A TEST OF PHOTOMETRIC REDSHIFTS FOR X-RAY-SELECTED SOURCES

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ABSTRACT

We test the effectiveness of photometric redshifts based on galaxy spectral template fitting for X-ray–luminous objects, using a sample of 65 sources detected by Chandra in the field of the Caltech Faint Galaxy Redshift Survey (CFGRS). We find that sources with quasar-dominated spectra (for which galaxy spectral templates are not appropriate) are easily identified and that photometric redshifts are robust for the rest of the sources in our sample. Specifically, for the 59 sources that are not quasar-dominated at optical wavelengths, we find that the photometric redshift estimates have scatter comparable to the field galaxy population in this region. There is no evidence for a trend of increasing dispersion with X-ray luminosity over the range \( L_X = 10^{39} - 5 \times 10^{43} \) ergs s\(^{-1}\), nor is there a trend with the ratio of X-ray to optical flux, \( f_X/f_R \). The practical implication of this work is that photometric redshifts should be robust for the majority (\( \sim 90\% \)) of the X-ray sources down to \( f_X \approx 10^{-16} \) ergs s\(^{-1}\) cm\(^{-2}\) that have optical counterparts brighter than \( R \approx 24 \). Furthermore, the same photometry can easily be used to identify the sources for which the photometric redshifts are likely to fail. Photometric redshift estimation can thus be utilized as an efficient tool in analyzing the statistical properties of upcoming large Chandra and XMM-Newton data sets and identifying interesting subsamples for further study.

Subject headings: galaxies: active — galaxies: distances and redshifts — X-rays: galaxies

1. INTRODUCTION

Photometric redshift estimation is a powerful tool in extragalactic astronomy, and significant effort has been expended in recent years developing robust redshift estimation techniques. The most widely employed approach is to use spectral templates (either empirical or from stellar synthesis models) to derive optimal fits to the observed galaxy colors (e.g., Lanzetta, Yahil, & Fernández-Soto 1996; Fernández-Soto, Lanzetta, & Yahil 1999; Benitez 2000; Furusawa et al. 2000). This approach has been highly successful for normal galaxies, achieving results as good as \( \sigma_z = 0.06(1+z) \) for the Hubble Deep Field (HDF; Fernández-Soto, Lanzetta, & Yahil 1999; Benitez 2000; Furusawa et al. 2000). Extending on this work, Budavári et al. (2001) and Richards et al. (2001) have recently found that photometric redshifts accurate to within \( \Delta z = 0.2 \) can be obtained for 70% of quasars in the Sloan Digital Sky Survey—even at \( z < 2.2 \), where quasar spectra lack a strong continuum break in the Sloan ugriz filters.

In this work we focus on X-ray–luminous objects, asking whether a self-consistent technique can be devised to obtain photometric redshifts for X-ray–selected samples. Recent work on deep Chandra fields indicates that the resolved X-ray background is comprised of a variety of objects, including early-type ellipticals, starburst galaxies, obscured active galactic nuclei (AGN), narrow- and broad-line AGN, and quasars (see, e.g., Mushotzky et al. 2000; Barger et al. 2001; Hornschemeier et al. 2001; Tozzi et al. 2001; Stern et al. 2002; Barger et al. 2002). Given the disparate nature of these sources, the effectiveness of photometric redshifts is a priori unclear. Recent spectroscopic observations in the Chandra Deep Field-North (CDF-N) highlight this concern. Barger et al. (2002) find that, out of a sample of 182 hard sources (2–8 keV detections) with spectroscopic follow-up, approximately half show signatures of AGN activity in their spectra.

