This slide is intentionally blank

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

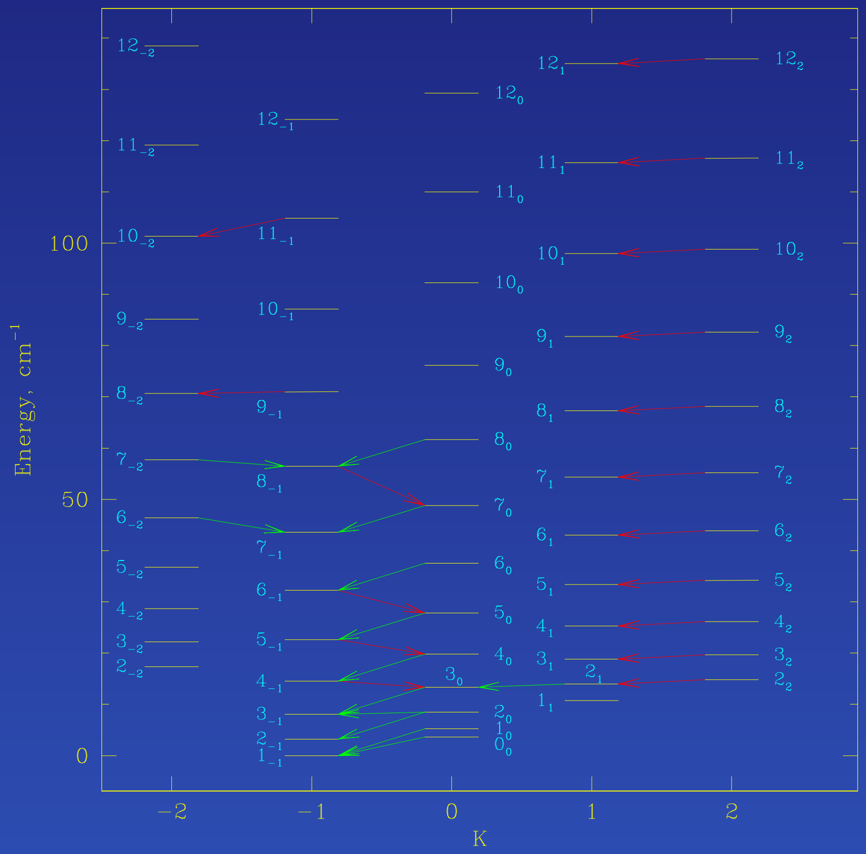
104 GHz survey(Mopra/Onsala)

G.M. Larionov

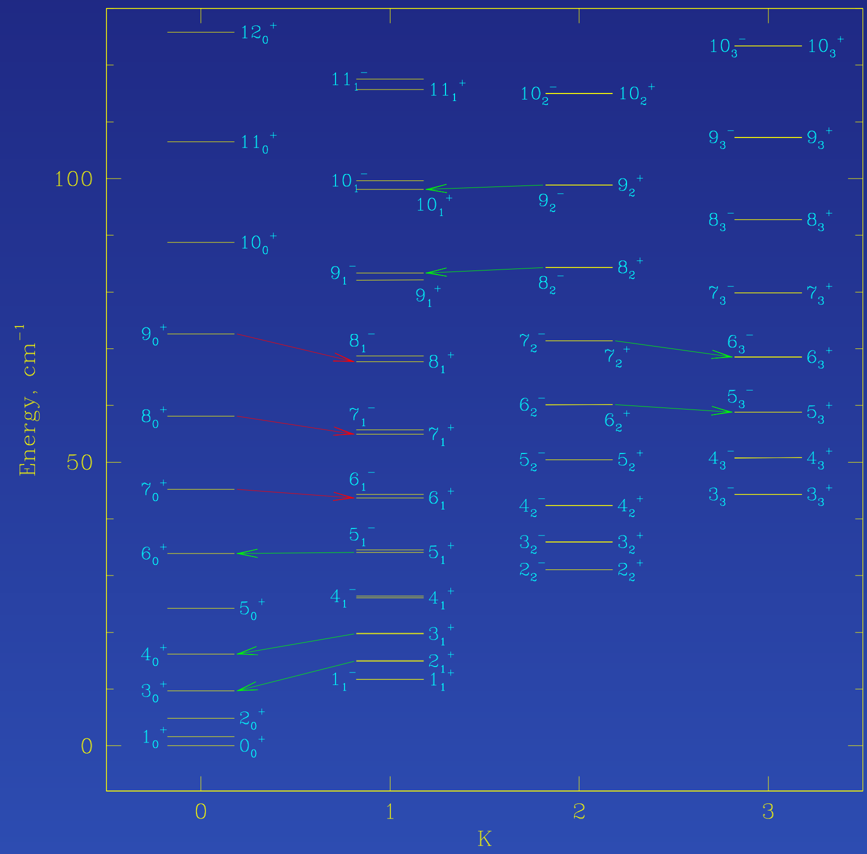
A.V. Alakoz

Energy levels

E-methanol



A-methanol



$\Delta J = 0, \pm 1 \; ; \; \Delta K = \pm 1$

$\Delta J = \pm 1 \; ; \; \Delta K = 0$

$J_{-2} - J_1$ series at $\sim$ 101 GHz

$\Delta J = 0, \pm 1 \; ; \; \Delta K = \pm 1 \; ; \; A^{\pm} \leftrightarrow A^{\pm}$

