences in \( \Gamma \) between observations, which may result from actual variability, differences in analyses or observatories, or both. There is clearly a large scatter, but the general trend that the bluest quasars have the steepest hard-band X-ray spectra is consistent with our results. For the filtered P04 sample, the Spearman and Kendall probabilities of no correlation between \( \Gamma \) and \( \alpha_{\text{p}} \) are 0.038 and 0.028, respectively. If the averages between the P04 and previous values are used, the no-correlation probabilities are 0.022 and 0.014 for the same sample. The BCES-estimator linear fit to the average \( \Gamma_{\text{HR}}-\alpha_{\text{UV}} \) data points is overplotted in Figure 8. To compare directly the BQS data with the data plotted in Figure 3d, a polygon encompassing the 1 \( \sigma \) range in slope and intercept for the linear fit is overplotted in Figure 8. The two independent fits are consistent within the 1 \( \sigma \) errors in both slope and intercept.

Neither of these results relating hard-band \( \Gamma \) to optical/UV color is independently conclusive, but the combined evidence, from the \( \Gamma_{\text{HR}}-\alpha_{\text{UV}} \) trend and the presented BQS data, points to a consistent picture. The hard-band X-ray and optical/UV continua are linked; the bluer quasars exhibit steeper X-ray spectra.

6. DISCUSSION

The observation that the large-blueshift quasars are blue in the optical/UV (Fig. 6b) and have higher intrinsic absorption column densities (Figs. 5 and 7) is consistent with large blueshifts occurring in quasars observed close to the plane of the accretion disk. In particular, the models of Hubeny et al. (2000, their Fig. 12) predict that edge-on accretion disks are bluer than face-on disks. Such large inclination angles with respect to the disk normal would be expected to yield larger X-ray absorption column densities if the absorbing material were found closest
to the disk. This scenario would also be consistent with the idea that BAL quasar outflows (known to have significant absorption in both the UV and X-rays) are equatorial. In addition, Reichard et al. (2003) suggest that BAL quasars are also intrinsically blue.

If we extend this connection, large-blueshift quasars may have orientation angles close to those of BAL quasars that do not actually intercept the UV-absorbing wind. The absence of significant C iv absorption in the large-blueshift quasars indicates that the X-ray–absorbing gas is either highly ionized (with little UV opacity) or does not obscure the UV continuum. The fraction of carbon ionized less than C v drops to below 1% in a photoionized plasma with \( \xi = L/nR^2 \approx 8 \) ergs cm\(^{-1}\) s\(^{-1}\) (where \( L \) is the integrated luminosity from 1 to 1000 ryd, \( n \) is the gas density, and \( R \) is the distance from the radiation source; Kallman & Bautista 2001). At this ionization parameter for \( z \approx 2 \), the actual column density of solar-metallicity gas giving the same opacity in the observed Chandra bandpass as \( 1.5 \times 10^{23} \) cm\(^{-2}\) of neutral gas is \( \sim 50\% \) larger.

The X-ray absorption seen in the large-blueshift quasars could be identified with the shielding gas postulated by Murray et al. (1995). This gas is required in their model to prevent soft X-rays from overionizing the disk-wind gas. Without it, radiation pressure by UV resonance line photons cannot radiatively drive the wind to the high velocities seen in BAL quasars. If this interpretation is correct, these data suggest that the shielding gas may have a larger covering fraction than the BAL outflow, and the blueshifted C iv emission could be interpreted as a disk-wind signature. For reference, BAL quasars typically show power-law X-ray spectra (\( \Gamma \approx 2 \)) with complex, intrinsic X-ray absorption of \( N_H \approx 10^{23} \) cm\(^{-2}\) (Green et al. 2001; Gallagher et al. 2002).

While the connection between extreme blueshift and X-ray absorption fits reasonably within the Murray et al. (1995) disk-wind paradigm as an effect of orientation, understanding the relation between \( \alpha_{UV} \) and \( \Gamma \) is more complicated. It is important to distinguish between this survey and previous work with ROSAT that focused on the observed 0.1–2.0 keV spectral slope, typically of \( z \leq 1 \) quasars. Correlations found with ROSAT (e.g., Puchnarewicz et al. 1996) are much more sensitive to small absorbing column densities and could also be driven by the soft excess. The soft excess, undetectable with these data, is often modeled as a thermal blackbody and is believed to originate in the inner accretion disk. For more relevant comparisons, there are many claims in the literature of correlations with the 2–10 keV \( \Gamma \) (e.g., Zdziarski et al. 1999; Reeves & Turner 2000; Dai et al. 2004; Wang et al. 2004). The claim of a correlation between \( \Gamma \) and \( L/L_{Edd} \) of Wang et al. (2004) is the most intriguing in the context of our sample.

Based on comparisons with black hole binaries (e.g., Zdziarski & Gierliński 2004), one might expect that objects with high accretion rates relative to Eddington will have softer hard X-ray spectra and a UV component that is more dominated by the disk (and thus bluer). In contrast, lower accretion rate objects will have harder X-ray spectra and may appear redder as the result of a weaker inner disk component to the big blue bump. This picture is grossly consistent with the correlation of \( \alpha_{UV} \) with \( \Gamma \).

Our two most significant results (the presence of intrinsic X-ray absorption at large blueshift and harder X-ray spectra correlating with redder colors) thus are consistent with both orientation and accretion-rate effects (either independently or together). The two-dimensional structure in the \( \Delta (g-i) \) versus blueshift distribution (Fig. 6b) implies that this is (at least) a two-parameter problem.

