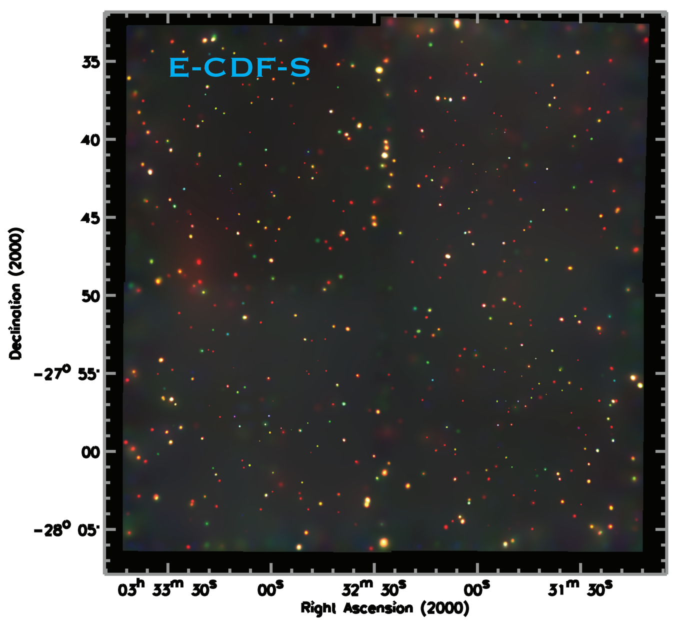

Constraining the Redshift Evolution of Off-Nuclear X-ray Sources using the *Chandra* Deep Fields

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Abstract

We analyze a population of intermediate-redshift ($z \approx 0.05$-0.3) off-nuclear X-ray sources located within the optical extent of optically-bright galaxies in the Great Observatories Origins Deep Survey (GOODS) and Galaxy Evolution from Morphology and SEDs (GEMS) fields. A total of 19 off-nuclear sources are classified using deep *Chandra* exposures from the *Chandra* Deep Field-North, *Chandra* Deep Field-South, and Extended *Chandra* Deep Field-South; ten of these sources are newly identified. These sources have average X-ray spectral shapes and optical environments similar to those of ultraluminous X-ray sources (ULXs) in the local univese. This sample improves the available source statistics for intermediate-redshift off-nuclear sources with 0.5–2.0 keV luminosities $L_X \geq 10^{39.5}$ erg s^{-1}, and places significant new constraints on the redshift evolution of the off-nuclear source frequency in field galaxies. We find that the fraction of intermediate-redshift field galaxies containing an off-nuclear source is elevated by a factor of ≈ 2 with respect to that observed for ULXs in the local universe for 0.5–2.0 keV luminosities in the range of $\approx 10^{39-40.5}$ erg s^{-1}; the rise in this fraction is broadly consistent with that expected from the observed increase in global star-formation density with redshift.

Main Results

- — We detect and classify 19, $z \approx 0.1$ off-nuclear sources using the Chandra Deep Fields (see Figure 2).
- — These sources have 0.5–2.0 keV luminosities of $10^{39-40.5}$ erg s^{-1} (Figure 1) and average 0.5–8.0 keV photon indices of $\Gamma_{\rm eff}$=1.9.
- — Roughly half of these off-nuclear sources are coincident with optical knots, which have diameters of $\approx$500–1000 pc and $\approx$6000 Å luminosities of $\approx 10^{40-41}$ erg s^{-1}; these properties are similar to those of giant H II regions in the local universe (see Figure 2 and "Off-Nuclear Source Properties" below).
- — We find that the true fraction of spiral galaxies hosting off-nuclear X-ray sources has evolved by a factor of ≈ 2 to $z \approx 0.1$, a value consistent with that plausibly expected from the global increase in star-formation density with redshift (see Figure 3 and "Analyses and Results" below).

