Near-infrared Spectroscopy of Young Stellar Objects around the Supernova Remnant G54.1+0.3

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   - (Young) Stellar Sources around G54.1+0.3

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   - Data Reduction

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   - Progenitor Mass of the SNR

5. NIR High-resolution Spectroscopy of Massive Stars & IGRINS

6. Summary
G54.1+0.3

**Young (~3000 yr), Crab-like SNR @ 8 kpc**

- AKARI observations (*Koo et al., 2008*)
  - Partial **loop-like structure bright in IR**
  - **Point-like sources with strong MIR excess** distributed along the IR loop

- JHK color-color and color-magnitude plots
  - Clustered around the positions of **OB stars with Av=6.9-9.2** (cf)Av(SNR) ≈ 8
  - Massive (pre-)main sequence stars (B1.5-O8)

*AKARI 15μm, VLA 4.85GHz / Spitzer 5.8μm(B), AKARI 15μm(G), Spitzer 24μm(R)*

(Koo et al., 2008)
(Young) Stellar Sources around G54.1+0.3


(Koo et al. 2008) **YSOs whose formation was triggered by the progenitor of G54.1+0.3**

- SED (starlike+MIR/FIR excess) with a dip at 6-10\(\mu\)m
- Circumstellar disk far away from the central star, heated by the YSOs

(Temim et al. 2010) **Early-type stars belonging to a cluster in which the SN exploded**

- *Spitzer* IRS spectrum of the IR shell similar to the spectrum of freshly-formed dust in Cas A
- SN ejecta embedding these stars

- **NIR Spectroscopic Observation** to
  - Determine spectral type of the objects
  - Check whether **circumstellar disk exists** around the star
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**NIR Spectroscopic Observation**

- Determine **spectral type of the objects**
- Check whether **circumstellar disk exists** around the star
NIR Spectroscopic Observation of the YSOs

- **TripleSpec**, a slit-based NIR cross-dispersed echelle spectrograph, on the 5-m Palomar Hale telescope in Aug. 2008
- 1″×30″ slit, pix.scale= 0.234″/pix., $\lambda = 1 \sim 2.4\mu m$, $R = 2500-2700$
- 7 of 11 YSOs and A0V standard stars with similar airmass
  - one (#4) has been excluded from further process because it is too faint to obtain enough S/N.

*Spitzer* 5.8µm(B), *AKARI* 15µm(G), *Spitzer* 24µm(R)
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*TripleSpec spectral image*
2. Observation and Data Reduction

Data Reduction

- Preprocessing
- Wavelength solution
- Subtract background
- Extract spectrum
- Flux calibration
- Normalize
- Telluric + Detector response
2. Observation and Data Reduction

Data Reduction

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Observed standard star spectrum

Vega model spectrum (Colina et al., 1996)

Standard star model spectrum

Telluric lines + Detector response
2. Observation and Data Reduction

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Telluric + Detector response
NIR Spectra of the YSOs

- Strong hydrogen lines + moderate / detectable He I lines, but no He II lines → late O- and early B-type
- No emission-like features → negligible nearby circumstellar material
Equivalent width measurements using a Gaussian profile

Comparing with the EW measurements from other studies to determine the spectral type

**Hanson et al. 1996, 1998; Meyer et al. 1998; Bik et al. 2005; Lenorzer et al. 2004**

**Br11 1.681, He I 1.701, & Brγ 2.166**

### Equivalent Width Measurements

<table>
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<tr>
<th>No.</th>
<th>He I</th>
<th>Paβ</th>
<th>He I</th>
<th>Br14</th>
<th>Br13</th>
<th>Br12</th>
<th>Br11</th>
<th>He I</th>
<th>He I</th>
<th>Brγ</th>
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<tr>
<td>1</td>
<td>1.279</td>
<td>1.282</td>
<td>1.297</td>
<td>1.589</td>
<td>1.611</td>
<td>1.641</td>
<td>1.681</td>
<td>1.701</td>
<td>2.113</td>
<td>2.166</td>
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<td>5</td>
<td>2.10±0.37</td>
<td>3.14±0.38</td>
<td>0.56±0.25</td>
<td>4.84±1.57</td>
<td>3.24±0.94</td>
<td>2.55±0.73</td>
<td>1.77±0.65</td>
<td>1.00±0.30</td>
<td>0.78±0.45</td>
<td>7.41±1.80</td>
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<td>1.18±0.53</td>
<td>3.91±0.54</td>
<td>0.31±0.28</td>
<td>6.39±1.02</td>
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<td>3.70±0.57</td>
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<td>1.54±0.31</td>
<td>3.60±0.34</td>
<td>0.60±0.27</td>
<td>4.17±0.60</td>
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<td>1.47±0.40</td>
<td>3.46±0.46</td>
<td>0.35±0.22</td>
<td>5.68±1.06</td>
<td>6.30±0.94</td>
<td>3.49±0.63</td>
<td>4.14±0.77</td>
<td>1.22±0.30</td>
<td>1.29±1.02</td>
<td>4.54±1.44</td>
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<tr>
<td>11</td>
<td>1.77±0.46</td>
<td>3.59±0.56</td>
<td>1.29±0.51</td>
<td>5.83±1.16</td>
<td>7.73±1.14</td>
<td>2.97±0.73</td>
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<td>0.79±0.43</td>
<td>0.67±0.80</td>
<td>6.26±1.92</td>
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Spectral Type Classification

- Hydrogen lines are sensitive to temperature ➔ spectral type range for individual objects
- He I line is insensitive to temperature but disappears around B3. ➔ the spectral type of O7 - B3
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  - the spectral type of O7 - B3
3. Result.