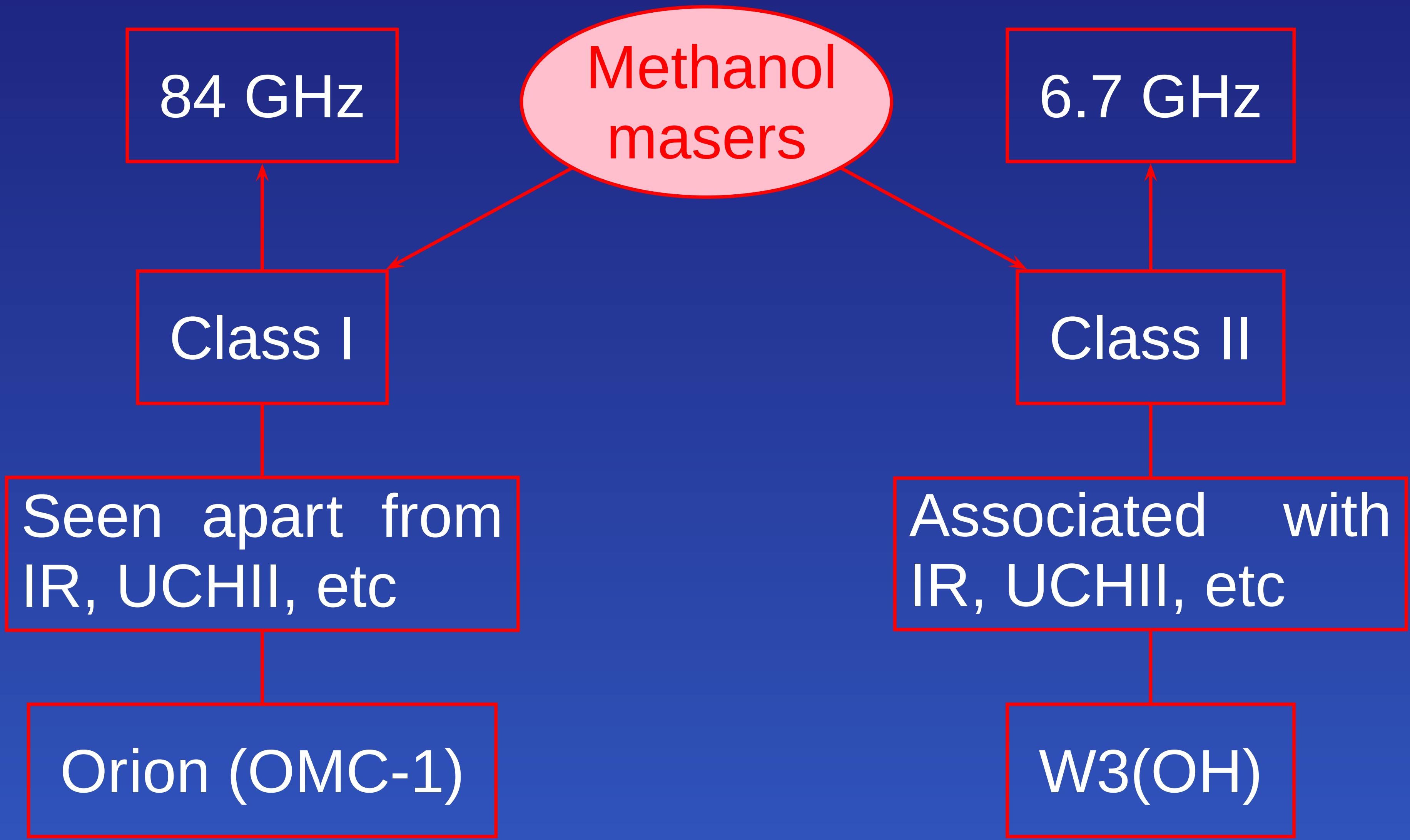
$\Delta J = \pm 1 \; ; \; \Delta K = 0 \; ; \; A^{\pm} \leftrightarrow A^{\pm}$