Introduction

Recently, the fraction of galaxies in the local universe ($\lesssim$50 Mpc) containing ULXs (as a function of X-ray luminosity) has been constrained statistically using *ROSAT* observations of a sample of 766 galaxies (Ptak & Colbert 2004; hereafter PC04) from the *Third Reference Catalog of Bright Galaxies* (RC3; de Vaucouleurs et al. 1991). PC04 find that $\approx$12% and $\approx$1% of all RC3 spiral galaxies have one or more ULXs with 2–10 keV luminosities $L_X \geq 10^{39}$ erg s^{-1} and $L_X \geq 10^{40}$ erg s^{-1}, respectively.

In the local universe, ULXs appear to be associated with intense star-formation activity (e.g., Gilfanov et al. 2004; Swartz et al. 2004). At increasing redshifts, it is plausibly expected that the fraction of galaxies hosting ULXs will increase as a result of the observed rise in global star-formation density with redshift (e.g., Madau et al. 1998). Deep multiwavelength extragalactic surveys that combine the optical imaging capabilities of the *Hubble Space Telescope* (*HST*) and the subarcsecond X-ray imaging of the *Chandra* X-ray Observatory (*Chandra*) have made the detection and classification of intermediate-redshift ($z \approx 0.05$–0.3; lookback times of $\approx$0.7–3.4 Gyr) off-nuclear sources possible (e.g., Hornschemeier et al. 2004; hereafter H04).

In this investigation, we estimate the true fraction of intermediate-redshift field galaxies hosting off-nuclear X-ray sources as a function of 0.5–2.0 keV luminosity and compare it with that observed in local galaxies (from PC04). We improve the source statistics available for intermediate-redshift, off-nuclear X-ray sources by combining the multiwavelength data within the $\approx$2 Ms *Chandra* Deep Field-North (CDF-N; Alexander et al. 2003) and $\approx$1 Ms *Chandra* Deep Field-South (CDF-S; Giacconi et al. 2002) with new *HST* and *Chandra* observations of the Extended *Chandra* Deep Field-South (E-CDF-S; Lehmer et al. 2005; see false-color X-ray image above). The E-CDF-S is composed of four contiguous $\approx$250 ks *Chandra* fields covering an $\approx$0.3 deg^2 region, which flanks the $\approx$1 Ms CDF-S; these observations are sensitive enough to detect $z \approx 0.1$ off-nuclear sources with projected physical offsets of $\geq$2 kpc and 0.5–2.0 keV luminosities of $\geq 3 \times 10^{39}$ erg s^{-1}, in the most sensitive regions.

