Near- to mid-Infrared Observation of Supernovae with AKARI/IRC

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the life of interstellar dust
-- where the interstellar dust is formed
-- how they evolve in the interstellar space
-- how they enrich the universe
AKARI Mission

JAXA/ISAS mission
for infrared astronomy
with ESA participation

Telescope with 685mm SiC Mirror
cooled by 179l LHe
& mechanical coolers

2 instruments: IRC & FIS

Launched on Feb. 22, 2006
Successfully performed near-
to far-infrared observation

LHe: 2006 May - 2007 Aug
(phases I&II)

Warm mission: 2008 June -
(phase III; 2-5μm imag. & spec.)
The sun-synchronous polar orbit at the altitude of 700 km

The primary achievements of AKARI Mission:
All-sky survey at 9, 18, 65, 90, 140 & 160µm
AKARI 9um all-sky image (Ishihara et al. 2008)
Sky coverage >94%
Detailed infrared structures
with higher spatial resolution
& with more excellent sensitivity
than IRAS mission
Pointed observations in 2 - 180μm with IRC & FIS
One pointed observation corresponds to ~10min integration
The observation chance of a certain target comes once in a 6months

More than 5000 pointed observations during Phases I&II
Still continuing the near-infrared pointed observations in Phase III
System spectral response curves of AKARI/IRC filters

Imaging filters

- Near-infrared (NIR)
- Mid-Infrared-Short (MIR-S)
- Mid-Infrared-Long (MIR-L)

9 imaging filters (2-25µm)

5-sigma sensitivity (µJy)

<table>
<thead>
<tr>
<th>Filter</th>
<th>AOT02</th>
<th>AOT03</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2</td>
<td>16</td>
<td>20</td>
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<td>N3</td>
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<td>19</td>
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<tr>
<td>N4</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>S7</td>
<td>74</td>
<td>91</td>
</tr>
<tr>
<td>S9W</td>
<td>76</td>
<td>93</td>
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<td>S11</td>
<td>132</td>
<td>162</td>
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<td>279</td>
<td>341</td>
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<td>L18W</td>
<td>273</td>
<td>335</td>
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<tr>
<td>L24</td>
<td>584</td>
<td>716</td>
</tr>
</tbody>
</table>

* Values in Phases I&II
AKARI’s spectroscopic ability in the near-infrared in the warm mission is quite unique and valuable.

Two Near-Infrared Dispersers with different spectral resolution power:
- Near-Infrared Prism (NP)
- Near-Infrared Grism (NG)

<table>
<thead>
<tr>
<th>Dispenser</th>
<th>Effective Coverage</th>
<th>Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>1.8µm-5.5µm</td>
<td>0.06 µm/pix at 3µm</td>
</tr>
<tr>
<td>NG</td>
<td>2.5µm-5.0µm</td>
<td>0.0097µm/pix</td>
</tr>
</tbody>
</table>

The 1-σ noise-equivalent flux for slit-less spectroscopy at the ecliptic poles:

<table>
<thead>
<tr>
<th>Dispenser</th>
<th>Phases I&amp;II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>~0.05mJy</td>
<td>~0.1mJy</td>
</tr>
<tr>
<td>NG</td>
<td>~0.1mJy</td>
<td>~0.2mJy</td>
</tr>
</tbody>
</table>
Infrared Emission of Interstellar dust

Interstellar dust grains; tiny solid particles with the size ranging from <1nm to >1μm drifting in the interstellar space powered by optical to UV photons reradiates in the near- to far-infrared wavelengths

Far-Infrared (60μm~)
Thermal emission from submicron dust in radiation equilibrium (BGs; ~100nm)

Near- to Mid-infrared (2μm~20μm)
amorphous silicate, amorphous carbons, etc Ice band features
Polycyclic Aromatic Hydrocarbons (PAHs; ~10Å, VSGs; 1~10nm)

