Studying the Evolution of Normal Galaxy Populations in X-rays: Results from the Deepest Chandra Surveys

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X-rays From Normal Galaxies

• Can be divided into early and late types.

• Late-types dominated by HMXBs, supernovae and remnants, hot gas, and young stars (current star-formation activity). Also contribution from LMXBs (past star formation and stellar mass).

• Early-types dominated by hot interstellar gas and LMXBs.
The Chandra Deep Fields (CDFs)

- The CDFs are the deepest *Chandra* surveys yet conducted and are the sites of several multiwavelength space- and ground-based programs (using, e.g., *HST*, *Spitzer*, radio, optical, near-IR, etc.).

Alexander et al. (2003)

Luo et al. (2008)

Lehmer et al. (2005a)

<table>
<thead>
<tr>
<th>2 Ms (23 day)</th>
<th>Alexander et al. (2003)</th>
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<tr>
<td>Roughly 60% Moon</td>
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<tr>
<td>~600 X-ray sources</td>
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| 2 Ms + 4 × 250 ks | Luo et al. (2008) |
| 1.5 × Moon |
| ~1000 X-ray sources |

Luo et al. (2008)

Lehmer et al. (2005a)

CDF-S and Extended CDF-S (E-CDF-S)

Chandra Deep Field-North (CDF-N)

HDF-N

GOODS-N

GOODS-S

UDF

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The majority of the X-ray detected sources in the CDFs are AGNs; however, at the lowest fluxes (i.e., below $10^{-16}$ ergs cm$^{-2}$ s$^{-1}$), normal galaxies start make up $\approx 25$–$35\%$ of the detected sources.

At flux levels below $10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ normal galaxies are expected to dominate over AGNs, making them an important population to study with deeper *Chandra* observations and future X-ray observatories.
Methods for Studying Distant Normal Galaxies

1. Direct detection (e.g., Ranalli+2003; Ptak+2007; Tzanavaris+2008)
   - Study of distant normal galaxy properties on an individual basis.
   - Evolution of the X-ray luminosity function.
   - Limited to the most luminous X-ray sources in deepest fields.

2. X-ray stacking (e.g., Lehmer+2007, 2008; Danielson+2010)
   - Representative populations of galaxies to highest possible redshift.
   - Study X-ray properties and evolution as a function of physical properties (optical lum, SFR, $M_\star$).
   - Only study in an average sense and removing potential AGN contamination is difficult.
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**Galaxy Selection in the CDFs**

- Classified \( \sim 3300 \ z = 0.1−1.4 \) CDF galaxies as early-types or late-types using rest-frame colors and *HST* morphologies.

- We generated samples of 2568 late-type and 691 early-type galaxies.
X-rays from Late-Type Galaxies


- X-rays can penetrate thick star-forming regions providing a relatively unobscured view of star formation activity.
- X-ray power of LTGs is strongly correlated with SFR.
- UV and infrared observations indicate that the global SF activity evolves strongly out to at least $z = 1$. 

![Graph showing the relationship between SFR and integrated X-ray luminosity](image.png)

![Graph showing the SFR-Density as a function of Redshift](image.png)
Physical Properties of LTG Sample

- For our 2568 LTGs, we estimated stellar masses using a combination of $K$-band luminosities and rest-frame optical colors and for 888 LTGs we estimated star-formation rates (SFRs) using UV+IR (MIPS 24 µm-detected) emission.
X-ray Properties of LTGs

- We detected 225 of the 2568 late-type galaxies in the CDFs.
- Candidate AGNs were identified using three primary criteria:
  1. Flat X-ray spectra (obscured AGNs) \( \Gamma < 1.0 \)
  2. X-ray-to-optical ratio (luminous AGNs) \( \frac{f_X}{f_{opt}} > 0.1 \)
  3. X-ray-to-SFR ratio (Seyferts and LLAGN) \( \frac{SFR(X-ray)}{SFR(IR+UV)} > 3 \)

- 121 AGNs and 104 normal LTGs (out of 2568 LTGs).

Want to study the X-ray undetected LTGs: Use stacking technique.
Stacking by Candlelight

Stacked image of 30 candles with 1/1000 sec exposure

⇒ effective stacked exposure of \((30 \times 1/1000 \text{ sec})\) 3/100 sec.
X-ray Stacking Analyses

X-ray stacking has recently become popular in studying populations of distant normal galaxies from $z = 0.1-6$ (e.g., Brandt+2001; Hornschemeier+2002; Nandra+2002; Laird+2005, 2006; Lehmer+2005, 2007, 2008; Watson+2009)
**Late-Type Galaxy Stacking**

- We identified AGN-dominant systems using X-ray spectra, X-ray to optical/IR flux ratios, and IR properties.

