THE STUDY OF THE INNER SHELLS AROUND EVOLVED STARS FROM SiO MASER EMISSION

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SiO MASERS: BASIC OBSERVATIONAL RESULTS

Rotational transitions: J=1–0, 2–1, up to 8–7 (345 GHz)

EXCITED vibrational states, v = 1, 2, 3, 4

($\geq$ 1800 K)

in more than 500 O-rich stars, and a few S-type objects

Bright AGBs (Miras, semiregulars, irregulars), OH/IR, SGs, a few PPNe

v=1 J=1–0, 2–1 and v=2 J=1–0 dominate

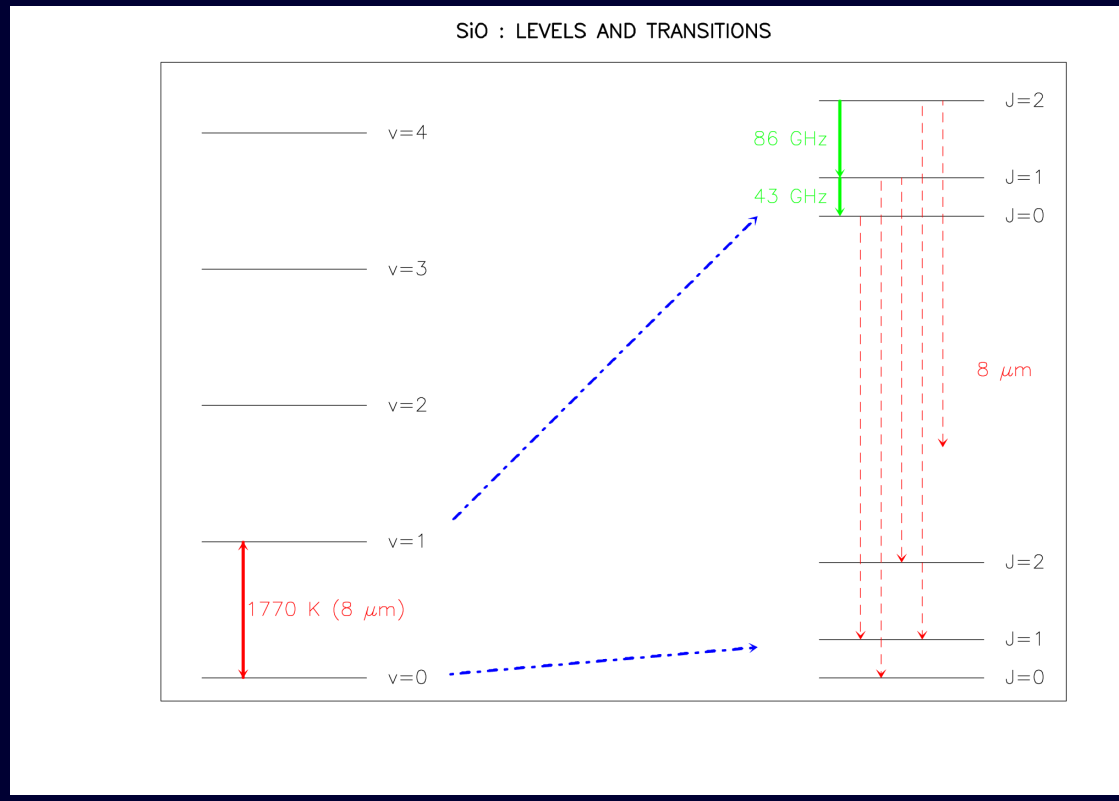
Spiky, narrow profiles, around stellar velocity (ΔV $\sim$ 2 – 10 km/s)

Good correlation with IR (8 μ $\equiv$ Δv=1)

also ^{29}SiO and ^{30}SiO (mainly v=0)

(e.g. Bujarrabal et al., A&A, 175, 164; Alcolea et al. A&A, 211, 187; A&A, 231, 431)

SiO MASERS: BASIC PUMPING PROPERTIES



$v \geq 1$ states populated from $v = 0$

+ fast radiative de-excitation, $A \geq 5\ s^{-1}$!!