$\Delta J = 0 \; ; \; \Delta K = 0 \; ; \; A^{\pm} \leftrightarrow A^{\mp}$

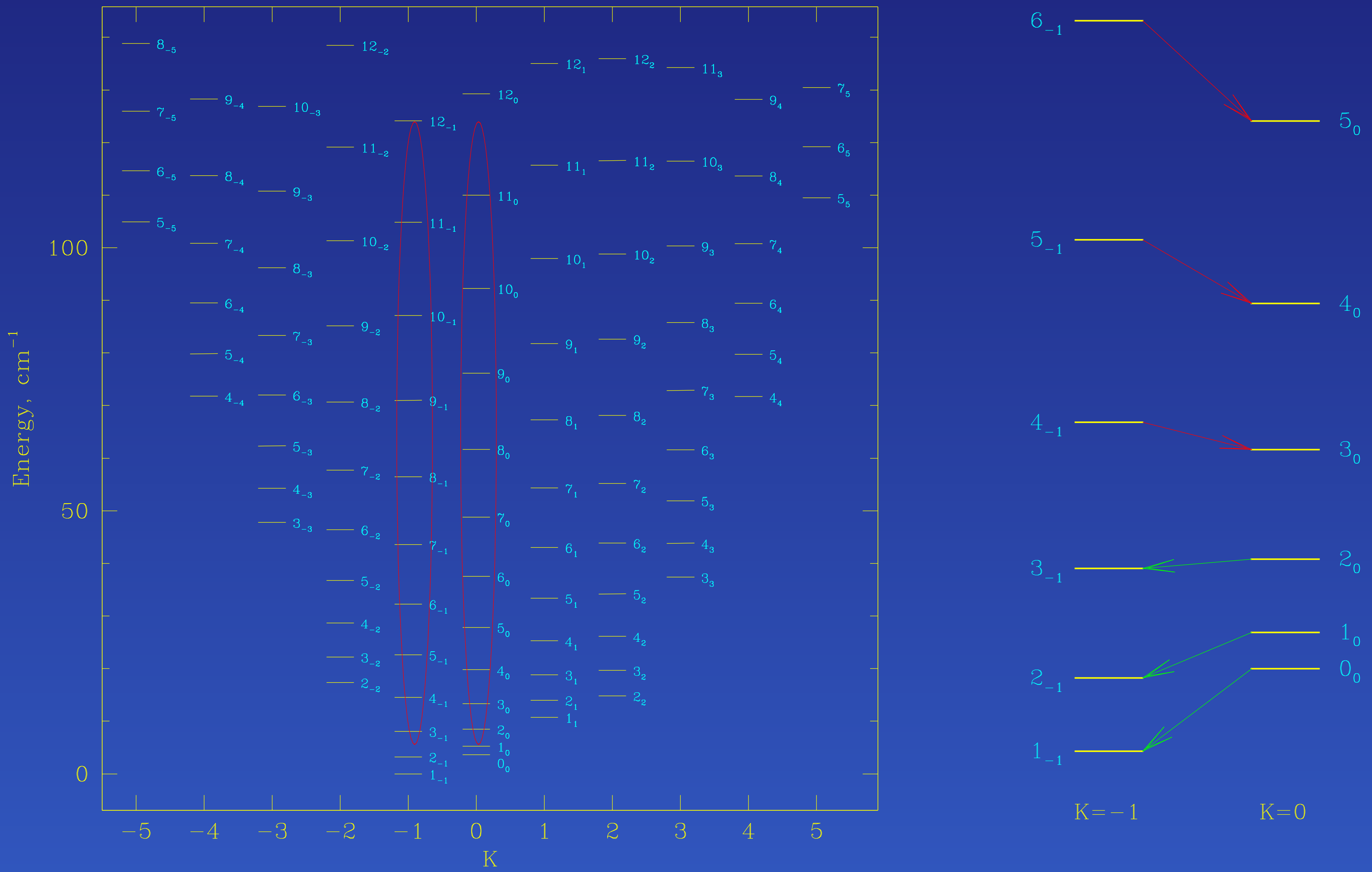
Known Class I maser transitions

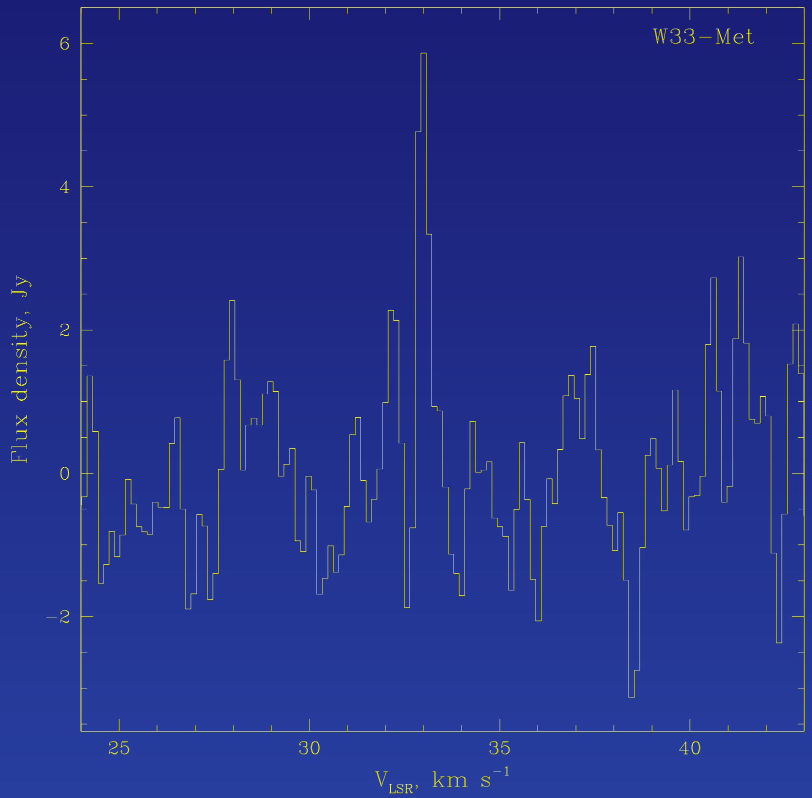
Transition	Frequency GHz	Reference
$9_{-1}-8_{-2}$ E	9.9	Slysh et al. (1993)
J_2–J_1 E series	~25	Barrett et al. (1971); Menten et al. (1986)
$4_{-1}-3_0$ E	36	Turner (1972)
7_0-6_1 A^+	44	Haschick et al. (1990)
$5_{-1}-4_0$ E	84	Zuckerman et al. (1972)
8_0-7_1 A^+	95	Ohishi et al. (1986)
$11_{-1}-10_{-2}$ E	104	Voronkov et al. (2005)
$6_{-1}-5_0$ E	133	Slysh et al. (1997)
9_0-8_1 A^+	146	Menten (1991a)
$8_{-1}-7_0$ E	229	Slysh et al. (2002)