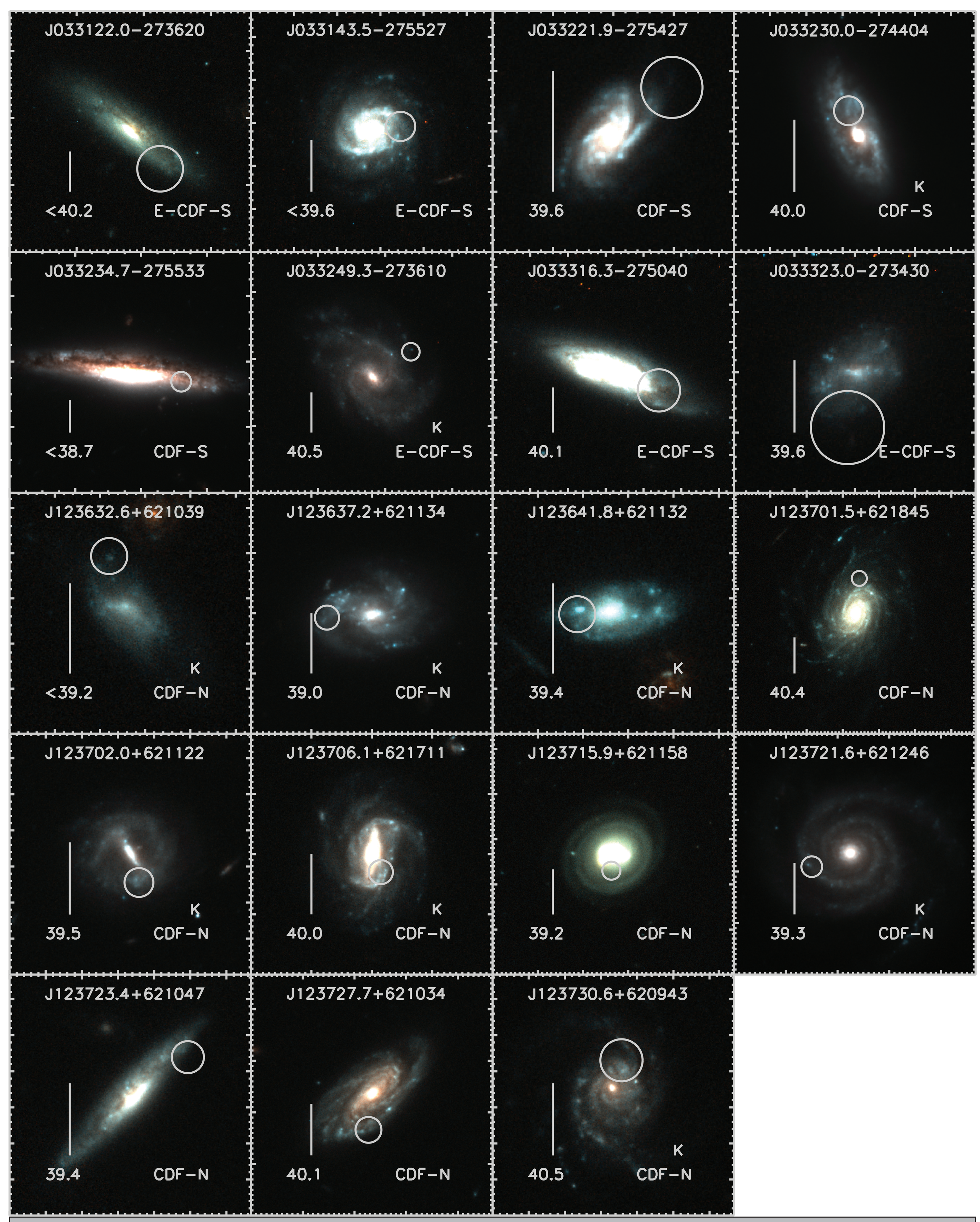

Figure 2 — ACS color images of off-nuclear X-ray source host galaxies; colors correspond to ACS bands V_{606} (blue), $(V_{606}+z_{850})/2$ (green), and z_{850} (red). In each image, we show the off-nuclear X-ray source positions (gray positional-error circles) source name (top), the survey in which the source is detected (lower right), and the logarithm of the 0.5–2.0 keV luminosity (lower left); a "K" is displayed if the off-nuclear source is coincident with an optical knot. The scale of each image can be deduced from the 3" bar in the left corner of each image.

Analyses and Results

The primary goal of this investigation is to determine whether the true luminosity-dependent fraction of spiral galaxies containing off-nuclear X-ray sources (f_T) evolves with cosmic time. We assessed observational constraints on the X-ray luminosity detection limit and angular resolution for both our sample and that of a matched PC04 subsample (matched by optical luminosity). To this end, we first measured the observed fraction of galaxies hosting off-nuclear sources (f_O); this takes into account the spatially varying sensitivity of the *Chandra* observations. We then use simulations to estimate the number of off-nuclear sources we expect to miss due to angular resolution limitations (i.e., the number of off-nuclear sources with offsets smaller than the resolution limits), and we applied corrections to the f_O to obtain f_T.

Figure 3a (below) shows f_T as a function of off-nuclear source 0.5–2.0 keV luminosity for both ULXs in local galaxies from the matched PC04 subsample (solid blue points with 1σ error bars) and our sample of off-nuclear X-ray sources in intermediate-redshift field galaxies (red dashed line with 1σ error envelope). We estimate $\approx$34±20% of intermediate-redshift spiral galaxies with νL_V (6000 Å) $\geq 10^{42.3}$ erg s^{-1} host off-nuclear sources with $L_X \geq 10^{39}$ erg s^{-1} versus $\approx$16±5% in the local universe.

