High-mass star formation in the HII region RCW 34

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HII region RCW 34

- Ring-like gas/dust distribution
- High velocity flow (Hα) from the north to south (Hydari-Malayeri88)
• Sequential star formation from the south to north (Bik+10)
  – Triggering formations of massive stars and YSOs
  – Age gradient is not clear
  – Hard to explain the formation of YSOs in the southern region
  – Initial condition is not clear

• Cloud-cloud collision (CCC)
  – Gravitationally unbound system (adaptable initial condition)
  – Easy for high mass accretion rate
1. Reveal the high-mass star-formation process in RCW 34 focussing on the CCC model
2. Investigate possible relations to other CCC candidates

=> Constraints on processes of the high-mass star formation and evolution of the ISM and star formation in the Galactic scale.
Data Used in This Study

<table>
<thead>
<tr>
<th></th>
<th>NANTEN2</th>
<th>ASTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO lines</td>
<td>12CO(J=2-1) 13CO(J=2-1)</td>
<td>12CO(J=3-2)</td>
</tr>
<tr>
<td>Observational date</td>
<td>2015/10,11</td>
<td>2015/11</td>
</tr>
<tr>
<td>View size</td>
<td>15’x15’</td>
<td>7.5’x7.5’</td>
</tr>
<tr>
<td>Beam size</td>
<td>90”</td>
<td>24”</td>
</tr>
<tr>
<td>Velocity resolution</td>
<td>0.5 km/s</td>
<td>0.3 km/s</td>
</tr>
<tr>
<td>Noise level</td>
<td>~0.3-0.5 K/ch</td>
<td>~0.3 K/ch</td>
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</table>
Gas distribution similar to the 8 µm ring
Faint emission in 12CO from the bubble; no significant signals in 13CO
O (and two B) star is located near the CO peak
• Two velocity components: 0-10 km/s (blue cloud), 10-14 km/s (red cloud)
  – blue cloud: ring-like structure with two peaks (at north and south)
  – red cloud: faint diffuse emission (no significant detection ever)
Comparison of Blue and Red Clouds

- Complementary gas distribution between the blue and red clouds
  - Red cloud covers the northern part of the bubble.
  - O star is located at the boundary between the two clouds
- Confirming two velocity profiles in the position-velocity map
12CO(J=3-2) Velocity Channel Map

- Elongated/clumpy gas structures
- Low significant diffuse emission in the bubble
High line intensity ratio (>1) around the O star
Velocity Spectrum

- Bridging feature connecting the two clouds
12CO(J=3-2) & 8μm Dust Emission

- Good correspondence between clumpy gas structures and 8 um emission
Molecular gas mass

- Assuming the line intensity ratio and $X_{\text{co}}$
  
  » $^{12}\text{CO}(J=2-1)/(1-0) = 0.6$ (Yoda+10)
  
  » $X_{\text{co}} = 1.0 \times 10^{21} \, \text{cm}^{-2} \, \text{K}^{-1} \, \text{km}^{-1} \, \text{s}$ (Okamoto+17)

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<tr>
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<th>Blue cloud</th>
<th>Red cloud</th>
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<tr>
<td>peak $N_{\text{H}_2} , (\text{cm}^{-2})$</td>
<td>$1.1 \times 10^{22}$</td>
<td>$1 \times 10^{21}$</td>
</tr>
<tr>
<td>Mass ($M_{\text{sun}}$)</td>
<td>$\sim1.4 \times 10^4$</td>
<td>$\sim600$</td>
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• Molecular gas mass
  – Assuming the line intensity ratio and $X_{\text{co}}$
    » $12\text{CO}(J=2-1)/(1-0) = 0.6$ (Yoda+10)
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      (Okamoto+17)

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<td>Mass ($M_{\odot}$)</td>
<td>$\sim 1.4 \times 10^4$</td>
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• Complementary gas distribution of the two clouds
• Good correspondence between the gas and 8µm distributions
• High-mass (single O and two early B type) stars are located nearby the boundary between the two clouds
• Gas disruption due to strong UV radiation from the high-mass stars
• Bridging feature connecting the two clouds.
• High line intensity ratio (>1) around the high-mass stars
  => Physical association between the gas and high-mass stars

High-mass stars in RCW 34 are possibly triggered by CCC
Comparison with Numerical Simulation

