X-ray Probes of Star Formation
Outside the Local Universe

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Star Formation/Galaxy Formation

- Deep Chandra Survey Results
- X-ray Galaxy Redshift Gap (0.05 < z < 0.30)
- Effect of Galaxy Environment: Coma Cluster
- Future of Deep X-ray Imaging Surveys
Deep Chandra Survey Results: Introduction/Review
“True” color images

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>CDF-S Exposure</th>
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<tbody>
<tr>
<td>0.5-2.0 keV</td>
<td>940 ks ACIS-I</td>
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<tr>
<td>2.0-4.0 keV</td>
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<tr>
<td>4.0-8.0 keV</td>
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CDF-N

(447 arcmin²)

1.945 Ms ACIS-I exposure

Alexander et al. (2003)

Giacconci et al. (2002)
Source density: 13600 ±3400 sources deg⁻²

Optically-selected
(I < 24) ~10⁵ deg⁻²

Hubble Deep Field-North

WFPC2
Williams et al. (1996)

Alexander et al. (2003)
Deep Chandra Survey Results: X-ray-SFR Connection
X-ray/SFR Connection at high z: Submillimeter (850 µm) sources

Dusty high-redshift starburst galaxies?

< 250 ks Chandra surveys
little overlap with 850 µm (submm) source population
(e.g., Fabian et al. 2000; Severgnini et al. 2000; Hornschemeier et al. 2000, 2001; Bautz et al. 2001; Barger et al. 2001)...
SFR-AGN Connection at high \( z \): Submillimeter sources

7 (54\%) of the sources are X-ray detected (Alexander et al. 2003)

- At least 5 are AGNs (38\% of bright submm galaxies)
  - almost all appear to be Compton-thin moderate-luminosity AGNs
- AGN X-ray luminosity not high enough to power submm emission
- confirms/extends results of Hornschemeier et al. (2000)

Borys et al. (2003)
0.5-8 keV luminosity may be an SFR indicator
(Bauer et al. 2002, Seibert et al. 2002,
Ranalli et al. 2002, Nandra et al. 2002,
X-ray-SFR Connection: ULX Population at $z=0.1$

Hornschemeier et al. (2003b, in press)

- 12 confident off-nuclear (ULX) sources in GOODS fields
- ACS BViz SFR history
- Since ULXs dominate $L_{\text{Xp}}$ at high SFR, constraint on X-ray point source luminosity
- Complementary to intensive studies of e.g., the Antennae (Fabbiano & Zezas 2001-2003)
36% of galaxies at $z=0.1$ have a ULX with $>2 \times 10^{39}$ erg s$^{-1}$

Compare with 8% in a nearby galaxy sample (Sipior, PhD thesis, Ho et al. 2001 LLAGN sample)

GOODS galaxies have higher SFR than local samples

Consistent with bright-end XLF slope $\alpha = 0.4$

Compare with Antennae XLF, $\alpha = 0.47$ (Zezas et al. 2002)

SIRTF data will more accurately characterize SFR

Hornschemeier et al. (2003b)
Deep Chandra Survey Results:
Evolution of
Galaxy X-ray Emission

...a little higher in redshift \((0.3 < z < 1.0)\)...
Probe X-ray binaries over timescales much longer than achievable in nearby Universe (e.g., White & Ghosh 1998)

Hornschemeier et al. (2002) placed constraints on the X-ray evolution of spirals, increase by at most factor of 2 by $z=1.0$

Recently more accurately calibrated in the wider-field XMM/2dF survey ($z=0.1$, Georgakakis et al. 2003)

X-ray components of ellipticals largely in place by $z=1$ (Immler et al. 2003)

120 galaxies; Immler et al. 2003
Evolution of Galaxy X-ray Emission: “Normal Galaxy” XLF at $z > 0.3$

- Little evolution of normal galaxy XLF up to $z \sim 1$
- Bayesian selection technique $L_X/HR$ alone effective at selecting normal galaxies
- XLF/IRLF Differences:
  - Likely AGN contamination at bright end
  - Poor statistics at faint end: small volume sampled
- At $z > 0.5$, XLF and IRLF match, X-ray/SFR relations “confirmed” (e.g., Ranalli et al. 2002)
Deep Chandra Survey Results:
X-ray Galaxy Redshift Gap
The X-ray Galaxy Redshift Gap
\((0.05 < z < 0.30)\)

\[ \Omega_M = 0.3, \Omega_{\Lambda} = 0.7, H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1} \]

Based on SDSS source density in g-band (Blanton et al. 2003)
Future of Deep X-ray Imaging Surveys
Hornschemeier et al. (2003a) X-ray Emissivity of Galaxies: Steeply Rising Normal Galaxy Number Counts

Quiescent Galaxy Fraction

- Below $3 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, ~30% of X-ray sources are galaxies

Hornschemeier et al. (2003a) 0.5-2 keV Number Counts
Confusion/background limit

- Chandra still close to photon-limited on-axis (0.5-2 keV) at 5 Ms ($\approx 7 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$)
5-10 Ms: What will we see?

- Starburst galaxies up to $z \sim 3$
  - Directly probe SFR evolution

- In HDF-N
  - 50-100 galaxies

- Within GOODS area
  - 400+ galaxies

- Through stacking:
  - probe at least 5-10× deeper
  - 10,000 galaxies

- Stellar-mass black holes
  - Plausibly expect 20—30

- Confusion at $\approx 2 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ for 2.0” spatial resolution

- 5-10 Ms Chandra survey is the most direct way to evaluate before Lyman Breaks at $z \sim 3$

$4 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$
Brandt et al. (2001)
Coma project:
Bahram Mobasher, Bianca Poggianti
Mark Bautz

SDSS-Chandra work:
T. Heckman (JHU), A. Ptak (JHU), E. Colbert (JHU)

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