$\tau > 1 \Rightarrow P_{rad} \sim A\,\beta \sim A/\tau \underset{\sim}{\propto} 1/g_u$

=> selectively overpopulates levels with higher J

=> chain of masers (mutually reinforced)

High excitation required => close to the star

Collisional (theoretical effort) or radiative excitation (observational support) ?

Effects of line overlap ? (with lines of H_2O or of SiO itself)

VARIABILITY OF SiO MASERS FROM AGB STARS

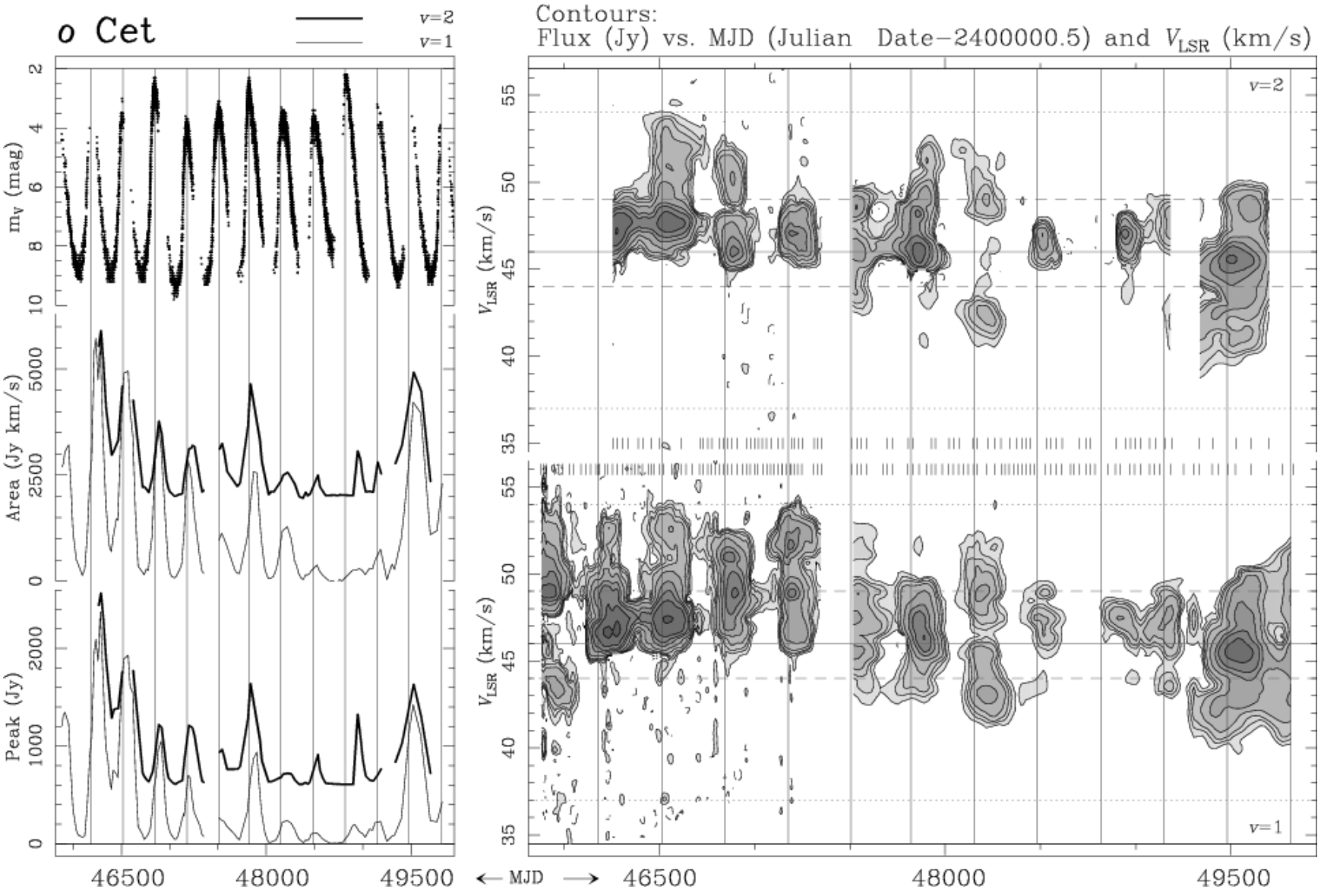
(AGB stars are strong pulsators, with periods $\sim$ 1 yr.)
SiO masers in them are also strongly variable with the same periods.

