Cosmic star formation history revealed with AKARI and Hyper Suprime Cam

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AKARI NEP team, AKARI ASS team
When and where stars/AGN were born?

We want to reveal cosmic star formation history.
Understanding star formation history of the Universe is one of the major goals, however…

Madau et al. (1996)
Lilly et al. (1996)

UV estimates are lower limits.

At $z \sim 1$, 80% of SF is obscured by dust. (Takeuchi+2007)
How do we measure obscured star formation?
AKARI infrared telescope can probe dusty star formation

But infrared telescope needs to be in space
To observe infrared, we need a space telescope. ➔ AKARI
AKARI: All sky survey in 9, 18, 60, 90, 140 and 160 μm
NEP field: 2, 3, 4, 7, 9, 11, 15, 18, and 24 μm
AKARI NEP Deep field: (Murata et al. 2013) 0.67 deg$^2$

2,3,4,7,9,11,15,18,24μm
AKARI has continuous filters in mid-IR, c.f. Spitzer has a gap between IRAC and MIPS.

- More accurate IR luminosity.
- No need for extrapolation for 8, 12μm LF!
AKARI NEP deep field

- $5\sigma$ limit = Sky noise limit
- 50% limit = completeness limit

Table 2. Summary of the survey

<table>
<thead>
<tr>
<th>band</th>
<th>total area (arcmin$^2$)</th>
<th>area* (arcmin$^2$)</th>
<th>$N_{sources}$ †</th>
<th>$5 \sigma$ limit ‡ ((\mu)Jy)</th>
<th>50% limit § ((\mu)Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>2099</td>
<td>2099</td>
<td>23323</td>
<td>14.2</td>
<td>42.5</td>
</tr>
<tr>
<td>N3</td>
<td>2123</td>
<td>2123</td>
<td>26193</td>
<td>11.0</td>
<td>34.6</td>
</tr>
<tr>
<td>N4</td>
<td>2080</td>
<td>2079</td>
<td>26318</td>
<td>8.0</td>
<td>29.0</td>
</tr>
<tr>
<td>S7</td>
<td>2093</td>
<td>1967</td>
<td>7702</td>
<td>48.9</td>
<td>54.0</td>
</tr>
<tr>
<td>S9W</td>
<td>2070</td>
<td>1720</td>
<td>3685</td>
<td>54.3</td>
<td>69.3</td>
</tr>
<tr>
<td>S11</td>
<td>1954</td>
<td>1113</td>
<td>4189</td>
<td>121.4</td>
<td>98.8</td>
</tr>
<tr>
<td>L15</td>
<td>2220</td>
<td>1094</td>
<td>0737</td>
<td>117.0</td>
<td>93.3</td>
</tr>
<tr>
<td>L18W</td>
<td>2226</td>
<td>1113</td>
<td>4189</td>
<td>121.4</td>
<td>98.8</td>
</tr>
<tr>
<td>L24</td>
<td>1958</td>
<td>1444</td>
<td>2813</td>
<td>275.8</td>
<td>209.8</td>
</tr>
</tbody>
</table>

Spitzer does not have these filters.
This continuous 9-band mid-IR imaging does not exist anywhere else.

(No IRAS, no Spitzer, no WISE)