Spectral Type Classification

- **Bri 1.681μm**
  - Hanson (98)
  - Meyer (98)
  - Lenorzer (04)
  - This work

- **Bry 2.166μm**
  - Hanson (96)
  - Lenorzer (04)
  - Bilt (05)
  - This work

- **He I 1.701μm**
  - Hanson (08)
  - Lenorzer (04) $v_{sys}=10\text{km/s}$
  - Lenorzer (04) $v_{sys}=20\text{km/s}$
  - This work

<table>
<thead>
<tr>
<th>No.</th>
<th>Sp. type</th>
<th>Temperature (K)</th>
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<tbody>
<tr>
<td>1</td>
<td>B0 - B3</td>
<td>30000 - 18700</td>
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<tr>
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<tr>
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<td>O8 - B3</td>
<td>34877 - 18700</td>
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<td>8</td>
<td>O9 - B1</td>
<td>32882 - 25400</td>
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<td>B0 - B2</td>
<td>30000 - 20900</td>
</tr>
<tr>
<td>11</td>
<td>B1 - B3</td>
<td>25400 - 18700</td>
</tr>
</tbody>
</table>

*Uncertainty of 3-5 subclasses due to low S/N and incomplete NIR spectral library*
4. Implications from this Work

Distance to the SNR

SED fitting using *Kurucz model* + *blackbody* with fixed temperature range derived from the spectra → **Distance & Extinction**

- $d_{\text{mean}} = 6.4 \pm 0.7 \text{ kpc} \ (4.2-7.6 \text{ kpc})$
- $9 \ (7.5-10) \text{kpc}$ from pulsar DM (*Camilo et al. 2002, Cordes-Lazio NE2001*)
- $8 \text{kpc} \ (Koo et al. 2008) \ / \ 6.2 \text{kpc} \ (Leahy et al. 2008)$ from HI spectrum and CO
- $A_V \text{mean} = 7.8 \pm 0.1 \ (7.7-8.0)$, except #7
- $8.4 \pm 0.5$ from X-ray absorbing H columns to the SNR (*Lu et al. 2002*)
4. Implications from this Work

**Progenitor Mass of the SNR**

- SED fitting with **fixed distance and Av** $\Rightarrow$ spectral type of 11 stars
  - **O9 - B2** (10-17$M_\odot$)

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**The progenitor of G54.1+0.3**

- To be a member of the same cluster *(Temim et al. 2010)*, the mass of the progenitor $\approx 17M_\odot$, but not be very massive ($\therefore$ no intermediate mass star)
  $\Rightarrow$ **SN IIP (?)** *(Chevalier 2005)*
NIR High-resolution Spectroscopy of Massive Stars

**Standard NIR spectral library of massive stars?**

- NIR spectra of massive stars are affected by **resolution, S/N, and their environments** (e.g. thermal contamination from nebular or circumstellar material)

- **Not many lines**: H, He I lines (+ He II and some metallic lines for mid/early-O) → difficult to use line ratio, especially for B stars, **only strength** is available.

To perform the **quantitative analysis of stellar profiles** *(Hanson et al. 2005)*

- **R ~ 10,000 & S/N > 150** are required.
5. High-resolution Spectroscopy & IGRINS

Spectroscopy of Massive Stars using IGRINS

- **High-resolution** (R ~ 40,000) enable
  - to resolve close lines (e.g. He I 2.112/2.113) and weak features (e.g. from wind)
  - to discriminate nebular emission produced by the surrounding H II region from the real stellar lines
  - to resolve underlying profiles of stars with low rotation or slow wind

- **NIR spectroscopy of Galactic O stars using IGRINS**
  - Galactic O star catalogue (*Maíz Apellániz et al. 2004; Sota et al. 2008*)
    - selected on the **optical spectroscopy alone**
    - **369 O stars + 8 WR+O system** + additional candidates (*June 2009, ver.2.2*)
  - To achieve S/N > 150 for K ~ 10 mag., 1 hr. integration on 2.7-m telescope
    - (*Dan Jaffe*) ~ 50 nights with IGRINS on 2.7-m telescope

- **High quality NIR spectral library of well-known O stars**
  - the study of massive stars in star forming regions or deeply embedded, distant massive stars with large visual extinction which are not observed in optical wavelengths
NIR spectroscopy of stellar sources around the G54.1+0.3 showed that they are O8-B3(O9-B2?) stars

- Distance to the SNR = 6.4 ± 0.7 kpc, Av = 7.8 ± 0.1
- This result constrains the progenitor mass of the SNR as ≳ 17M⊙ if it were a member of the star cluster ~ SN IIP origin.

Since there is currently no standard NIR spectral library of massive stars, determination of spectral type of stars using NIR spectra is difficult, and performing a quantitative analysis of stellar spectra requires high resolution ( > 10,000) and high S/N ( > 150).

Using IGRINS, we can construct a NIR high-resolution spectral library with high S/N of optically well-known Galactic O stars and WR+O system which is essential for the future study of deeply embedded, distant massive stars.