It is plausible that the frequency of off-nuclear source incidence would rise as a function of redshift due to the observed global increase in star-formation density, which is measured to be $\approx$1.2–3.0 times higher at $z \approx 0.05$–0.3 than it is in the local universe (e.g., Pérez-González et al. 2005; Schiminovich et al. 2005). Furthermore, since the number of ULXs in spiral galaxies is observed to increase linearly with star-formation rate (e.g., Swartz et al. 2004), it is reasonable to expect that the frequency of off-nuclear source incidence for field galaxies would roughly scale linearly with the star-formation density. In Figure 3b (below) we show the ratio of off-nuclear source incidence fraction of our intermediate-redshift sample and the matched PC04 subsample (i.e., f_T[int-z]/(f_T[PC04]) as filled gold triangles with 1σ error bars. The dashed horizontal green line shows the median fraction ratio computed at different off-nuclear source luminosities; this indicates f_T rises by a factor of $\approx$1.9 from $z = 0.0$ to $z \approx 0.11$. The dark shaded region shows the expected ratios for the case where the off-nuclear source incidence fractions scale with star-formation density; the black dotted horizontal line shows the case where there is no evolution. We note that these computed ratios appear to be broadly consistent with the expected scaling of off-nuclear source incidence with redshift due to the increased global star-formation density.