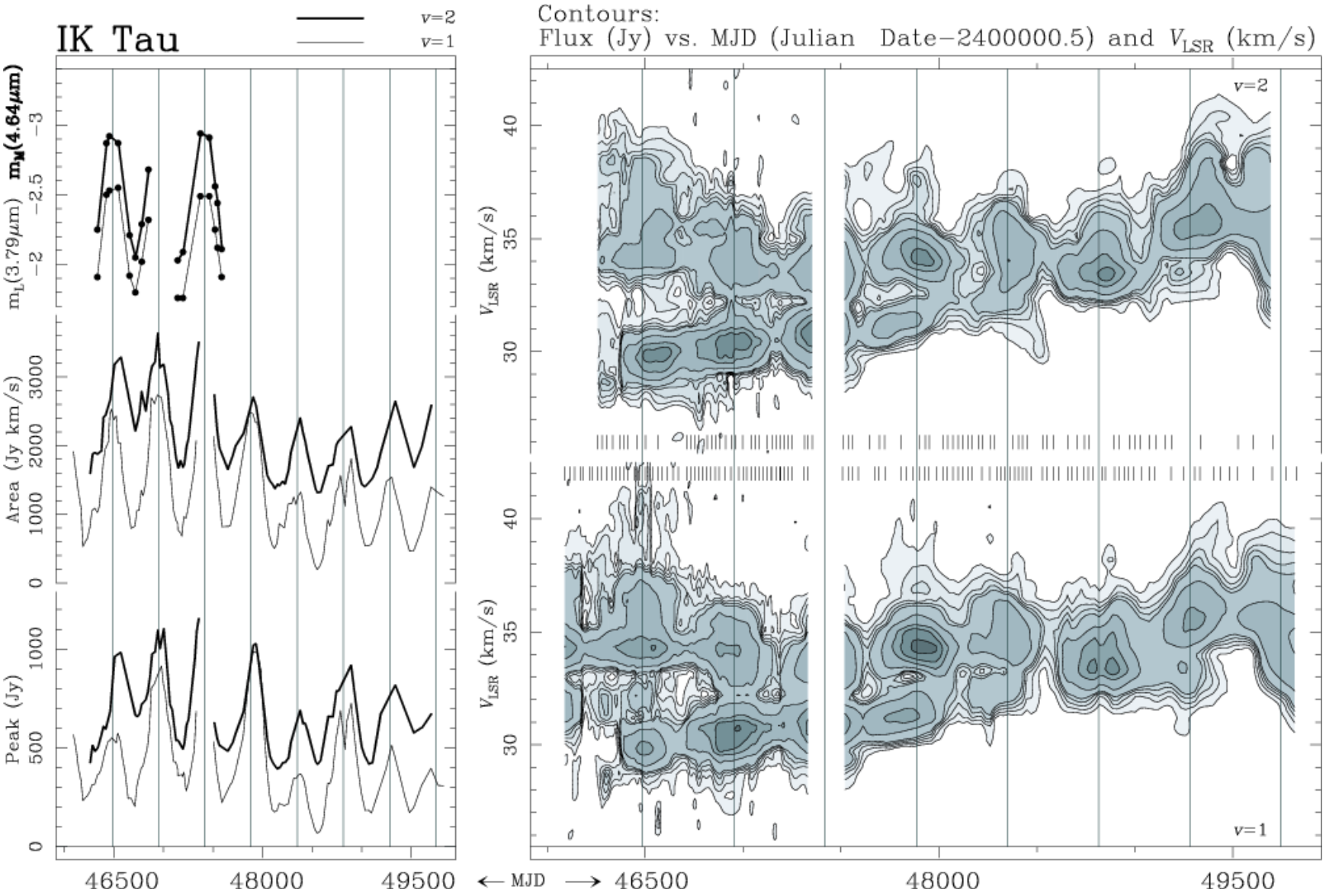
11-years, short spaced monitoring:
$\sim$ 15–20 sources; J=1-0, v=1,2; $\sim$ 4000 spectra