As argued by Barger et al. (2002), one can reasonably expect that traditional galaxy spectral template fitting should be reliable for the 50% of sources that lack an AGN spectral signature. Similarly, it is likely that quasar spectral templates can be utilized for AGN-dominated sources (although this expectation has not yet been verified). It is unclear, however, whether either approach is robust for the intermediate sources in which both the AGN and the galaxy stellar population contribute significantly to the optical spectrum. Do photometric redshifts based on galaxy spectral template fitting gradually degrade with increasing fractional luminosity contribution from the AGN, or do they remain robust until the AGN contribution reaches some critical level? The Hubble Deep Field, which is the canonical field for testing photometric redshifts, offers little insight. There are only six X-ray–luminous sources with spectroscopic redshifts in the HDF—the majority of which are low-luminosity. Photometric redshift comparisons in the HDF, such as the blind check of Cohen et al. (2000), thus cannot test the reliability of photometric redshift estimators in the interesting regime of properties.\(^1\)

There are strong practical motivations for using an expanded sample of X-ray–selected sources to assess the

\(^1\) One of these six sources is an outlier in the blind photometric redshift tests of Cohen et al. (2000); however, it has also been argued by Fernández-Soto et al. (2001) that the spectroscopic redshift for this source is incorrect. Two of the other objects are listed as faint X-ray sources in Hornschemeier et al. (2001) but do not appear in the \( \approx 1 \) Ms Chandra catalogs of Brandt et al. (2001).
reliability of photometric redshifts for these objects. Foremost, an efficient means of redshift estimation is required to maximize the return from large area Chandra and XMM-Newton surveys, such as the Lockman Hole survey (Chandra, PI: Barger), the Chandra Multiwavelength Project (ChaMP, Wilkes et al. 2000), the XMM-LSS survey (Pierre et al. 2001), and the upcoming Chandra survey in the NOAO Deep-Wide Field (9 deg², PIs: Jones & Murray). A number of the issues that these surveys aim to address, such as evolution in the AGN X-ray luminosity function and evolution in the correlation function of faint X-ray sources, are statistical in nature and do not require the accuracy of spectroscopic redshifts. For example, the survey in the NOAO Deep Wide Field aims to study the X-ray spatial correlation function using an expected ~2200 sources (C. Jones 2002, private communication). This project has no associated large spectroscopic program and will depend on the use of photometric redshifts to achieve its key scientific goal. If one can attain a level of accuracy for these photometric redshifts comparable to what is achieved for “normal” galaxies, photometric redshifts will be a valuable tool. If not, then the limitations of photometric redshift techniques must be established.

In this paper we assess the validity of photometric redshifts in the Caltech Faint Galaxy Redshift Survey field (CFGRS, Cohen et al. 2000; Hogg et al. 2000) using the Brandt et al. (2001) catalog of X-ray sources in the CDF-N. We first compare the scatter in photometric redshift estimates for X-ray–detected sources with a control sample of quiescent galaxies and quantify the fraction of X-ray sources with bright optical counterparts for which traditional galaxy spectral template fitting is valid. Next, we search for trends between the redshift residuals and other physical quantities, testing whether there is a range in X-ray luminosity (L_X) or flux ratio (f_X/f_R) over which photometric redshifts degrade. Finally, we ask whether the objects for which photometric redshifts are likely to fail (e.g., quasars) can be easily identified using the optical photometry. The data are described in §2, and the results are presented in §3. In §4 we summarize our work and discuss prospects for future studies with larger and fainter samples. We assume \( \Omega_0 = 0.3, \Omega_{\Lambda} = 0.7, \) and \( H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}. \)

2. DATA

We focus on the CFGRS field because of the multiwavelength observations and extensive spectroscopy available for this region. We include in our sample X-ray sources detected by Brandt et al. (2001) that lie within the CFGRS, have published spectroscopic redshifts, and have unambiguous optical counterparts. The Brandt et al. (2001) source list is derived from the 975.3 ks Chandra image of the CDF-N, with minimum detectable fluxes near the aim point corresponding to \( f_X \approx 1.9 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \) in the hard band (2–8 keV) and \( f_X \approx 2.9 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \) in the soft band (0.5–2 keV). Spectroscopic redshifts (Cohen et al. 2000; Hornschemeier et al. 2001; Barger et al. 2002) and \( U_n, G, R, K_s \) photometry (Hogg et al. 2000) exist for 66 of these sources, which are listed in Table 1. For the majority of these objects, the spectra are also published in Figure 6 of Barger et al. (2002).