Infrared emission from interstellar dust in general interstellar environment of our Galaxy
Infrared observations are quite useful to investigate the properties of the interstellar dust. AKARI Mission plays an important role in the interstellar physics and chemistry.
AKARI’s latest results on the studies of interstellar dust
## Interstellar dust budgets

<table>
<thead>
<tr>
<th>Source</th>
<th>Carbon dust injection rate ($M_\odot kpc^{-2} Myr^{-1}$)</th>
<th>Silicate and metal dust injection rate ($M_\odot kpc^{-2} Myr^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-rich giants</td>
<td>3.0</td>
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<tr>
<td>O-rich giants</td>
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<tr>
<td>Novae</td>
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<tr>
<td>SN type Ia</td>
<td>0.3</td>
<td>2.0</td>
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<tr>
<td>OB stars</td>
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</tr>
<tr>
<td>Red supergiants</td>
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<td>0.2</td>
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<tr>
<td>Wolf-Rayet</td>
<td>0.06</td>
<td>---</td>
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<tr>
<td>SN type II</td>
<td>2</td>
<td>10</td>
</tr>
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</table>

(Tielens 2006)
Dust Formation in the core-collapse Supernovae

- Dust Formation in the ejecta of core-collapse supernovae (SNe)
  -> Important to explore the origin of dust in the early universe
  e.g., The amount of $0.1M_{\text{solar}}$ dust formation is needed for a core-collapse supernova to account for the dust content of high red-shift galaxies. (Morgan & Edmunds 2003)

- The dust condensation in the ejecta of core-collapse SNe is theoretically suggested (Kozasa et al. 1991; Todini & Ferrera 2001)

- Observational Evidence for the dust formation in SN ejecta
  - Type II SN2003gd: $0.02M_{\text{solar}}$ (Sugerman et al. 2006)
    -> $4 \times 10^{-5}M_{\text{solar}}$ (Meikle et al. 2007)
  - Type II SN1987A: $7.5 \times 10^{-4}M_{\text{solar}}$ (Ercolano et al. 2007)
  - Cas A: $0.003M_{\text{solar}}$ (Hines et al. 2004) or $0.02M_{\text{solar}}$ (Rho et al. 2004)
    -> much smaller amount of dust formation

A gap still remains in produced dust mass in core-collapse SN ejecta between those observational results and theoretical prediction of $0.1 - 1M_{\text{solar}}$ (Nozawa et al. 2003)
Supernova 2006jc

- A peculiar Type Ib supernova (SN)
- discovered on 2006 October 9.75(UT) (Nakano et al. 2006) in UGC4904
- The progenitor had experienced a LBV-like luminous outburst event
  2 years prior to the SN event (Pastorello et al. 2007; Foley et al. 2007)

Evidence for Dust Formation in the SN ejecta
- Presence of an continuum excess emission at red/near-infrared
- The fading of red-shifted side of the narrow He I emission lines
- Increase in the optical extinction

These characteristics are observed simultaneously between 51 and 75 days after the brightness peak (Smith et al. 2007)
Observation of SN2006jc with AKARI/IRC

- Observation ID: 5124071 (AOT04), 512472 (AOT02b)
- 00:36:22 (UT) and 02:15:47 (UT) on 29 April 2007 (epoch of 220 days)

AKARI Infrared Camera (IRC)
- NIR NP (prism 2-5.5 µm) & N3 (3 µm)
- MIR-S S7 (7 µm), S9W (9 µm), S11 (11 µm)

(a) RGB color image of SN2006jc made with NIR/N3 (blue), MIR-S/S7 (Green), and S11 (red) bands.