=>
Systematic phase lag with respect to optical cycle: + 0.1-0.15 (= IR/optical lag).
Systematically IN phase with IR cycle (within 0.05).
(Pardo et al., A&A, 424, 145)

Very difficult to explain if the pumping is collisional:
A shock needs several periods to reach the masing shell from the photosphere,
and such a time must vary from star to star.

Naturally explained if radiatively pumped.


o Cet
v=2
v=1
Contours:
Flux (Jy) vs. MJD (Julian Date−2400000.5) and V_{LSR} (km/s)
m_V (mag)
Area (Jy km/s)
Peak (Jy)
V_{LSR} (km/s)
v=2
v=1
46500
48000
49500
← MJD →


IK Tau
v=2
v=1
Contours:
Flux (Jy) vs. MJD (Julian Date−2400000.5) and V_{LSR} (km/s)
$m_L(3.79\mu m)$ $m_N(4.64\mu m)$
Area (Jy km/s)
Peak (Jy)
V_{LSR} (km/s)
← MJD →
46500
48000
49500

PHASE OF SiO MASER MAXIMA, v=1,2 J=1-0, in AGB stars from Fourier analysis

v=1 peak	v=1 area	v=2 peak	v=2 area	average	period	name
SiO max. phase w.r.t. op. max.:						
0.09	0.08	0.11	0.12	0.10	461.5	GY Aql (smr)
0.15	0.14	0.11	0.10	0.13	397.0	R Aqr
0.15	0.12	0.12	0.14	0.13	542.5	TX Cam
0.17	0.19	0.13	0.13	0.16	362.0	R Cnc
0.13	0.13	0.10	0.07	0.11	434.5	R Cas
0.12	0.10	0.17	0.14	0.13	331.5	o Cet
0.19	0.14	0.18	0.18	0.17	403.5	U Her
0.01	0.07	0.03	0.09	0.05	384.5	W Hya (smr?)
0.10	0.09	0.05	0.09	0.08	314.0	R Leo
0.11	0.13	0.12	0.16	0.13	374.5	R LMi
			average :	0.12		
SiO max. phase w.r.t. IR max.:						
0.06	0.03	-0.01	-0.04	0.01	467.5	IK Tau (IR var.)
0.04	0.02	-0.06	-0.07	-0.02	650.5	IRC+10011 (IR var.)
			average :	-0.01		

RELATIVE SPATIAL DISTRIBUTIONS OF THE DIFFERENT MASER LINES

In general: rings at a few stellar radii (see e.g. Diamond et al. 1994, ApJ, 430, L61; Cotton et al. 2006, A&A, 456, 339)

v=1, J=1–0 vs v=2, J=1–0 :