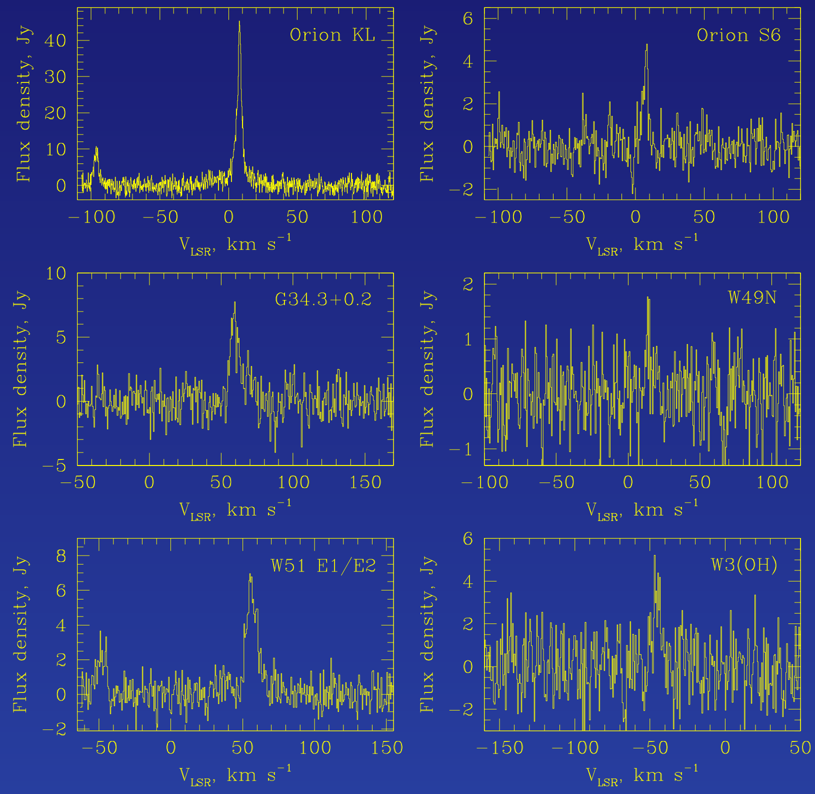
Two classes of methanol masers



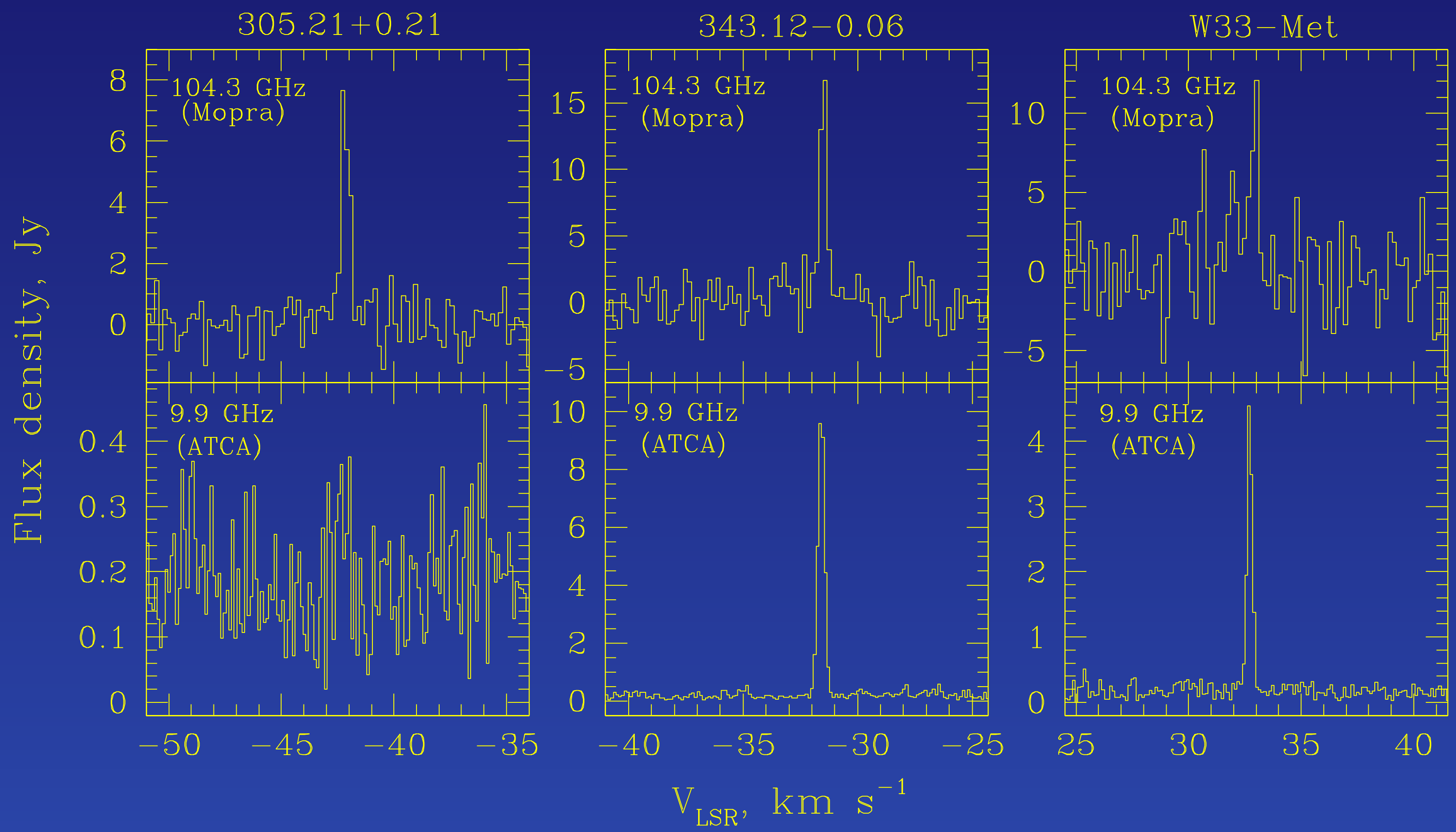
E-Methanol energy level diagram





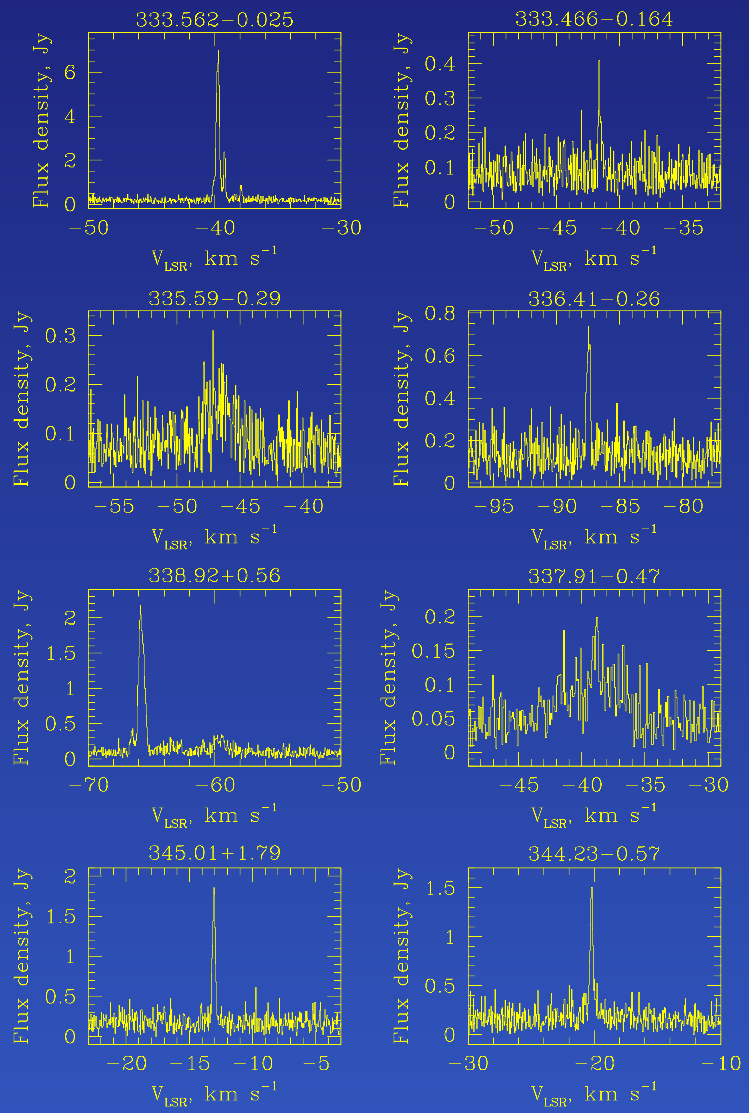


- A “northern” search for the 104 GHz masers brought only one obvious maser in W33-Met and 6 broad line sources (Voronkov et al., ApSS, 2005, 295, 217; astro-ph/0407275) out of 39 targets observed
- The situation with the 9.9 GHz masers was similar. Slysh et al. (ApJ, 1994, 268, 464) detected a maser in W33-Met and 2 broad line sources out of 11 targets observed



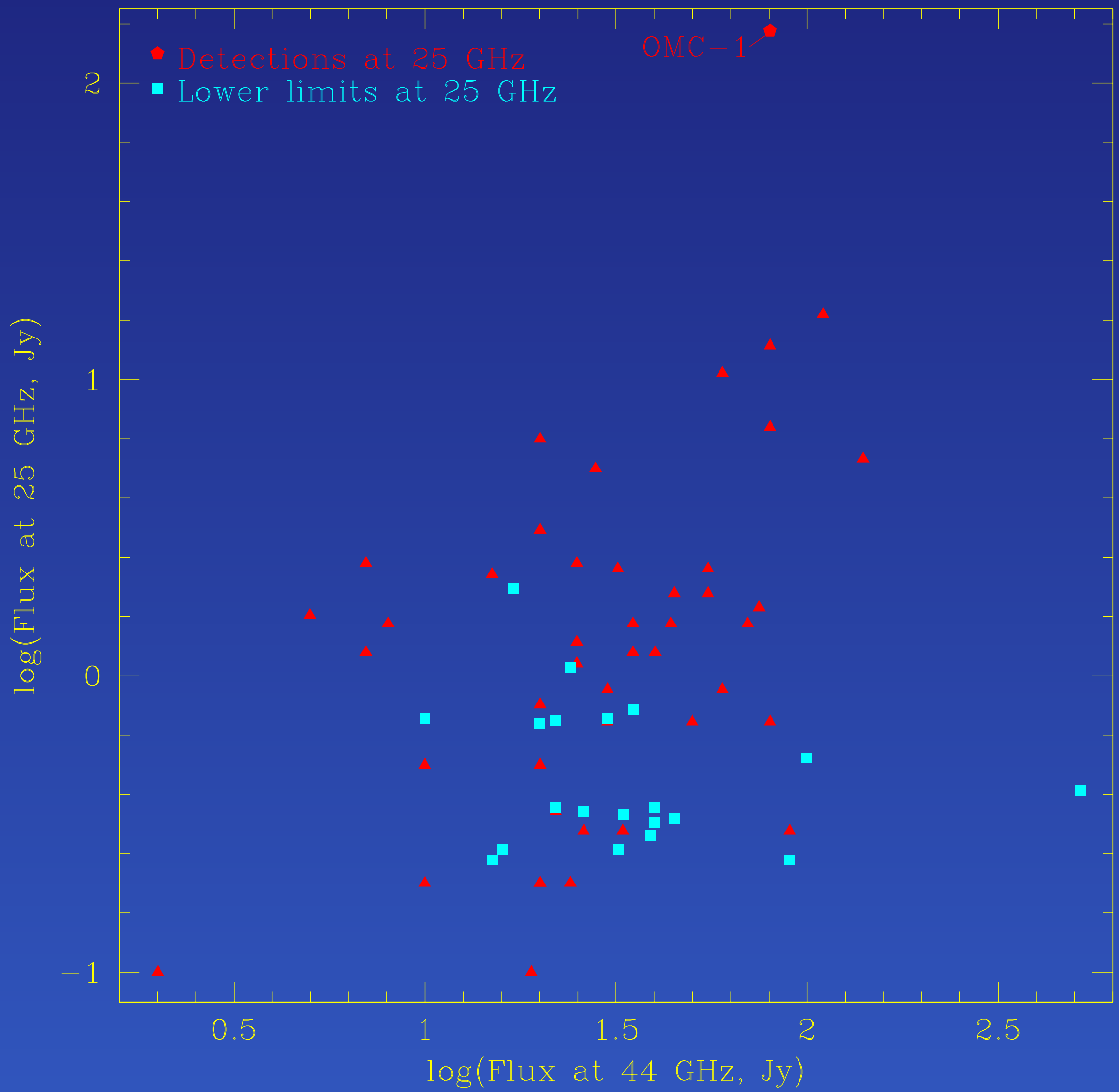
- New 104 GHz observations with the Mopra radio telescope: two new masers, 5 marginal detections and 3 broad line sources out of 69 targets observed
- Test ATCA observations at 9.9 GHz towards 104 GHz masers: one definite and one marginal maser detection. A normal survey: 3 more new masers out of 40 targets observed.

