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Class I methanol masers in G343.12-0.06

Maxim Voronkov

Australia Telescope National Facility
Class I methanol masers in

IRAS 16547-4247

Maxim Voronkov

Australia Telescope National Facility
Other people contributed to the project

VLT Observations, Infrared data
K.J. Brooks
S.P. Ellingsen

Evolutionary stages/analysis
J.L. Caswell

Modelling
A.M. Sobolev
A.B. Ostrovskii

104 GHz survey (Mopra/Onsala)
G.M. Larionov
A.V. Alakoz
\[ \Delta J = 0, \pm 1 ; \Delta K = \pm 1 \]
\[ \Delta J = \pm 1 ; \Delta K = 0 \]
\[ J_{-2} - J_{1} \text{ series at } \sim 101 \text{ GHz} \]

\[ \Delta J = 0, \pm 1 ; \Delta K = \pm 1 ; A^\pm \leftrightarrow A^\mp \]
\[ \Delta J = \pm 1 ; \Delta K = 0 ; A^\pm \leftrightarrow A^\mp \]
\[ \Delta J = 0 ; \Delta K = 0 ; A^\pm \leftrightarrow A^\mp \]
### Known Class I maser transitions

<table>
<thead>
<tr>
<th>Transition</th>
<th>Frequency (GHz)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9_{-1} - 8_{-2}$ E</td>
<td>9.9</td>
<td>Slysh et al. (1993)</td>
</tr>
<tr>
<td>$J_2 - J_1$ E series</td>
<td>$\sim 25$</td>
<td>Barrett et al. (1971); Menten et al. (1986)</td>
</tr>
<tr>
<td>$4_{-1} - 3_0$ E</td>
<td>36</td>
<td>Turner (1972)</td>
</tr>
<tr>
<td>$7_0 - 6_1$ A$^+$</td>
<td>44</td>
<td>Haschick et al. (1990)</td>
</tr>
<tr>
<td>$5_{-1} - 4_0$ E</td>
<td>84</td>
<td>Zuckerman et al. (1972)</td>
</tr>
<tr>
<td>$8_0 - 7_1$ A$^+$</td>
<td>95</td>
<td>Ohishi et al. (1986)</td>
</tr>
<tr>
<td>$11_{-1} - 10_{-2}$ E</td>
<td>104</td>
<td>Voronkov et al. (2005)</td>
</tr>
<tr>
<td>$6_{-1} - 5_0$ E</td>
<td>133</td>
<td>Slysh et al. (1997)</td>
</tr>
<tr>
<td>$9_0 - 8_1$ A$^+$</td>
<td>146</td>
<td>Menten (1991a)</td>
</tr>
<tr>
<td>$8_{-1} - 7_0$ E</td>
<td>229</td>
<td>Slysh et al. (2002)</td>
</tr>
</tbody>
</table>
Two classes of methanol masers

- **Class I**
  - 84 GHz
  - Seen apart from IR, UCHII, etc
  - Orion (OMC-1)

- **Class II**
  - 6.7 GHz
  - Associated with IR, UCHII, etc
  - W3(OH)
E-Methanol energy level diagram

The situation with the 9.9 GHz masers was similar. Slysh et al. (ApJ, 1994, 268, 464) detected a maser in W33-Met and 2 broad line sources out of 11 targets observed.
- New **104 GHz** observations with the Mopra radio telescope: two new masers, 5 marginal detections and 3 broad line sources out of 69 targets observed.

- Test ATCA observations at **9.9 GHz** towards **104 GHz** masers: one definite and one marginal maser detection. A normal survey: 3 more new masers out of 40 targets observed.
An ATCA search for 25 GHz masers

- J₂-J₁ E series
- These masers were believed to be rare (only 4 masers were known prior to this work).
- ATCA observations of the J=5 transition brought 67 detections out of 102 targets observed
An ATCA search for 25 GHz masers

- $J_2-J_1$ E series
- These masers were believed to be rare (only 4 masers were known prior to this work).
- ATCA observations of the $J=5$ transition brought 67 detections out of 102 targets observed.
- There is no flux correlation with the widespread class I masers at 44 and 95 GHz.
This is the only source, where masers were detected in all observed class I methanol maser transitions.

The source harbours a highly energetic collimated molecular outflow driven by a radio jet.

In total, 12 maser transitions were observed in a short period of time: 9.9 GHz, 25 GHz (a series J=2 to J=9), 84 GHz, 95 GHz, and 104 GHz.

Such observations are very important for maser modelling, but have never been done before.

This is the first interferometric observation of the 9.9 and 104 GHz masers.

This is the first detection of the 84 GHz maser as well as 7 transitions of the 25 GHz series in G343.12-0.06.
- Only one spot (B) is active in all observed transitions
- The three most southern spots show a clear association with the shocked gas traced by the H$_2$ 2.12 $\mu$m emission associated with the radio jet and their velocities are close to that of the molecular core within which the jet is embedded
The rest frequency for the $9_{-1} - 8_{-2}$ E transition should be refined to $9936.2007 \pm 0.0007$.