- Numerical simulation of CCC (Takahira+14; Haworth+15a/b)
  - Synthetic observation (12CO(J=1-0))
  - Supersonic collision of isotropic two clouds with difference size
  - Inverted V-shaped and cavity-like structures similar to the observational results

\[ V = 10 \text{ km/s} \]

Simulation

\[ t = 1.6 \text{ Myr}, V = 7 \text{ km/s} \]

12CO(J=2-1)

- Follow-up observations (Mopra, ALMA)
- More realistic simulation following the observational results
Collision Time Scale

- Displacement of the molecular cloud ($\Delta = 1$ pc)
  - Further morphological correspondence

- Velocity difference ($V_{lsr} = 5$ km/s)
  - Collision angle ($\theta = 30$-60 deg)
  => Collision time scale
  $\Delta t = (0.1$-$0.35)$ Myr

=> Time scale to form the O star < ~0.2 Myr

- Time scale to form class I objects
  - a few $\times 10^5$ yr (Whitney+03)
  - Formation of YSOs possibly trigged by CCC
### Comparison with Other CCC Candidates

<table>
<thead>
<tr>
<th>Name</th>
<th>Number of O stars</th>
<th>Cloud Mass</th>
<th>Molecular Column Density</th>
<th>Relative Velocity</th>
<th>Collision Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCW 38</td>
<td>~20</td>
<td>(30, 2)</td>
<td>(10, 1)</td>
<td>12</td>
<td>~0.1</td>
</tr>
<tr>
<td>NGC 3603</td>
<td>~30</td>
<td>(70, 10)</td>
<td>(10, 1)</td>
<td>15</td>
<td>~1</td>
</tr>
<tr>
<td>RCW 120</td>
<td>1 (O8V or O9V)</td>
<td>(50, 4)</td>
<td>(3, 0.8)</td>
<td>20</td>
<td>~0.2</td>
</tr>
<tr>
<td>M20</td>
<td>1 (O7.5)</td>
<td>(1, 1)</td>
<td>(1, 1)</td>
<td>7.5</td>
<td>~0.3</td>
</tr>
<tr>
<td>RCW 34</td>
<td>1 (O8.5V)</td>
<td>(14, 0.6)</td>
<td>(1.1, 0.1)</td>
<td>5</td>
<td>~0.2</td>
</tr>
<tr>
<td>RCW 36</td>
<td>2(O9V &amp; O9.5V)</td>
<td>(5, 1)</td>
<td>(0.3, 0.7)</td>
<td>5</td>
<td>~0.2</td>
</tr>
</tbody>
</table>

- Massive star-forming cluster => $N_{H_2} = \sim 10^{23} \text{ cm}^{-2}$
- HII region with one or two O stars => $N_{H_2} = \sim 10^{22} \text{ cm}^{-2}$
- Similar time scale to form massive stars in the VMR => Possible correlation with the formation of the whole system
• Molecular gas distribution in the HII region RCW 34 with 12CO(J=2-1), (J=3-2) and 13CO(J=2-1) lines using the NANTEN2 and ASTE telescopes.
• We found two molecular clouds with different velocities, 0-10 km/s and 10-14 km/s
  – Complementary spatial distribution
  – Physically association with O star (Line intensity ratio and 8µm emission)
=> High-mass star-formation possibly triggered by CCC
• Consistent results with a numerical simulation
• Collisional time scale estimated from the velocity difference
  => Time scale to form the high-mass star is <~0.2 Myr

Future Plan
• Observation with high spatial resolution and wide field of view.
  – 12CO(J=1-0) with Mopra、Southern region with ASTE
  – High spatial resolution with ASTE => filamentary gas distribution
• More realistic simulation based on the observational results
Back Up
Motivation

- Models of high-mass star formation
  - Core accretion, Competitive accretion, Collect & Collapse

- Cloud-cloud collision (CCC)
  - Gravitationally unbound system (adaptable initial condition)
  - Easy for high mass accretion rate

- High-mass star-forming regions in the Vela Molecular Ridge (VMR)
  - RCW 38 (Fukui+16) / RCW 36 (Sano+18) / RCW 32 (Enokiya+18)

=> High-mass star-formation possibly triggered by CCC

Explore the CCC scenario for RCW 34

=> Revealing the high-mass star-forming process and evolitional processes of the ISM/stars in the Galactic scale.
Collect & Collapse

• More clumps (YSOs) should be observed in the southern area of the O star

Sequential star formation from the south to north (Bik+10)

• Unclear age gradient
• Hard to explain the formation of YSOs.