An ATCA search for 25 GHz masers



- 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

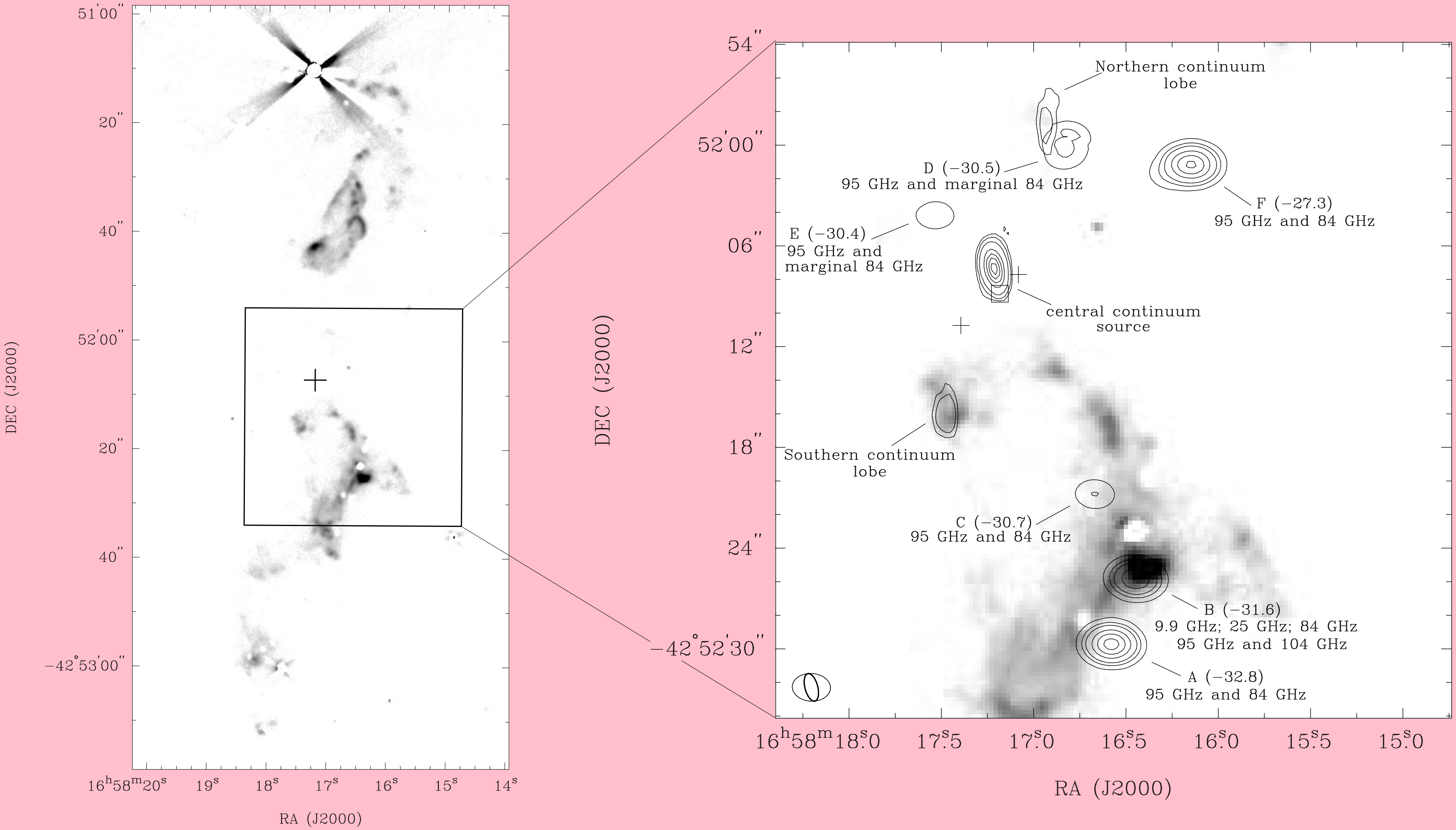
An ATCA search for 25 GHz masers



- 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.