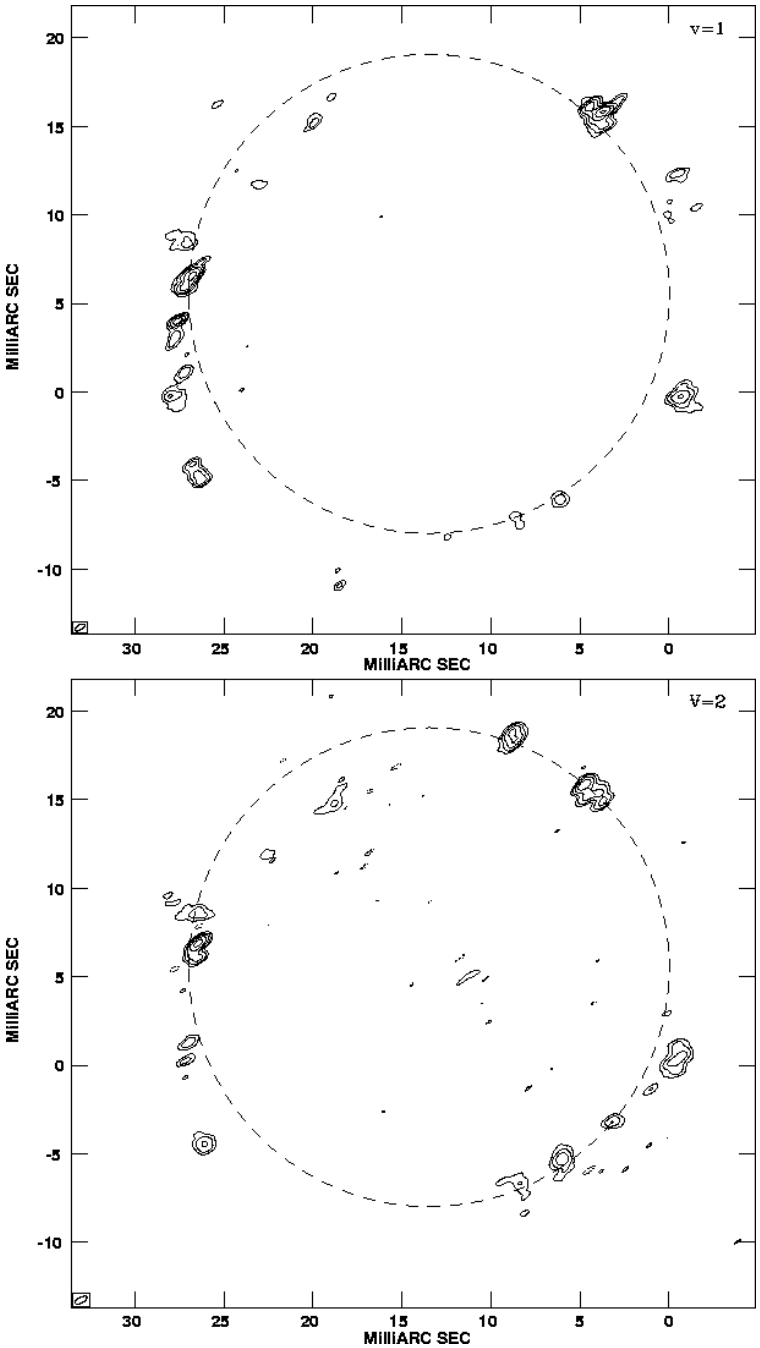
Nearby, but very rare coincidences