NEP is a treasure AKARI left us.
## Extensive follow-up observations

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Band</th>
<th>Sensitivity/Number of objects/exposure time</th>
<th>Area (deg$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKARI/IRC</td>
<td>2.5-24$\mu$m</td>
<td>$L15=18.5,AB$</td>
<td>5.4</td>
</tr>
<tr>
<td>Subaru/S-Cam</td>
<td>$BVRI'z'$</td>
<td>$R=27.4,AB$</td>
<td>0.25</td>
</tr>
<tr>
<td>Subaru/FOCAS</td>
<td>optical spect.</td>
<td>57 sources in NEP</td>
<td></td>
</tr>
<tr>
<td>MMT6m</td>
<td>optical spec.</td>
<td>$\sim1800$ obj</td>
<td>5.4</td>
</tr>
<tr>
<td>KPNO-2.1m</td>
<td>$J, H$</td>
<td>21.6, 21.3</td>
<td>5.4</td>
</tr>
<tr>
<td>Maidanak 1.5m</td>
<td>$B, R, I$</td>
<td>$R=23.1$, $J=21.6$, $H=21.3$</td>
<td>3.4</td>
</tr>
<tr>
<td>KPNO2m/FLAMINGOS</td>
<td>$J, H$</td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>WIRCAM</td>
<td>Y, J, K</td>
<td>24AB</td>
<td>1</td>
</tr>
<tr>
<td>MegaCam</td>
<td>$ugriz$</td>
<td>$r \leq 25.9,AB$</td>
<td>1</td>
</tr>
<tr>
<td>GALEX</td>
<td>NUV, FUV</td>
<td>$\text{NUV}=26$</td>
<td>1.5</td>
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<tr>
<td>WSRT</td>
<td>20cm</td>
<td>$\sim100$ $\mu$Jy</td>
<td>0.25</td>
</tr>
<tr>
<td>VLA-archive</td>
<td>10cm</td>
<td>$200$ $\mu$Jy</td>
<td>5.4</td>
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<tr>
<td>GMRT</td>
<td>610MHz</td>
<td>$60-80$ $\mu$Jy</td>
<td>0.25</td>
</tr>
<tr>
<td>Keck/Deimos</td>
<td>optical spec.</td>
<td>$\sim1000$ obj</td>
<td>0.25</td>
</tr>
<tr>
<td>Subaru/FMOS</td>
<td>near-IR spec.</td>
<td>$\sim700$ obj</td>
<td>0.25</td>
</tr>
<tr>
<td>Herschel</td>
<td>100,160 $\mu$m</td>
<td>5-10 mJy</td>
<td>0.5</td>
</tr>
<tr>
<td>Herschel</td>
<td>250-500 $\mu$m</td>
<td>$\sim10$ mJy</td>
<td>7.1</td>
</tr>
<tr>
<td>Chandra</td>
<td>X-ray</td>
<td>30-80ks</td>
<td>0.25</td>
</tr>
<tr>
<td>SCUBA2</td>
<td>submm</td>
<td>1mJy</td>
<td>0.25</td>
</tr>
<tr>
<td>Subaru/HSC</td>
<td>$r$</td>
<td>$r=27.2$ (Fig.2)</td>
<td>5.4</td>
</tr>
</tbody>
</table>
Photo-z with Lephare (Arnout & Ilbert)

$FUV,NUV,B,V,R,i,z,Y,J,K$

$\Delta z / (1+z) \approx 0.043$

AGNs are excluded.

$\rightarrow V_{\text{max}}$ to compute LFs

(Oi et al. 2014)

Subaru SuprimeCam
Previous Result 1

$8\mu m$ LF

At 8μm, PAH emissions are important for SF

C-H, C-C bending/stretching modes

Transiently heated by UV photons from young stars, then emit mid-IR band emissions

**Fig. B.1.** Spectral energy distribution of the two templates from the Dale & Helou (2002) library used in the simulation. The solid blue line corresponds to $\alpha = 3.5$ (the cold template) and the dashed red line corresponds to $\alpha = 1.3$ (the warm template). Both templates are normalized to the same total infrared luminosity ($L_{IR} = 10^{11} L_\odot$).
8μm shows good correlation with total $L_{IR}$
Based on AKARI all sky survey

$\log \left[ L_{\text{IR}}(L_\odot) \right]$ (CHEL)

$\log \left[ \nu L_\nu, \text{Spitzer} \right] 8\mu m(L_\odot)$

$L_{\text{total}}$

$L_{8\mu m}$

Goto et al. 2011a
AKARI MIR filters can trace $L_{8\mu m}$ evolution without using extrapolation from SED models.