(b) NIR/NP (prism 2-5.5 µm) data of SN2006jc

Dispersion direction

SN2006jc

10''
Near to Mid-Infrared Spectral Energy Distribution of SN2006jc at the epoch of 220 days
Near Infrared spectrum of SN2006jc

Spherical dust grains of a certain kind X
A uniform particle radius $a_X$, a total mass of $M_X$ and the equilibrium temperature of $T_X(K)$
Located at a distance of $R$ from the observer
Optically thin

\[
 f^X(\lambda) = M_X \left( \frac{4}{3} \pi \rho_X a_X^3 \right)^{-1} \pi B_\nu(\lambda, T_X) Q^{abs}_X(\lambda) \left( \frac{a_X}{R} \right)^2
\]

(a) Amorphous carbons ($X=\text{a.car.}$)

\[
 T_{\text{a.car.}} = 800 \pm 10 \ (K) \\
 M_{\text{a.car.}} = 6.9 \pm 0.5 \times 10^{-5} \ M_{\text{solar}}
\]

(b) Astronomical silicate ($X=\text{a.sil.}$)

\[
 T_{\text{a.sil.}} = 920 \pm 10 \ (K) \\
 M_{\text{a.sil.}} = 4.2 \pm 0.3 \times 10^{-4} \ M_{\text{solar}}
\]
Excess emission in the mid-infrared (Two Temperature Amorphous Carbon Model)

\[ X_1 = \text{hot amorphous carbon}, \quad X_2 = \text{warm amorphous carbon} \]

- New found dust in the ejecta of SN2006jc
- Pre-existing circumstellar dust formed in the mass loss wind associated with the Wolf-Rayet Stellar activity (Williams et al. 1992; Waters et al. 1997; Molster et al. 1999; Voors et al. 2000)

- Modelled spectrum (total)
- Amorphous carbon: \( T = 800 \pm 10 \) K
- Amorphous carbon: \( T = 320 \pm 10 \) K

- \( T_{\text{hot.car.}} = 800 \pm 10 \) (K)
- \( M_{\text{hot.car.}} = 6.9 \pm 0.5 \times 10^{-5} \) \( M_{\text{solar}} \)

- \( T_{\text{warm.car.}} = 320 \pm 10 \) (K)
- \( M_{\text{warm.car.}} = 2.7^{+0.7}_{-0.5} \times 10^{-3} \) \( M_{\text{solar}} \)
Geometry of Dust around the SN2006jc

$r_{220}$: the distance that the light travels for 220 days
$\sim 5.7 \times 10^{12}$ km

$r_{dd}$: the radius of the dust-depleted region made by the irradiation of shock breakout assuming the shock breakout luminosity of $L_{sb} = 10 \times L_{peak} \sim 7 \times 10^{43}$ erg s$^{-1}$ and the evaporation temperature of $T_{ev} = 1800$K
$\sim 2 \times 10^{12}$ km

$r_{ejecta}$: the distance that the ejecta travels for 220 days assuming the ejecta velocity to be $3 \times 10^4$ km/s (Tominaga et al. 2008)
$\sim 5.7 \times 10^{11}$ km

If the total mass $M_{hot,car.} = 6.9 \pm 0.5 \times 10^{-5} M_{solar}$ of spherical amorphous carbon grains with a single radius of $a=0.01 \mu m$ are contained uniformly within a sphere with $r_{ejecta}$, the optical depth at $3.2 \mu m$ becomes $\tau(3.2)=4.9 \times 10^{-2}$.
$\rightarrow$ consistent with the assumption that the dust emission is optically thin.
Spitzer IRAC photometric data of SN2006jc at the epoch ~230 days;

The dust formation in the cool dense shell (CDS) produced by the interaction of the ejecta onward-shock with a dense shell of the circumstellar material
→ $3 \times 10^{-4} M_\odot$ of amorphous carbon as the mass of newly formed dust

Excess emission in the mid-infrared
→ Dust condensation in the mass loss wind associated with the prior events to the SN explosion
Near- to Mid-infrared observations of SN2006jc on 220 days with AKARI/IRC -> We succeeded in obtaining the thermal emission spectrum of newly formed dust in the ejecta of the type Ib supernova for the first time

The near- to mid-infrared spectrum of SN2006jc at the epoch of 220 days is well explained by the two temperature amorphous carbon model