- The LTGs were divided into bins $L_B$, $M_*$, and SFR in various redshift slices. These samples were then stacked after removing AGN-dominant systems.

- AGN Contamination expected at $< 5-30\%$ level.
Stacking Results for LTG Samples

- Strong (factor of 4–10) redshift evolution in $L_X$ for $L_B$ and $M_\star$-selected samples from $z \approx 0–1.4$.

- Evidence for “cosmic downsizing” where low-mass systems are undergoing larger fractional growth than high-mass galaxies.

- $L_X$ and SFR are well correlated out to at least $z \approx 1.4$.
X-rays from Early-Type Galaxies


Constrain the evolution of hot gas emission in massive ETGs and LMXBs in lower-mass ETGs out to \( z \approx 1 \).

- Optically luminous and massive ETGs \((L_B > 3 \times 10^{10} \, L_B,\odot)\); 0.5–2 keV emission dominated by hot (~1 keV) gas and 2–8 keV dominated by LMXBs.

- Optically faint and lower mass ETGs \((L_B < 3 \times 10^{10} \, L_B,\odot)\); dominated by LMXBs.
Early-Type Galaxy Stacking

• We divided our sample of 691 ETGs into redshift bins and optically luminous/massive and optically faint/lower-mass galaxy populations.

• The non-AGN sub-populations were then stacked to measure how the X-ray emission from hot gas (luminous/massive ETGs) and LMXB+hot gas (faint/lower-mass ETGs) changes with cosmic time.
Early-Type Galaxy Stacking

- Little evolution in X-ray power from luminous/massive ETGs out to $z = 1$. If these sources are dominated by hot gas emission, then the hot gas emission has undergone little evolution over the last $\sim 8$ Gyr despite having a typical cooling time of $0.1–0.5$ Gyr.

- By contrast X-ray emission from faint/lower-mass ETGs evolve strongly $(1+z)^2-4$; similar to the evolution of star-formation and AGN activity.
AGN Feedback in Massive ETGs?

- In local massive ETGs, feedback from radio AGNs is likely responsible for keeping the gas hot and inhibiting significant star formation and SMBH growth.

- We find the fraction of radio AGN fraction of ETGs increases monotonically with galaxy mass, while the X-ray AGN activity (tracing SMBH growth) appears to flatten at high galaxy mass, similar to that of local ETGs (e.g., Best+2005).
LMXB Evolution in Lower-Mass ETGs?

- We find evidence for strong evolution in the X-ray emission from lower-mass ETGs (LMXB dominant).

- If this is indeed due to LMXB evolution, we may be seeing the signatures of past star-formation activity.
Summary of Key Results

Late-Type Galaxies (Lehmer+2008; ApJ, 681, 1163)

1. X-ray power is well correlated with SFR \((1-100 ~M_\odot \text{ yr}^{-1})\) over the redshift range \(z = 0-1.4\), suggesting X-ray emission provides a reasonable tracer of star-formation out to at least \(z = 1.4\).

2. We have found significant evolution \((1+z)^{3-5}\) in the X-ray emission from the LTG population in general and find evidence for “cosmic downsizing.”

Early-Type Galaxies (Danielson+2010, in-prep; Lehmer+2007; ApJ, 657, 681)

1. Mean \(L_X\) from massive/optically luminous ETGs does not evolve significantly from \(z = 0-1\) possibly due to hot gas being kept hot by AGN feedback.

2. We find significant X-ray evolution \((1+z)^{2-4}\) for lower-mass/faint ETGs possibly due to evolution of LMXB population.
Future Direction of this Work

- Incorporate constraints from additional deep Chandra surveys (e.g., COSMOS, AEGIS, etc.) to widen the accessible volumes, increase number statistics, and enable studies of X-ray properties of normal galaxies as a function of environment.

- Utilize local observations (both archival and new) to place new local constraints on mean X-ray luminosities of populations and understand contributions from various X-ray emitting populations.

- Conduct deeper Chandra surveys to increase number of individually detected normal galaxies available for study and improve constraints on X-ray luminosity function evolution for normal galaxies.