Brightness temperature exceeds $5.3 \times 10^7$ and $2.0 \times 10^4$ K at 9.9 and 104 GHz, respectively.
Masers at 84 and 95 GHz

\[ F(95 \text{ GHz}) = (2.1 \pm 0.3) \times F(84 \text{ GHz}) + (2.6 \pm 2.5) \]

- The additive term is not statistically significant.
- The slope has an additional uncertainty of 30\% (about 0.6) related to the absolute flux scale calibration.
- In DR 21, the 95-GHz maser is approximately 5.5 times brighter than the 84-GHz maser (Batrla & Menten, 1988; Plambeck & Menten, 1990).
$R$ is the ratio of the integrated flux density to that of the J=5 transition at 25 GHz, $\tau$ is the optical depth and $T_b$ is the brightness temperature.

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\nu$ (GHz)</th>
<th>$\log(R)$</th>
<th>$\log(T_b, K)$</th>
<th>$\tau$</th>
<th>$\log(R)$</th>
<th>$\log(T_b, K)$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9_1 - 8_2$ E</td>
<td>9.9</td>
<td>0.2</td>
<td>8.92</td>
<td>17.9</td>
<td>0.2</td>
<td>8.81</td>
<td>19.1</td>
</tr>
<tr>
<td>$2_2 - 2_1$ E</td>
<td>25</td>
<td>-1.8</td>
<td>6.34</td>
<td>-10.1</td>
<td>-2.0</td>
<td>5.29</td>
<td>-9.9</td>
</tr>
<tr>
<td>$3_2 - 3_1$ E</td>
<td>25</td>
<td>-0.1</td>
<td>7.98</td>
<td>-13.7</td>
<td>-0.4</td>
<td>7.36</td>
<td>-14.6</td>
</tr>
<tr>
<td>$4_2 - 4_1$ E</td>
<td>25</td>
<td>0.1</td>
<td>8.27</td>
<td>-14.2</td>
<td>-0.1</td>
<td>7.56</td>
<td>-15.0</td>
</tr>
<tr>
<td>$5_2 - 5_1$ E</td>
<td>25</td>
<td>0</td>
<td>8.34</td>
<td>-14.3</td>
<td>0</td>
<td>7.55</td>
<td>-14.9</td>
</tr>
<tr>
<td>$6_2 - 6_1$ E</td>
<td>25</td>
<td>0.1</td>
<td>8.43</td>
<td>-14.5</td>
<td>0.1</td>
<td>7.36</td>
<td>-14.5</td>
</tr>
<tr>
<td>$7_2 - 7_1$ E</td>
<td>25</td>
<td>0</td>
<td>8.47</td>
<td>14.7</td>
<td>0.1</td>
<td>7.00</td>
<td>13.7</td>
</tr>
<tr>
<td>$8_2 - 8_1$ E</td>
<td>25</td>
<td>0.1</td>
<td>8.45</td>
<td>14.7</td>
<td>0.1</td>
<td>6.27</td>
<td>12.2</td>
</tr>
<tr>
<td>$9_2 - 9_1$ E</td>
<td>25</td>
<td>-0.3</td>
<td>8.45</td>
<td>-14.8</td>
<td>0.1</td>
<td>5.36</td>
<td>-10.2</td>
</tr>
</tbody>
</table>

- It is hard to explain relative brightnesses of the 25 GHz series simultaneously with the 84, 95 and 104 GHz transitions.
- Gradients? If yes, the projected scale is less than 300 AU.
- No 6.7 GHz maser has been detected in this source, although there are H$_2$O and OH masers near the central source.

- Ellingsen (2006, ApJ, 638, 241) has found that the sources associated with class I masers have redder GLIMPSE colours $\Rightarrow$ they are younger.

- The OH maser is present $\Rightarrow$ an evolved stage.

- Is the source too young or too old to have a 6.7 GHz maser?
The source driving jet/outflow/masers has no associated GLIMPSE source.

Another bright source is present in the 5.8-\(\mu m\) and 3.6-\(\mu m\) GLIMPSE images. This source dominates in the 12-\(\mu m\) MSX band as well.

The 21-\(\mu m\) emission is centred on the central continuum source \(\Rightarrow\) it is deeply embedded and young.
- Warm dense gas, rich in methanol is enough for class I masers ⇒ they can appear at the very early evolutionary stage
- Class I masers do not depend on shocks once the methanol abundance is increased ⇒ they can last long
- Class II masers need an infrared source for pumping ⇒ they are located near the (proto)star and can be destroyed more easily.
Summary

- The class I methanol maser emission consists of a cluster of 6 spots spread over an area of 30" in extent. Five spots were detected in only the 84- and 95-GHz transitions (for two spots the 84-GHz detection is marginal), while the sixth spot shows activity in all 12 observed transitions.

- The three most southern maser spots show clear association with a jet-driven molecular outflow. Their velocities are close to that of the molecular core within which the jet is embedded. This fact supports the idea that the class I masers reside in the interface regions of outflows.

- Comparison with OH and H$_2$O masers, infrared data, and the lack of class II methanol maser at 6.7 GHz suggest that the evolutionary stage where the class I masers are present may last longer than that with the class II masers. The evolutionary status of this source is not clear at present: the presence of the OH masers usually means that the source is evolved, but the infrared data suggest otherwise.

- We report the first interferometric observations of the rare 9.9- and 104-GHz masers. It is shown that the spectra contain a very narrow spike and the brightness temperature exceeds $5.3 \times 10^7$ and $2.0 \times 10^4$ K at 9.9 and 104 GHz, respectively.

- High spectral resolution data leads us to suggest that the rest frequency for the $9_{-1} - 8_{-2}$ E transition should be refined to $9936.2007 \pm 0.0007$. 