Of the 66 sources, only four are in the HDF proper and have previous published photometric redshifts using seven-color Hubble Space Telescope photometry. For one galaxy, HDF 36569–1302, Fernández-Soto et al. (2001) dispute the spectroscopic redshift, arguing that the published value is attributable to the halo of a nearby, brighter galaxy. Due to this uncertainty, we exclude HDF 36569–1302 from our analysis, yielding a final sample of 65 sources. Figure 1 shows the distribution of optical and X-ray properties in our subsample, compared to properties of the rest of the extragalactic sources from Brandt et al. (2001) that lie within the CFGRS region. Our subsample includes 80% of the extragalactic sources with optical counterparts brighter than \( R = 24.5 \) (90% with counterparts brighter than \( R = 24 \)). Because spectroscopic redshifts are lacking for sources with \( R > 24.5 \), we are unable to study this subset of the population, which includes the majority of faint X-ray sources with high \( f_X/f_R \). We emphasize that the results presented in this paper are not necessarily applicable to these sources.

3. PHOTOMETRIC REDSHIFTS

3.1. Redshift Estimation Technique

We utilize the Bayesian photometric redshift code of Benitez (2000), BPZ, to derive photometric redshifts for our sample. This code employs spectral template fitting, but also takes into account the \( I \) band magnitude of the galaxy. Specifically, the code utilizes the F814 magnitude distribution of the HDF as a Bayesian prior probability distribution, which enables superior discrimination when color degeneracies exist between low- and high-redshift galaxies. For the current analysis we have only four filters, so the Bayesian magnitude prior is necessary to break these color degeneracies and minimize the number of spurious outliers. Our
| Source | Identification number | $f_x$ (10^{-15} erg s^{-1} cm^{-2} | $z$ | $z_{\text{phot}}$ | BL$^f$ | Comments$^g$ |
|--------|-----------------------|----------------------------------|----|----------------|---------|--------------|
| 080...  | B01a                  | 0.54                            | 0.454 | 0.40 |         |         |
| 087...  | B01a                  | 0.52                            | 0.534 | 0.56 |         |         |
| 089...  |                    H01b | 16.08                           | 1.022 | 0.93 | Y       |         |
| 092...  |                    H01b | 0.32                            | 0.473 | 0.48 |         |         |
| 098...  |                    H01b | 3.04                            | 1.014 | 0.97 |         |         |
| 101...  |                    H01b | 16.33                           | 2.590 | Q   | Y       | QSO$^b$ |
| 102...  |                    H01b | 0.22                            | 0.483 | 0.35 |         |         |
| 105...  |                    H01b | 1.00                            | 0.747 | 0.78 |         |         |
| 110...  |                    H01b | <0.14                           | 1.218 | 1.08 |         |         |
| 111...  |                    H01b | 3.59                            | 0.762 | Q   |         |         |
| 117...  |                    H01b | 2.31                            | 1.013 | 1.16 |         |         |
| 118...  |                    H01b | 2.27                            | 0.848 | 0.97 |         |         |
| 121...  |                    H01b | 1.53                            | 0.953 | Q   |         |         |
| 125...  |                    H01b | 0.25                            | 0.845 | 0.34 |         |         |
| 131...  |                    H01b | 0.85                            | 1.016 | 1.07 |         |         |
| 134...  |                    H01b | 0.43                            | 0.456 | 0.44 |         |         |
| 136...  |                    H01b | 0.31                            | 1.219 | 1.42 |         |         |
| 139...  |                    H01b | 0.19                            | 0.847 | 0.95 |         |         |
| 141...  |                    H01b | 0.95                            | 0.410 | 0.31 |         |         |
| 142...  |                    H01b | 2.97                            | 2.005 | Q   |         |         |
| 144...  |                    H01b | 10.09                           | 0.957 | 0.72 |         |         |
| 145...  |                    H01b | 4.94                            | 0.555 | 0.45 |         |         |
| 148...  |                    H01b | <0.12                           | 0.081 | 0.08 |         |         |
| 149...  |                    H01b | 0.58                            | 0.357 | 0.83 |         |         |
| 154...  |                    H01b | 0.98                            | 0.510 | 0.36 |         |         |
| 155...  |                    H01b | 0.27                            | 0.848 | 0.82 |         |         |
| 156...  |                    H01b | 0.26                            | 0.943 | 0.79 |         |         |
| 159...  |                    H01b | 1.33                            | 0.518 | 0.64 |         |         |
| 160...  |                    H01b | 0.38                            | 0.089 | 0.05 | $z_{FS} = 0.10$ |         |
| 163...  |                    H01b | 3.20                            | 0.857 | 0.92 |         |         |
| 165...  |                    H01b | 0.21                            | 1.011 | 0.94 | $z_{FS} = 0.85$ |         |
| 171...  |                    H01b | 22.79                           | 0.961 | 0.97 |         |         |
| 172...  |                    H01b | 0.53                            | 0.851 | 0.74 |         |         |