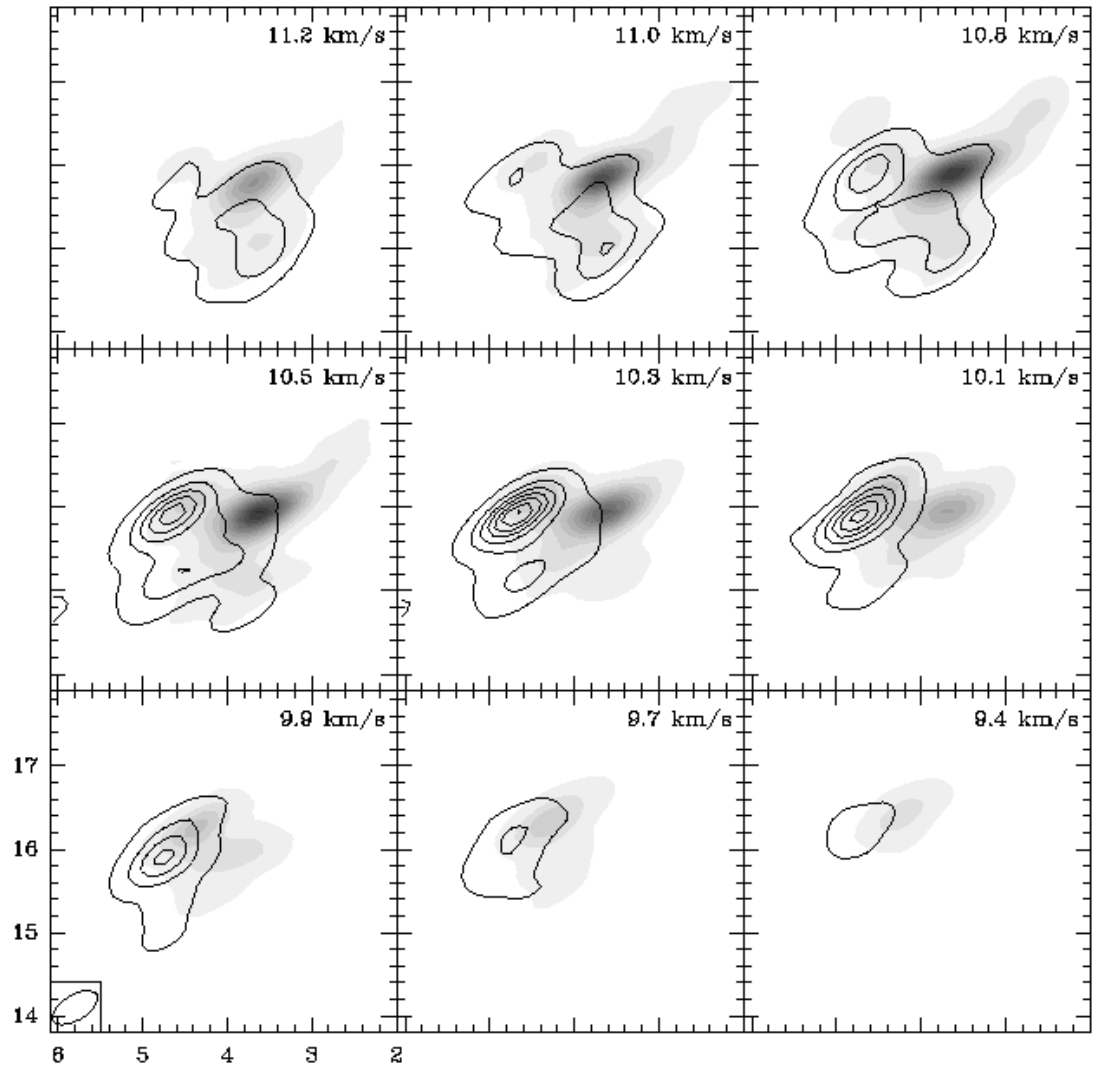
v=2 J=1–0 slightly (but systematically) inner ring