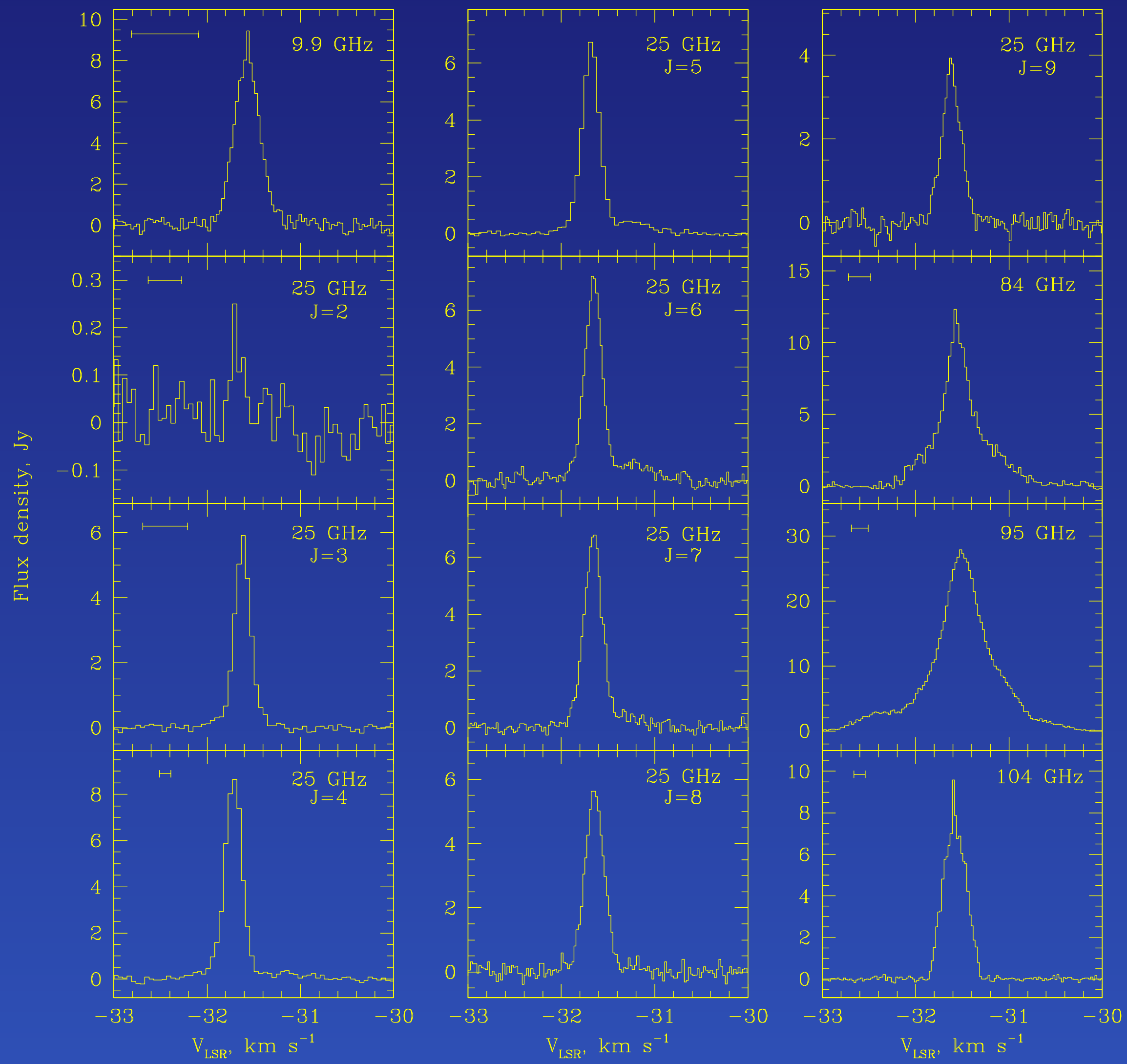
ATCA observations of G343.12-0.06

- 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.



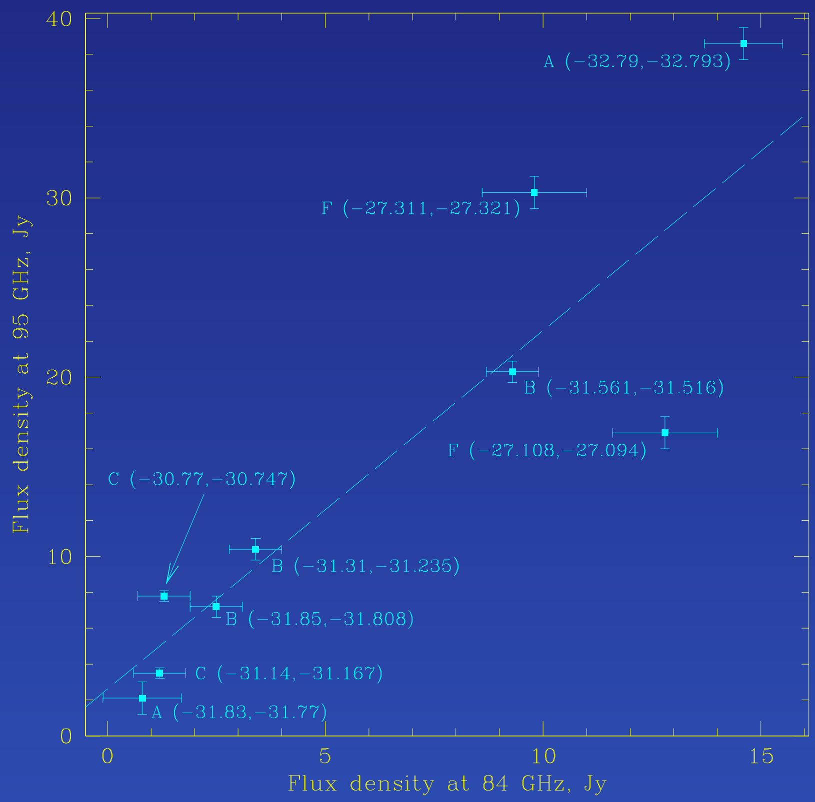
- Only one spot (B) is active in all observed transitions
- The three most southern spots show a clear association with the shocked gas traced by the H_2 2.12 μm emission associated with the radio jet and their velocities are close to that of the molecular core within which the jet is embedded

Spectra of the spot B



- The rest frequency for the $9_{-1} - 8_{-2}$ E transition should be refined to 9936.2007±0.0007.
- Brightness temperature exceeds 5.3×10^7 and 2.0×10^4 K at 9.9 and 104 GHz, respectively.

Masers at 84 and 95 GHz



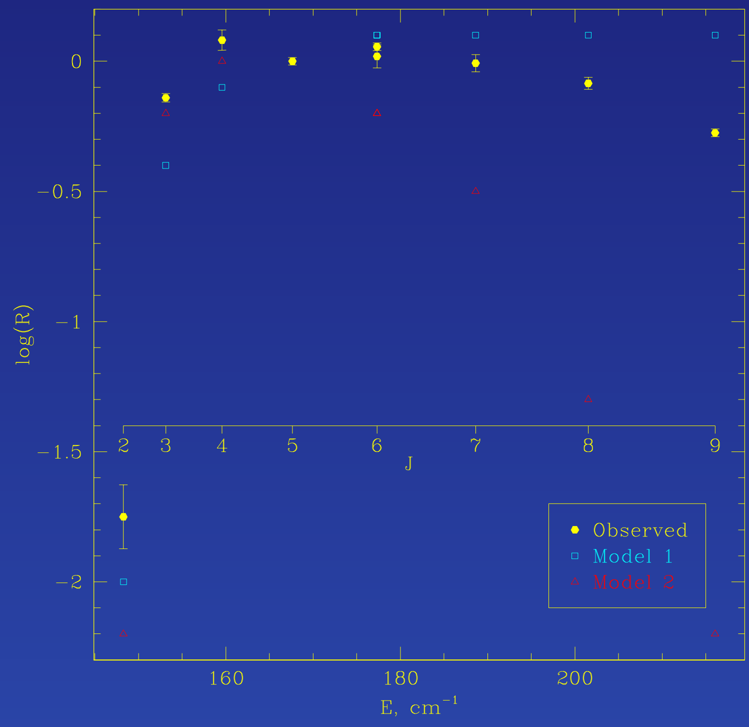
$$F(\text{95 GHz}) =$$
$$(2.1 \pm 0.3) \times F(\text{84 GHz}) + (2.6 \pm 2.5)$$

- 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).