$^a$ Identification number from Brandt et al. 2001.
$^b$ Identification number from Hornschemeier et al. 2001.
$^c$ Full band flux (0.5–8 keV) from Brandt et al. 2001.
$^d$ Spectroscopic redshifts are taken from Barger et al. 2002. The one exception is source 220, for which the redshift is taken from Cohen et al. 2000.
$^e$ Q denotes that the photometry for this source was best fitted by a quasar spectral template.
$^f$ Y denotes that this source was found to have broad emission lines in the spectra by Barger et al. 2002.
$^g$ For sources in the HDF, we list the photometric redshift from Fernández-Soto et al. 2001. Source 203 was excluded from our analysis because of the disputed redshift.
$^h$ Liu et al. 1999.
results should be valid for any code that utilizes spectral template fitting. To verify this expectation, we also derive photometric redshifts using another publicly available code, HYPERZ (Bolzonella, Miralles, & Pelló 2000). While BPZ is more robust to outliers for our data set, we confirm with HYPERZ that our results are insensitive to which photometric code is used.

The standard six spectral templates described in Benitez (2000) are used for this analysis. Four are based on spectral energy distributions (SEDs) in Coleman, Wu, & Weedman (1980) (E/S0, Sbc, Scd, and Irr), and two are derived from spectra for starburst galaxies in Kinney et al. (1996). One challenge for the current analysis is that we lack I-band data for comparison with the HDF magnitude priors. Fortunately, the code is not strongly sensitive to errors in the I-band magnitude used for the prior, so we make the coarse assumption that $R - F814 \approx 1$ (comparable to an elliptical galaxy at $z \approx 0.5$) for all galaxies in the sample. We also test the code with $R - F814 = 0$, finding that the choice of fiducial color yields a negligible difference in estimated redshifts.

We employ a two-part approach in deriving photometric redshifts. A necessary first step is to identify objects with quasar-dominated spectra at optical wavelengths, since photometric redshifts based on galaxy spectral templates are likely to fail for these sources. If these objects can be identified, then photometric redshifts can potentially be derived for them by other means (e.g., see Budavári et al. 2001; Richards et al. 2001). To this end, we construct a quasar template using the optical Sloan Digital Sky Survey (SDSS) composite spectrum of Vanden Berk et al. (2001), coupled with infrared spectra of PDS 456 from Simpson et al. (1999). For the SDSS composite, we apply a correction for stellar contamination, assuming that the contamination increases linearly from 10% at 6000 Å to 30% at 8500 Å, for all galaxies in the sample. We also test the code with $R - F814 = 0$, finding that the choice of fiducial color yields a negligible difference in estimated redshifts.