Each transition 'avoids' the other

Expected from theory(ies): require very different excitations

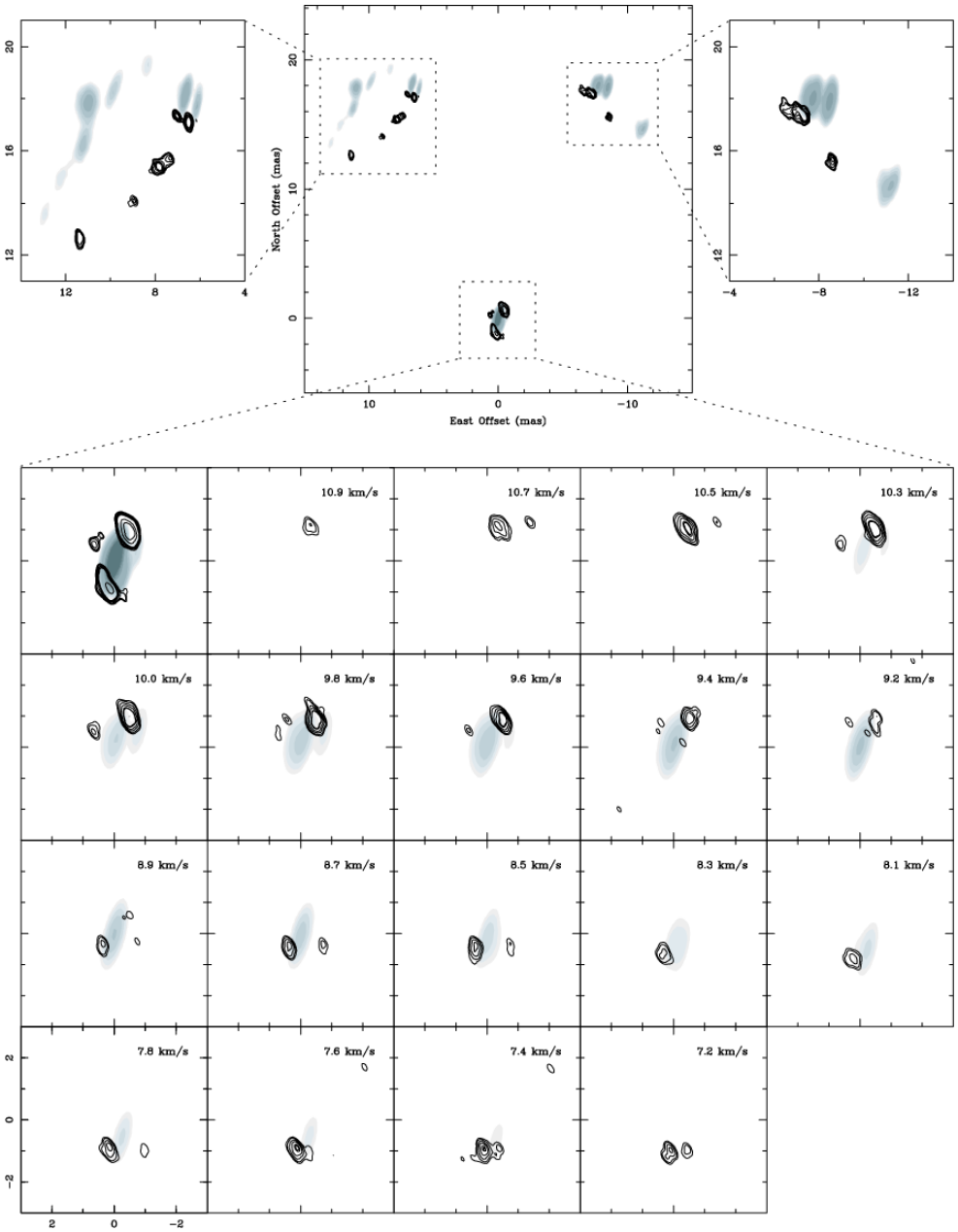
(Desmurs et al. 2000, A&A 360, 189)





TX Cam v=1,2 J=1–0

(Desmurs et al. 2000, A&A 360, 189)



IRC +10011

v=1, J=1–0: greys

v=2, J=1–0: contours

(Soria-Ruiz et al. 2004, A&A 424, 145)

RELATIVE POSITIONS OF THE DIFFERENT MASER LINES

v=1, J=1–0 vs v=1, J=2–1 :