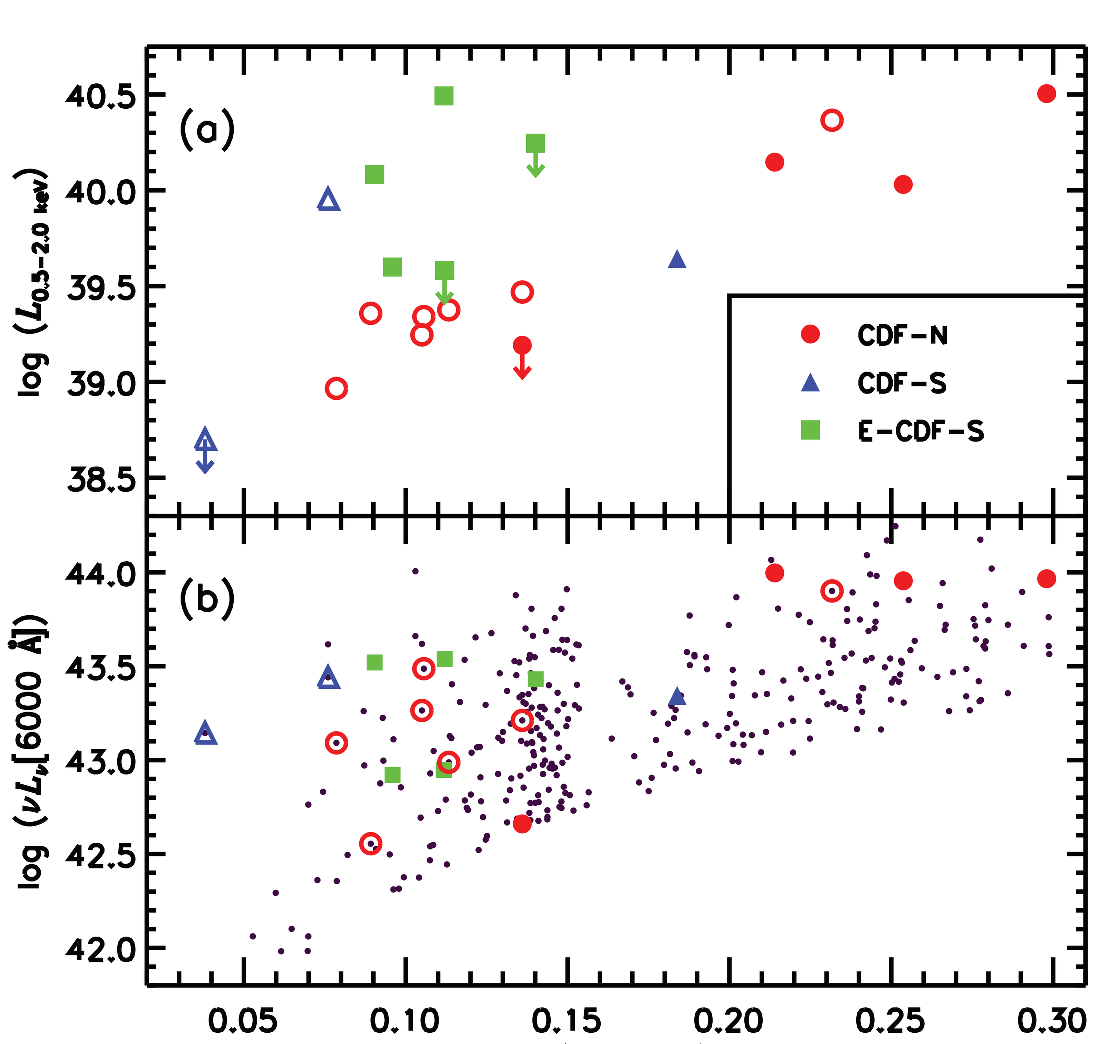

Figure 1 — (a) X-ray luminosity and redshift distribution of each off-nuclear X-ray source. Symbols correspond to sources detected in the CDF-N (red circles), CDF-S (blue triangles), and E-CDF-S (green squares); filled symbols correspond to sources unique to this investigation. (b) Rest-frame 6000 Å optical luminosity for spiral galaxies with $V_{606} < 21$ as a function of redshift (small filled circles). Galaxies hosting off-nuclear sources have been outlined with the symbols following Figure 1a.

Off-Nuclear Source Properties

We identified a total of 19 off-nuclear source candidates within the optical extent of $V_{606} < 21$ field galaxies in the *Chandra* Deep Fields. These sources have a median redshift of ($z \approx 0.11$) and span a 0.5–2.0 keV luminosity range of $\approx 10^{38.9-40.5}$ erg s^{-1}; the median host-galaxy optical luminosity is νL_V (6000 Å) $\approx 1.9 \times 10^{43}$ erg s^{-1}. Figure 1a (left) shows the 0.5–2.0 keV luminosity of each off-nuclear source as a function of redshift and Figure 1b (left) shows the luminosity at 6000 Å for the host galaxies and field galaxies with ($V_{606} < 21$). Figure 2 (above) shows each host galaxies with the off-nuclear X-ray source position outlined as a gray circle with radius equal to the *Chandra* positional error. This color-composite image is composed of Advanced Camera for Surveys (ACS) images from the V_{606} (blue) and z_{850} (red) bandpasses and an interpolated $(V_{606}+z_{850})/2$ image (green). All off-nuclear sources are coincident with galaxies of late-type morphology, consistent with that expected from investigations of ULXs in the local universe (e.g., Irwin et al. 2003).

Nine of the 19 off-nuclear X-ray sources appear to be coincident with optical knots of emission (noted with a "K" in the images of Figure 2 above). These regions have apparent optical diameters of $\approx$500–1000 pc and optical luminosities of νL_V (6000 Å) $\approx 10^{40-41}$ erg s^{-1}. Their colors are relatively blue compared to the colors of their host galaxy, suggesting these knots are likely star-forming regions consistent with giant H II regions in the local universe (e.g., Kennicutt 1984).

We constrained the average X-ray spectral shape of our off-nuclear sources by stacking the 0.5–2.0 keV and 2–8 keV source counts and exposures. For the 19 off-nuclear X-ray sources, the mean effective photon index is $\Gamma_{\rm eff}$ = 1.87±0.03, a value consistent with ULXs observed in the local universe (e.g., Liu & Mirabel 2005 and references therein).