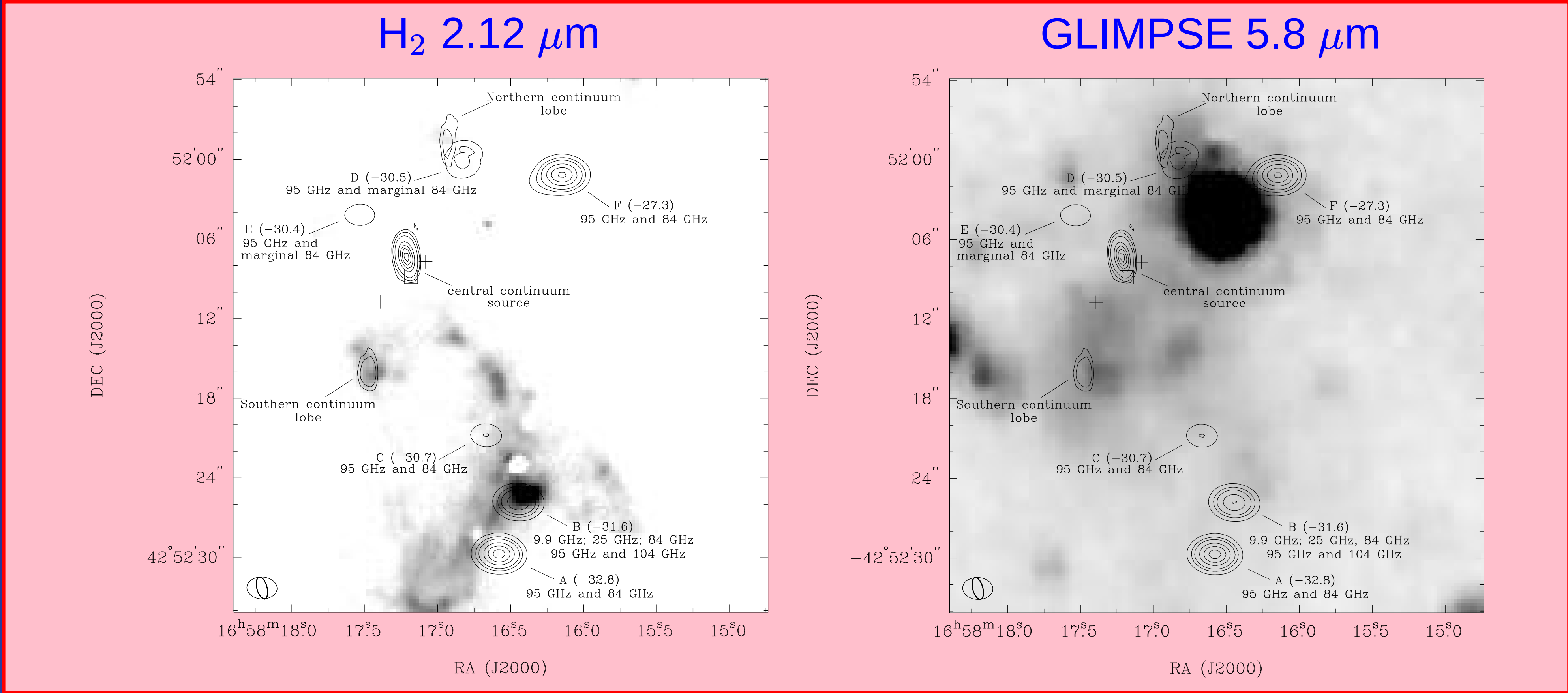
Maser models

R is the ratio of the integrated flux density to that of the J=5 transition at 25 GHz, τ is the optical depth and T_b is the brightness temperature.

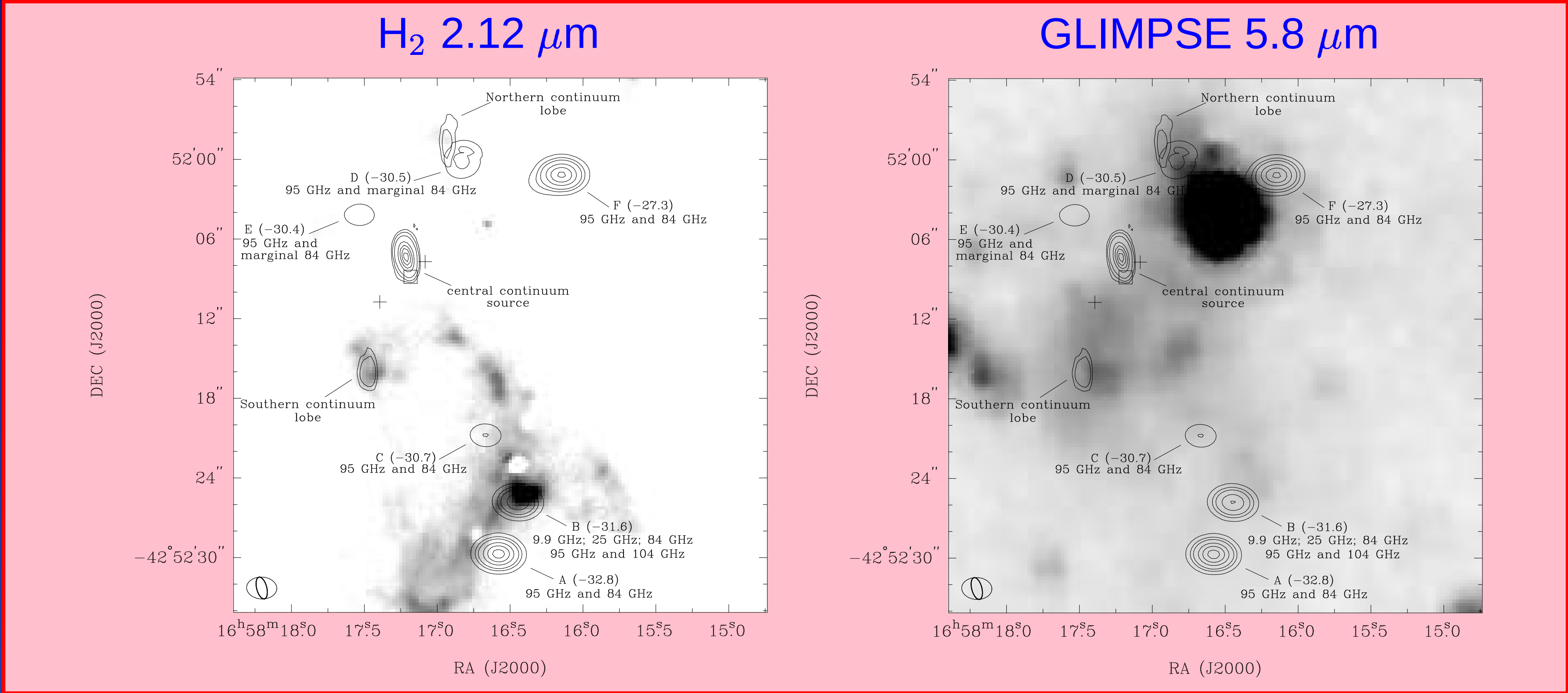
Transition	ν	Observed	Model 1			Model 2		
	(GHz)	$\log(R)$	$\log(T_b, K)$	τ	$\log(R)$	$\log(T_b, K)$	τ	$\log(R)$
$9_{-1} - 8_{-2}$ E	9.9	0.2	8.92	−17.9	−0.2	8.81	−19.1	0.5
$2_2 - 2_1$ E	25	−1.8	6.34	−10.1	−2.0	5.29	−9.9	−2.2
$3_2 - 3_1$ E	25	−0.1	7.98	−13.7	−0.4	7.36	−14.6	−0.2
$4_2 - 4_1$ E	25	0.1	8.27	−14.2	−0.1	7.56	−15.0	0
$5_2 - 5_1$ E	25	0	8.34	−14.3	0	7.55	−14.9	0
$6_2 - 6_1$ E	25	0.1	8.43	−14.5	0.1	7.36	−14.5	−0.2
$7_2 - 7_1$ E	25	0	8.47	−14.7	0.1	7.00	−13.7	−0.5
$8_2 - 8_1$ E	25	−0.1	8.45	−14.7	0.1	6.27	−12.2	−1.3
$9_2 - 9_1$ E	25	−0.3	8.45	−14.8	0.1	5.36	−10.2	−2.2
$5_{-1} - 4_0$ E	84	0.5	2.38	20.9	−4.9	6.95	−12.3	0.5
$8_0 - 7_1$ A^+	95	1.0	1.95	71.9	−5.2	6.83	−11.9	0.4
$11_{-1} - 10_{-2}$ E	104	0.1	2.93	1.2	−4.2	5.58	−10.7	−0.7



