The Hard X-Ray Luminosity Function of High-Redshift ($z > 3$) AGN

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accepted yesterday! (on astro-ph today)
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**Introduction**

**AGN Population Evolution**

*z < 3:
AGN “downsizing” (LDDE; e.g. Miyaji+00, Ueda+03, Hasinger+05, La Franca+05, Silverman+08, Ebrero+09, Yencho+09, Ueda+14)

*z > 3:
not well assessed.*

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*Ueda+14*
High-Redshift AGN Population Evolution

Need for large, complete and reliable samples

- Deep (4 Ms CDF-S) and wide (XMM-COSMOS, Chandra-COSMOS, SXDS) X-ray surveys
- Multi-wavelength coverage.
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3 ≤ z < 5.1 AGN sample

AGN sample

141 X-ray (0.5 – 2 keV) detected AGN at 3 ≤ z < 5.1

- ~ 5 x Hiroi+12 sample
- ~ 2 x Civano+11 sample

using the most up-to-date redshift information and a careful and clean (e.g. no strong radio-loud AGN) selection in the 4 Ms CDFS (Vito+13), XMM-COSMOS (Brusa+10, Salvato+11, Civano+12), Chandra-COSMOS (Civano+12, Lilly+ in prep.) and SXDS (Hiroi+12) fields. Redshift completeness > 95%.
Spectral parameters

- $\Gamma = 1.8$ fixed
- $N_H$ from uniform spectral analysis (CDFS, C-COSMOS) or HR (SXDS, Hiroi+12). Objects from X-COSMOS assumed unobscured.
- Intrinsic $L_{2-10\text{ keV}}$ from spectral analysis (CDFS, C-COSMOS), literature (SXDS, Hiroi+12), or extrapolated from soft-band flux from catalogue (X-COSMOS, Cappelluti+09)
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$$\phi = \phi^U + \phi^A$$

$\phi$ as in Page&Carrera 2000

$\log N_H < 23$

\[\downarrow\]

**UNABSORBED** (105 objects)

$\downarrow \Omega^U$

$\log N_H > 23$

\[\downarrow\]

**ABSORBED** (36 objects)

\[\downarrow \Omega^A\]

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[Graphs showing sky coverage vs. flux for X-Cosmos, SXDS, C-Cosmos, and CDFS regions.]
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**The Hard X-Ray Luminosity Function**

**Evolutionary models**

\[ \Phi(L, z) = \frac{A(z)}{\left[ \left( \frac{L}{L_*(z)} \right)^{\gamma_1} + \left( \frac{L}{L_*(z)} \right)^{\gamma_2} \right]} \]

- **PLE**: $L_*(z) \propto L_*(3) \cdot (1 + z)^{P_{Plum}}$
- **PDE**: $A(z) \propto A(3) \cdot (1 + z)^{P_{den}}$
- **ILDE**: PLE + PDE
- **LDE**: PLE + $A(z) \propto A(3) \cdot 10^{P_{den} (1 + z)}$
- **LDDE**: $A(z) \propto A(3) \cdot (1 + z)^{P_{den} + \beta (\log L - 44)}$

![Graph showing evolutionary models with different parameters and luminosity functions.](image)
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Fit to unbinned data through a Maximum Likelihood procedure

<table>
<thead>
<tr>
<th>MODEL</th>
<th>2DKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLE</td>
<td>0.05</td>
</tr>
<tr>
<td>PDE</td>
<td>0.38</td>
</tr>
<tr>
<td>ILDE</td>
<td>0.38</td>
</tr>
<tr>
<td>LADE</td>
<td>0.46</td>
</tr>
<tr>
<td>LDDE</td>
<td>0.42</td>
</tr>
</tbody>
</table>

$2DKS \gtrsim 0.20$

model and data not significantly different
Correction for redshift incompleteness: $\Theta = \Theta(z, L_X, N_H)$

- 65 sources with no redshift information (but flux known)
- All of them assumed to be at $3 < z < 5.1$
- Assumed same fraction of absorbed sources (at similar fluxes) and same redshift distribution of the sources with redshift
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Fit to unbinned data after completeness correction

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<td>PLE</td>
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<tr>
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</table>
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Obscured AGN fraction

\[ F(\log N_H > 23) = \frac{\phi^A}{(\phi^A + \phi^U)} \]

- Constant with luminosity ($\chi^2$ fit returns $F_{23} = 0.54 \pm 0.05$)
- ...but the most obscured sources at low-L are probably missing!
- Evolution from $z = 0$ to $z > 3$
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Space density

$$\Phi = \frac{dN}{dV} = \sum_{i=1}^{N} \frac{1}{V_{\text{max},i}}$$

- $\Phi \propto (1 + z)^p$ with $p = -6.00^{+0.84}_{-0.87}$, in agreement with Hiroi+12, but larger dataset and different method (Maximum Likelihood fit on unbinned data vs. $\chi^2$ minimization)
- We confirm the decline in the space density of luminous high-redshift AGN (factor of $\sim 10$ from $z=3$ to 5)
No evidence for the “up-sizing” (i.e. flatter space density for less luminous AGN at z > 3) suggested by Ueda+14

Larger sample of $L_X < 10^{44}$ AGN needed to discriminate between PDE and LDDE
Conclusions

- Evolution of the HXLF at $z > 3$ dominated by a negative density term (PDE). More complex models mimic the behaviour of the PDE model. Larger samples of low-luminosity ($L_X < 10^{44}$) AGN needed to constrain a possible luminosity-dependent density evolution at high-z.