We initially include this quasar spectral template in the SED library and run the photometric redshift code without the Bayesian prior. Six of the 65 sources in our sample, including the two highest redshift sources, are best fitted by the quasar spectrum. One of these sources has previously been identified as a quasar (Liu et al. 1999; HorncHEMEIER et al. 2001); a second was identified by Hornschemeier et al. (2001) as a broad-line AGN. We exclude these six sources from the subsequent analysis but record the photometric redshift estimates and include them in subsequent figures. For the remaining 59 X-ray sources, all of which are at $z < 1.3$, we perform a second iteration of the redshift estimation in which we exclude the quasar spectrum and include the Bayesian prior. The results are shown in Figures 3a–3b. We derive a scatter $\sigma_z = 0.10(1 + z)$ for these sources.

3.2. Comparison with Normal Galaxy Sample

Cohen et al. (2000) provide spectroscopic redshifts for a total of 529 galaxies in the Hogg et al. (2000) photometric catalog, enabling construction of an X-ray–quiet comparison sample. Excluding the Chandra sources and galaxies at $z > 1.3$, the redshift dispersion for this catalog is $\sigma_z = 0.18(1 + z)$. This scatter is dominated by a handful of outliers; if we employ $\sigma$ clipping with rejection of outliers beyond $3.5 \sigma$, then 11 out of 461 galaxies are rejected, and the dispersion reduces to $\sigma_z = 0.14(1 + z)$. This value is larger than the scatter for the HDF $[\sigma_z < 0.10(1 + z)]$ for seven filters; e.g., Fernández-Soto, Lanzetta, & Yahil 1999; Benitez 2000; Bolzonella et al. 2000; Furusawa et al. 2000), but it is not unreasonable, given the larger photometric uncertainties and smaller number of passbands in this analysis. Comparing with the X-ray subsample, we conclude that, with the exception of clearly quasar-dominated sources, the dispersion in photometric redshifts is no greater for X-ray sources than for the field galaxy population.

To verify these results, we also derive photometric redshifts using HYPERZ. The HYPERZ code was utilized by Berger et al. (2002), who concluded that the lack of priors, coupled with their lack of $U$-band data, significantly hindered the reliability of their photo-$z$'s. Our comparison of BPZ and HYPERZ confirms that the inclusion of a magnitude prior significantly improves the robustness, particularly with a limited number of passbands. With HYPERZ, 12% of the sources in the quiescent sample—and a comparable fraction of the X-ray–luminous sources—are outliers with $\Delta z > 1$. In contrast, only 2% of sources in the quiescent sample are outliers with BPZ. Nonetheless, if these outliers are excluded, then HYPERZ and BPZ typically yield consistent photometric redshifts for individual X-ray–selected sources (Fig. 4). Furthermore, HYPERZ yields dispersions comparable to BPZ, with values $\sigma_z = 0.14(1 + z)$ for the full field sample and $\sigma_z = 0.13(1 + z)$ for the X-ray sources. Both codes thus indicate that the dispersion is comparable for the X-ray–luminous and quiescent samples.

2 This is a selection effect; if a source at $z \approx 2$ is not a quasar, then it will be optically faint and likely not have been targeted for spectroscopy.