8$\mu$m at $z=0.375, z=0.775, z=1.25, z=2$

Extrapolation from SED model was the largest uncertainty in previous work.
8μm LF (via Vmax, completeness correction)

- Continuous & strong evolution
- Larger than Babbedge+, smaller than Caputi+
- No extrapolation for ours.
Previous Results:

12μm LF
12μm is easier to be modeled, yet still sensitive SF

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12μm LF

\[ \phi(Mpc^{-3} \text{ dex}^{-1}) \]

\[ \log [\nu L_\nu (12\mu m) (L_\odot)] \]

- \( z = 0.2 \)
- \( z = 0.5 \)
- \( z = 0.9 \)
- \( 0.84 < z < 1.16 \)
- \( 0.38 < z < 0.62 \)
- \( 0.15 < z < 0.35 \)

Perez-Gonzalez et al.

Rush et al. \( (0 < z < 0.3) \)

Toba et al. \( (0 < z < 0.05) \)
$L_{TIR}$ with Lephare SED fit

Fig. 11. An example of the SED fit. The red dashed line shows the best-fit SED for the UV-optical-NIR SED, mainly to estimate photometric redshift. The blue solid line shows the best-fit model for the IR SED at $\lambda > 6\mu m$, to estimate $L_{TIR}$. 

9 mid-IR bands still help.
Total IR LF
What about SFH?

IR luminosity density ($\Omega_{\text{IR}}$)

= LF x luminosity integrated.

$\Omega_{\text{IR}} = \text{SFR/AGN density}$

$SFR (M_\odot \text{ yr}^{-1}) = 1.72 \times 10^{-10} L_{\text{TIR}} (L_\odot)$

Kennicutt+98
Cosmic star formation history

- Continuous increase to \( z = 2 \)
- ULIRG contribution \( \times 10 \) larger by \( z = 2 \)
- \( \Omega_{\text{IR}} / (\Omega_{\text{IR}} + \Omega_{\text{UV}}) > 0.9 \) at \( z = 1.3 \),
  - \( \Omega_{\text{IR}} \) is important.
- \( \Omega_{\text{IR}} = (1+z)^{4.4 \pm 1.0} \)

\[ \Omega_{\text{IR}} / (\Omega_{\text{IR}} + \Omega_{\text{UV}}) > 0.9 \text{ at } z = 1.3 \]
Cosmic star formation history
all by AKARI

\[ \Omega_{\text{IR SFR}} \propto (1+z)^{4.0 \pm 0.5} \]
However, not all AKARI data were used!

- Limited by smaller optical/near-IR coverage
- Photo-z needed for $L_{\text{IR}}$
AKARI NEP WIDE (5.4 deg²)

Scam, 0.25deg²
We need 8m depth for dusty sources.

- AKARI sources have no optical data

~X20

Red:Scam

Black:CFHT
Subaru’s Hyper Suprime Cam has become available.
New HSC observation covering 5.4deg$^2$, PI: Goto

X20 larger area

Thank you HSC!
HSC grizy data over 5.4deg²

g' 27.5mag
r 26.5
i' 25.4
z' 24.7
y 24.3
HSC grizy data over 5.4deg²
Result 1: 8μm LF with HSC
$8\mu m$ LF (via Vmax, completeness correction)

- $x10$ larger area
- Smaller errors

\[
\phi (\text{Mpc}^{-3} \text{ dex}^{-1})
\]

\[
\text{log} \left[ \nu L_\nu (8\mu m) (L_\odot) \right]
\]

Preliminary
Results2:

12μm LF with HSC
• X10 larger sample

• Smaller errors

Preliminary
Result 3

Total IR LF with HSC
Total IR LF

- X10 larger sample
- Smaller errorbar

Preliminary
AKARI’s 9-band continuous mid-IR coverage exists nowhere else.

We obtained new HSC imaging data, that cover whole AKARI NEP field 

\[ (5.4 \text{ deg}^2) \Rightarrow \text{area x20} \]

Updated IR LFs will be
- more accurate
- more robust against cosmic variance.