- 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.

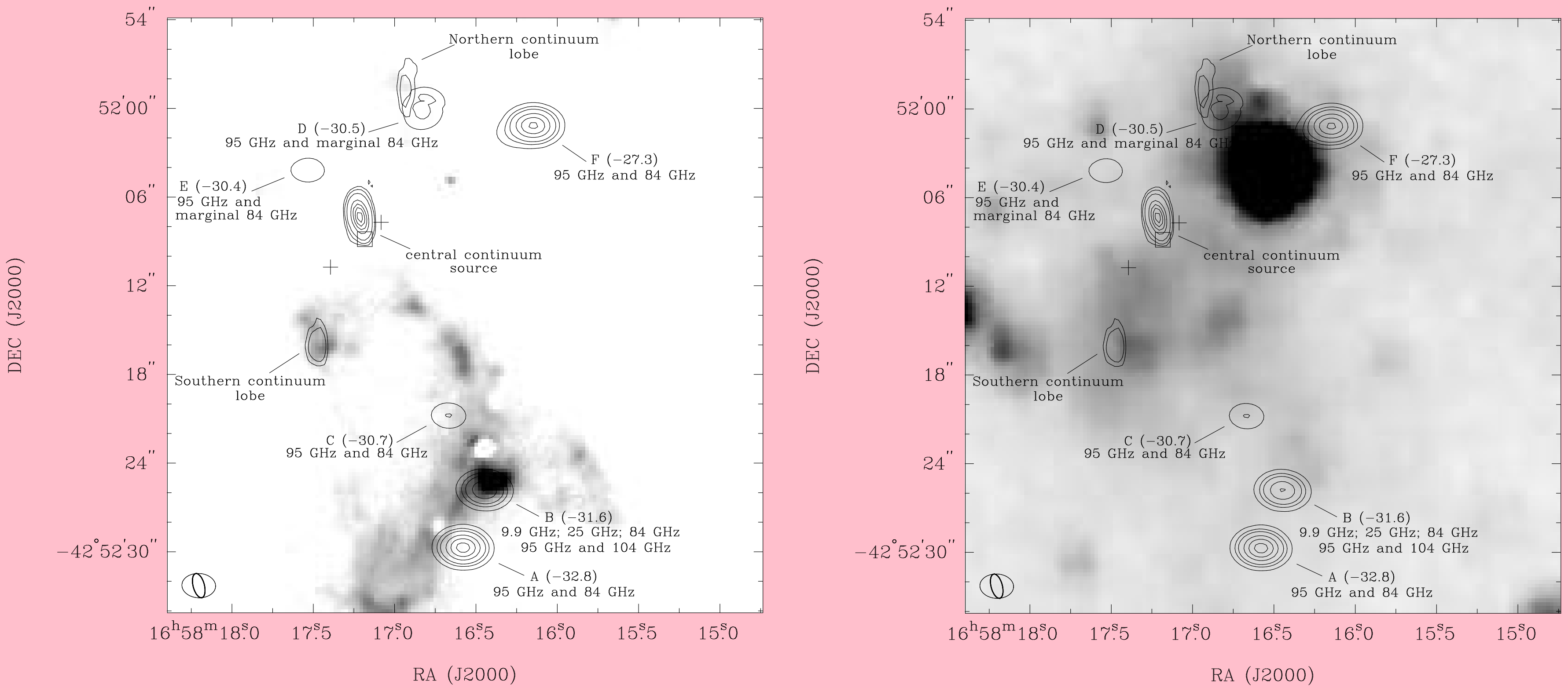


- No 6.7 GHz maser has been detected in this source, although there are H_2O and OH masers near the central source
- Ellingsen (2006, ApJ, 638, 241) has found that the sources associated with class I masers have redder GLIMPSE colours $\Rightarrow$ they are younger
- The OH maser is present $\Rightarrow$ 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-μm and 3.6-μm GLIMPSE images. This source dominates in the 12-μm *MSX* band as well.
- The 21-μm emission is centred on the central continuum source $\Rightarrow$ it is deeply embedded and young

H_2 2.12 μm — GLIMPSE 5.8 μm



- Warm dense gas, rich in methanol is enough for class I masers $\Rightarrow$ they can appear at the very early evolutionary stage
- Class I masers do not depend on shocks once the methanol abundance is increased $\Rightarrow$ they can last long
- Class II masers need an infrared source for pumping $\Rightarrow$ 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_2O 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 5.3×10^7 and 2.0×10^4 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±0.0007.