3 HYPERZ does appear to underestimate the redshift for sources at $z \sim 0.7$, however.
3.3. Dependence on X-Ray Properties

The results of the preceding sections indicate that photometric redshifts are robust for \( \sim 90\% \) of X-ray sources with \( R \leq 24.5 \) down to \( f_X \approx 10^{-16} \text{ ergs s}^{-1} \text{ cm}^{-2} \), including some sources with a moderate AGN contribution. One naively expects increased scatter in the photometric redshifts with increasing optical contribution from the AGN. A direct test of this expectation would require fitting a linear superposition of normal galaxy and quasar spectral templates to obtain the fractional contribution, which is beyond the scope of the current analysis. Instead, we ask whether the probability of failure is correlated with the X-ray properties of the source—specifically, the X-ray luminosity and the ratio of X-ray to optical flux \( f_X/f_R \). The latter quantity is the best analog measure of the relative AGN and starlight contributions, but with the caveat that there exists a factor of 10 range in \( f_X/f_R \) within which sources can be either AGN- or starlight-dominated.

In Figure 5 we plot \( d_z/(1 + z) \) against \( L_X \), where \( d_z = z_{\text{phot}} - z_{\text{spec}} \), to assess whether the redshift estimates degrade above some threshold luminosity. Aside from objects that are best fitted by the quasar spectral template, there is no indication of degradation up to \( L_X = 5 \times 10^{43} \text{ light years}^2 \text{ ergs s}^{-1} \), the luminosity of the brightest non–quasar-dominated sources in our sample. We also find no statistically significant trend with \( f_X/f_R \) (Fig. 6); however, the probability of identifying a source as quasar-dominated increases significantly for sources with \( f_X/f_R \gtrsim 0.5 \). Nearly 30\% of sources above this threshold (5 of 18) are best fitted by the quasar template, as opposed to only one of 47 at lower \( f_X/f_R \). These results imply, somewhat surprisingly, that the photometric redshift estimates are fairly insensitive to the presence of an AGN unless the AGN dominates the optical spectrum.

4. SUMMARY

We use a sample of X-ray sources detected by Chandra in the Caltech Faint Galaxy Redshift Survey region to test the robustness of photometric redshifts for these objects. For the 59 out of 65 sources with colors that are not best fitted by a quasar spectral template, we find no degradation in the accuracy of photometric redshifts, as compared to the field.
galaxy population. We also find that the redshift residuals exhibit no trend as a function of X-ray luminosity or $f_X/f_R$ for these sources. We demonstrate that it is feasible to quickly identify objects whose spectra are quasar-dominated at optical wavelengths and derive robust photometric redshifts for the other ~90% of sources that have optical counterparts brighter than $R < 24$, which includes roughly two-thirds of all sources with $f_X > 10^{42}$ ergs s$^{-1}$ cm$^{-2}$ (Barger et al. 2002). Consequently, photometric redshift estimation should be a valuable tool for upcoming large samples of optically bright, X-ray–selected objects. This paper is a first step toward quantifying the robustness of photometric redshifts for systems in the transition regime between quiescent galaxies and quasars. The next required step is extension to fainter optical magnitudes. Given that the majority of fainter sources have high $f_X/f_R$, it is unclear whether photometric redshifts will be as effective for this population, but the motivation for testing their robustness is strong. There is speculation that these optically faint, high $f_X/f_R$ sources possibly include obscured AGNs at $z < 5$ (e.g., Stern et al. 2002), and photometric redshifts may be the only viable approach for studying this population.

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Fig. 5.—Photometric redshift error as a function of X-ray luminosity. The symbols are the same as in Fig. 3. The dashed lines correspond to $\sigma_z = 0.14(1+z)$. The vertical axis is set to match the dynamic range of the non–quasar-dominated sources. Consequently, two highly discrepant quasar-dominated sources with $dz/(1+z) \approx 1.5$ and $L_X \approx 4 \times 10^{42}$ ergs s$^{-1}$ cm$^{-2}$ are not visible in this plot.

Fig. 6.—Photometric redshift error as a function of $f_X/f_R$. The symbols are the same as in Fig. 3, and the dashed lines correspond to $\sigma_z = 0.14(1+z)$. As in Fig. 5, two quasar-dominated sources with $dz/(1+z) \approx 1.5$ and $f_X/f_R \approx 2-4$ are not visible in this plot.