- Obscured ($\log N_H > 23$) AGN fraction is $0.54 \pm 0.05$. No evidence for an anti-correlation with luminosity, but evolution from $z = 0$!

- The space density of luminous AGN declines by a factor of $\sim 10$ from $z=3$ to $5$

- No evident dependency of the decline slope on luminosity, but larger low-L samples are required

Future perspective

Larger samples of (low-luminosity) AGN thanks to the 7 Ms in CDFS (+ deep follow-up and/or proper photo-z)
## Fit parameters

<table>
<thead>
<tr>
<th>MOD.</th>
<th>$A$</th>
<th>$L_\text{x}$</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$P_{\text{Plum}}$</th>
<th>$P_{\text{den}}$</th>
<th>$\beta$</th>
<th>2DKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLE</td>
<td>0.65$^{+0.06}_{-0.06}$</td>
<td>6.56$^{+2.38}_{-2.22}$</td>
<td>0.21$^{+0.16}_{-0.20}$</td>
<td>2.58$^{+0.75}_{-0.60}$</td>
<td>$-3.73^{+0.77}_{-0.92}$</td>
<td>—</td>
<td>—</td>
<td>0.05</td>
</tr>
<tr>
<td>PDE</td>
<td>1.10$^{+0.11}_{-0.11}$</td>
<td>5.26$^{+1.06}_{-1.20}$</td>
<td>0.22$^{+0.13}_{-0.16}$</td>
<td>3.79$^{+1.08}_{-0.87}$</td>
<td>—</td>
<td>$-6.00^{+0.84}_{-0.87}$</td>
<td>—</td>
<td>0.38</td>
</tr>
<tr>
<td>ILDE</td>
<td>1.13$^{+0.11}_{-0.11}$</td>
<td>5.13$^{+1.32}_{-1.53}$</td>
<td>0.21$^{+0.13}_{-0.17}$</td>
<td>3.75$^{+1.10}_{-0.91}$</td>
<td>$0.13^{+0.94}_{-0.81}$</td>
<td>$-6.13^{+1.17}_{-1.23}$</td>
<td>—</td>
<td>0.38</td>
</tr>
<tr>
<td>LADE</td>
<td>1.08$^{+0.11}_{-0.11}$</td>
<td>5.10$^{+1.33}_{-1.54}$</td>
<td>0.21$^{+0.13}_{-0.18}$</td>
<td>3.74$^{+1.11}_{-0.91}$</td>
<td>$0.16^{+0.95}_{-0.82}$</td>
<td>$-0.57^{+0.11}_{-0.11}$</td>
<td>—</td>
<td>0.46</td>
</tr>
<tr>
<td>LDDE</td>
<td>1.05$^{+0.10}_{-0.10}$</td>
<td>5.24$^{+1.05}_{-1.19}$</td>
<td>0.28$^{+0.16}_{-0.19}$</td>
<td>3.87$^{+1.08}_{-0.88}$</td>
<td>—</td>
<td>$-6.43^{+1.12}_{-1.17}$</td>
<td>$1.18^{+2.06}_{-2.00}$</td>
<td>0.42</td>
</tr>
</tbody>
</table>
Binned HXLF

\[ \phi = \frac{\Phi}{d\log L} = \frac{d^2N}{dV \, d\log L} \]

Assuming \( \phi \) does not vary in the \( \Delta z \)-\( \Delta \log L \) bin (i.e. narrow \( \Delta z \)-\( \Delta \log L \) bin)

\[ \phi|_{(\Delta z, \Delta \log L)} = \frac{N(\Delta z, \Delta \log L)}{V(\Delta z, \Delta \log L)} = \frac{N(\Delta z, \Delta \log L)}{\int \int \Omega \Theta \frac{dV}{dz} \, dz \, d\log L} \]
Binned HXLF: Page & Carrera 2000 vs $V_{MAX}$

(Page & Carrera, 2000)
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Conclusions

**Likelihood estimator**

\[ \mathcal{L} = -2 \sum_{i=1}^{N} \ln[\phi(z_i, L_i)] + 2 \iint \phi(z, L) \Omega \frac{dV}{dz} dz dL \]

(Marshall+1983)