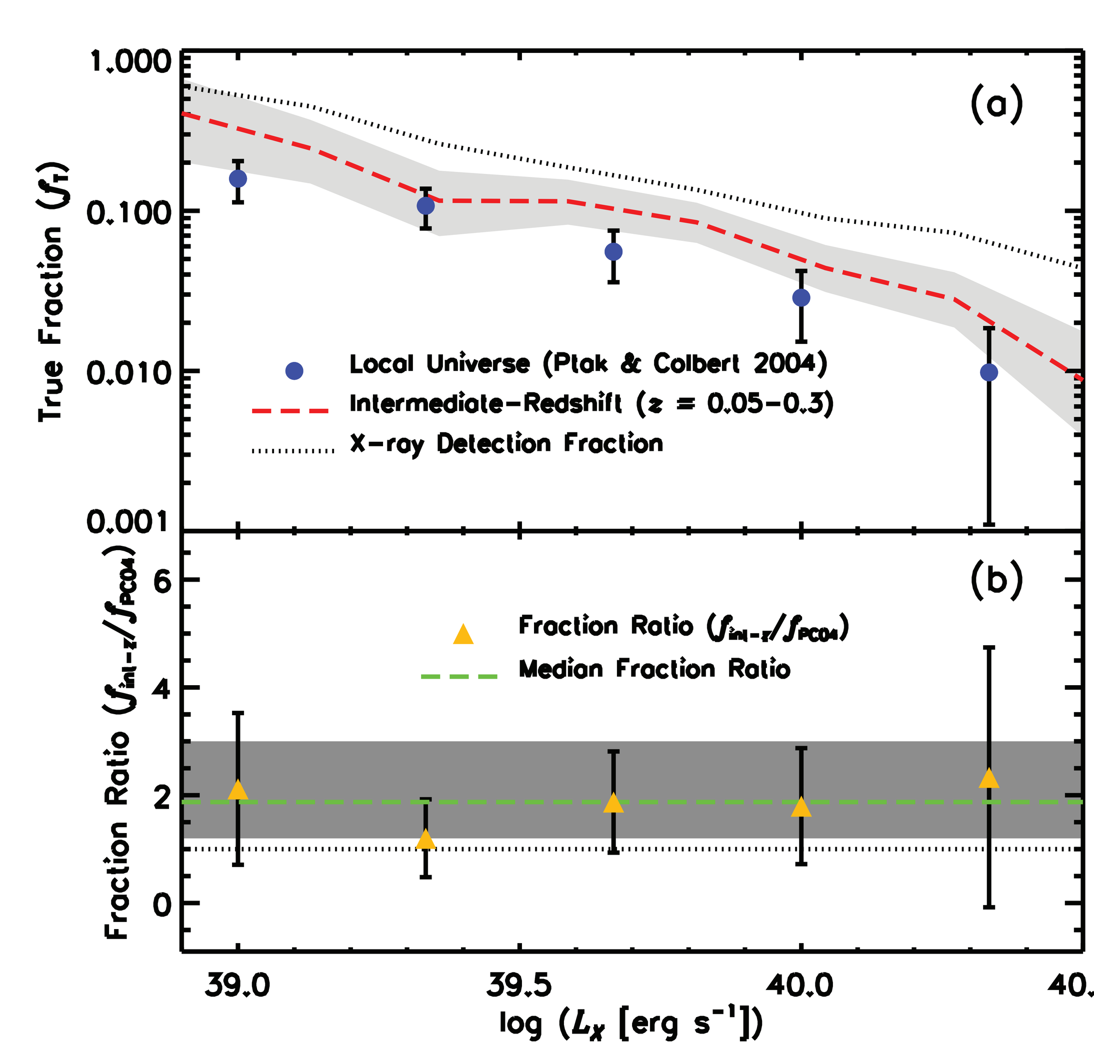

Figure 3 — (a) True fraction (f_T) of galaxies in the Chandra deep fields hosting an off-nuclear source with 0.5–2.0 keV luminosity of L_X or greater (dashed red line with shaded 1σ error envelope). The dotted line shows the actual X-ray detection fraction for the spiral galaxies in our sample. The filled blue circles with error bars represent the equivalent true fraction for the matched PC04 subsample. (b) Fraction ratio f_T[int-z]/f_T[PC04] (orange triangles wth error bars; the green dashed line shows the median). The shaded region shows the expected increase in f_T due to the global increase in star-formation density with redshift.

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