The absorption seen in the X-ray spectra of the largest-blueshift objects suggests that we are looking “down the wind” in such objects; in other words, that they are observed at the most extreme inclination angles possible with respect to the disk normal for an optically thick wind before UV BAL signatures are manifested. Large-blueshift objects also tend to have weak C iv equivalent widths. Therefore, the association of (1) high accretion rates and small C iv equivalent widths (Baskin & Laor 2004), (2) BAL quasars with bluer intrinsic spectra and large blueshifts (Reichard et al. 2003), and (3) BAL quasars with high accretion rates (Boroson 2002; Yuan & Wills 2003) means that the extreme population that shows bluer UV continua, large blueshift, weaker C iv, and absorbed X-ray spectra may represent the most extreme accretors with the largest inclination angles possible for a given wind geometry. Such a scenario would be qualitatively consistent with the narrowing of the color-blueshift distribution toward large blueshift velocities seen in Figure 6b.

However, moving to less extreme blueshifts, the situation in this scenario gets complicated, because both objects with less powerful winds (because they are less luminous though still active accretors or because they are accreting less actively) at extreme angles and objects with very powerful winds at less extreme angles contribute. This leads to the stretch in the \( \Delta (g-i) \) color distribution (the ordinate in Fig. 6b), which is widest close to \( \sim 0 \) km s\(^{-1}\) blueshift. Here we assume that the intrinsic \( \Delta (g-i) \) color is a marker of Eddington accretion rate, with bluer continua resulting from higher accretion rates at a given orientation angle. This speculative interpretation of the two-dimensional \( \Delta (g-i) \)-blueshift distribution can be tested with observing programs tuned to isolate the two phenomenological parameters, color and blueshift, in an attempt to map them onto the underlying physical drivers. In this interpretation, we conjecture that choosing a narrow range of color and luminosity would allow blueshift to be an orientation indicator, whereas choosing a range in blueshift and luminosity allows color to be an indicator of accretion rate (because this would remove any orientation dependence of the color).

Alternately, Leighly (2004) suggests that blueshifted emission comes from a strong wind that arises in active galactic nuclei only under certain conditions. If blueshifts always indicate the presence of winds, the histogram in Figure 6a implies that nearly all broad-line quasars have winds, and our detection of X-ray absorption in large-blueshift quasars is broadly consistent with this model. However, simply invoking a wind from the near face of an optically thick accretion disk to explain large C iv blueshifts (see also Elvis 2004) does not necessarily yield a simple shift, nor does it trivially explain the weakness of the lines found in large-blueshift quasars.

Lastly, the relationship between the blueshifts and the C iv equivalent widths (EWs) deserves further discussion. Any successful model of the broad-line region must account for both the blueshifts and the EWs of the emission lines. For example, it may be reasonable to unify the Baldwin (1977) effect and emission-line blueshifts, especially given the findings by Richards et al. (2002) that the C iv blueshift effect is not apparently dominated by luminosity, by Baskin & Laor (2004) that the Baldwin effect is driven by \( L/L_{Edd} \) rather than \( L \), and by Francis & Koratkar (1995) that the Baldwin effect is strongest in the red wing of the C iv emission line. Perhaps as \( L/L_{Edd} \) increases, the greater dominance of radiative driving over gravity produces a faster wind with a larger opening angle relative to the disk normal. Such winds will cover less of the sky from the point of view of the continuum source, thereby intercepting less
ionizing radiation and lowering the EW of C iv and other lines emitted by the wind.

7. CONCLUSIONS

From our analysis of Chandra ACIS observations of 13 radio-quiet SDSS quasars and their optical/UV spectral properties, we present the following conclusions:

1. Those quasars in our sample with C iv blueshifts $\geq 1100$ km s$^{-1}$ show evidence from joint fitting of the X-ray spectra for intrinsic X-ray absorption with $N_H \sim 10^{22}$ cm$^{-2}$. We interpret the presence of X-ray absorption in the large-blueshift sample as support for the orientation interpretation of the C iv blueshift put forth by Richards et al. (2002) whereby large-blueshift quasars are seen at inclination angles close to the line of sight through the wind (which may have a range of opening angles). This result is broadly consistent with the disk-wind model of quasar broad-line regions of Murray et al. (1995).

2. We find that there is a trend of steeper hard-band X-ray continua with bluer $\alpha_{UV}$ spectral index in our sample; this result is supported by a complementary analysis of independent Bright Quasar Survey data from the literature. We find the Eddington accretion rate, $L/L_{\text{Edd}}$, to be a likely candidate for the primary physical driver of this trend.

Extending this study to larger samples with higher quality X-ray data is certainly warranted to test these claims. Specifically, given the lack of C iv absorption in the SDSS spectra of the large-blueshift sample, we predict that high-quality X-ray spectroscopy will reveal this gas to be ionized with $\xi > 8$ ergs cm$^{-1}$. With the large effective area and 0.3–10.0 keV bandpass, sensitive XMM-Newton observations could significantly constrain both the column density and ionization state of the absorption for each quasar in the large-blueshift sample. Furthermore, high signal-to-noise ratio X-ray observations of a quasar sample tuned to isolate the relationship between optical/UV and X-ray continua hold promise for understanding the effect of Eddington accretion rate on quasar spectral energy distributions.

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