(i) Hot amorphous carbon ($T_{\text{hot.car.}} = 800\pm10$ K, $M_{\text{hot.car.}} = 6.9\pm0.5 \times 10^{-5} M_{\odot}$) → newly formed amorphous carbon in the ejecta of SN2006jc

(ii) Warm amorphous carbon ($T_{\text{warm.car.}} = 320\pm10$ K, $M_{\text{warm.car.}} = 2.7^{+0.7}_{-0.5} \times 10^{-3} M_{\odot}$) → Pre-existing circum-stellar dust formed in the mass loss wind associated with the Wolf-Rayet Stellar activity

The dust mass of the hot amorphous carbon ($6.9\pm0.5 \times 10^{-5} M_{\odot}$) is more than 3 orders of magnitude smaller than the amount needed for a core collapse supernova to contribute efficiently to the early-Universe dust budget (i.e., $\sim1 M_{\odot}$: Morgan & Edmunds 2003)

Dust condensation not only in the SN ejecta itself but also in the mass loss wind associated with the prior events to the SN explosion could make a significant contribution to the dust formation by a massive star in its whole evolitional history
Future programs

Near-infrared imaging and spectroscopy of several supernovae including SN2008D, SN2008S, SN2008ax, SN2008bo with AKARI/IRC

<table>
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<tr>
<th>Identifications</th>
<th>Observation date (UST)</th>
<th>Epoch (days)</th>
<th>Observation mode</th>
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<td>N2</td>
<td>N3</td>
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<td>SN2006jc</td>
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<td>28-29, Apr., 2008</td>
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<td>SN2008D</td>
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<td>SN2008bo</td>
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<td>~160</td>
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<td>09-10, Mar., 2009</td>
<td>~340</td>
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</tbody>
</table>

White; observations executed
Blue; observations scheduled
Future programs
AKARI Phase 3 Open Time Program
Near-IR Spectroscopy of Galaxies; Waiting for Supernovae momentarily (NEWSY) (P.I.; Sakon, I.)

AKARI/IRC is, so far, the only instrument that is capable of obtaining the near-infrared spectra (covering from 2 to 5.5\(\mu\)m) of supernovae within 6 months after explosion.

Constructing a near-infrared slit-less spectroscopic database of nearby galaxies in preparation for a future supernova there.

The obtained database is directly used to estimate the spectroscopic patterns of the host galaxy and to obtain the spectrum of supernova with higher accuracy once the supernova explosions occurs in the future.

Nearby Galaxies (<30Mpc) with relatively higher supernova rate are selected; NGC722, NGC908, NGC1097, NGC1187, NGC1313, NGC1365, NGC1448, NGC1559, NGC2207, NGC2276, NGC2403, NGC2841, NGC3169, NGC3184, NGC3198, NGC3631, NGC3646, NGC3690, NGC3810, NGC3953, NGC4157, NGC4939, NGC5033, NGC5161, NGC5468, NGC6754, NGC6943, NGC6946, NGC6951, IC5201, ESO576-40
Summary

*AKARI* has been playing important roles in the studies on the interstellar dust with high spatial resolution, nice sensitivity, and wide infrared wavelength coverage. *AKARI’s* near infrared spectroscopic abilities during the warm mission is quite valuable in the observational studies of future supernovae.
Data Reduction Procedure for Near-Infrared Spectrum of SN2006jc

Subtraction of the UGC4904 component is crucial to obtain the pure spectrum of SN2006jc.

\[
I_{Y[20:25]}^{UGC4904}(X) = \sum_{k=-\infty}^{\infty} \eta_{Y[20:25]}(k)I_{Y[28:29]}(X-k)
\]

\[
S_{Y[20:25]}^{UGC4904}(X) = \sum_{k=-\infty}^{\infty} \eta_{Y[20:25]}(k)S_{Y[28:29]}(X-k)
\]

\[
S_{Y[20:25]}^{SN2006jc}(X) = S_{Y[20:25]}(X) - S_{Y[20:25]}^{UGC4904}(X)
\]