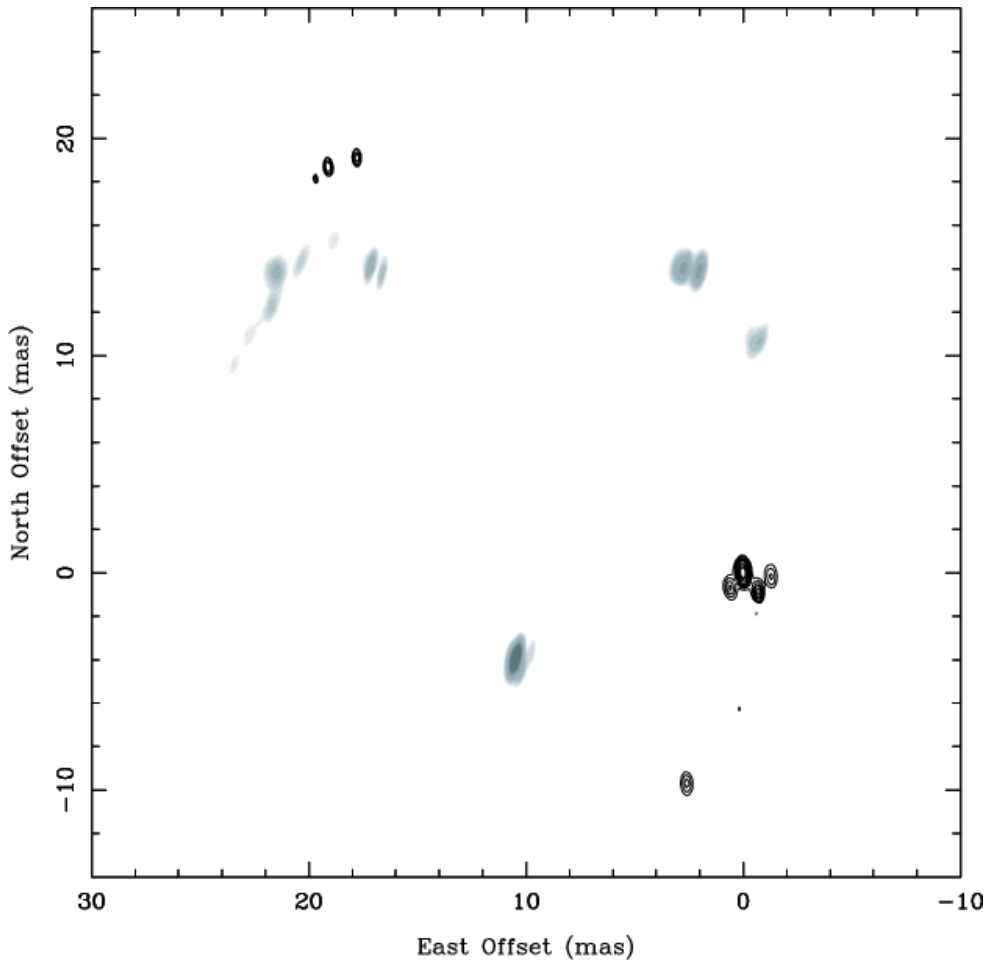
Again, concentric rings.

But very different distributions !

v=1 J=2–1 outwards (in the few observed cases)

Totally unexpected from theoretical considerations
(maser chains, similar excitation)

Invoke line overlap ?



IRC +10011

v=1, J=1–0: greys

v=1, J=2–1: contours

(Soria-Ruiz et al. 2004, A&A 424, 145)

RELATIVE POSITIONS OF THE DIFFERENT MASER LINES

^{29}SiO v=0, J=1–0

Again, concentric rings.

TOO SIMILAR TO THE OTHERS !

In spite of the very low excitation required

A result in fact expected from low-resolution observations

(systematically similar spectra as in other lines)

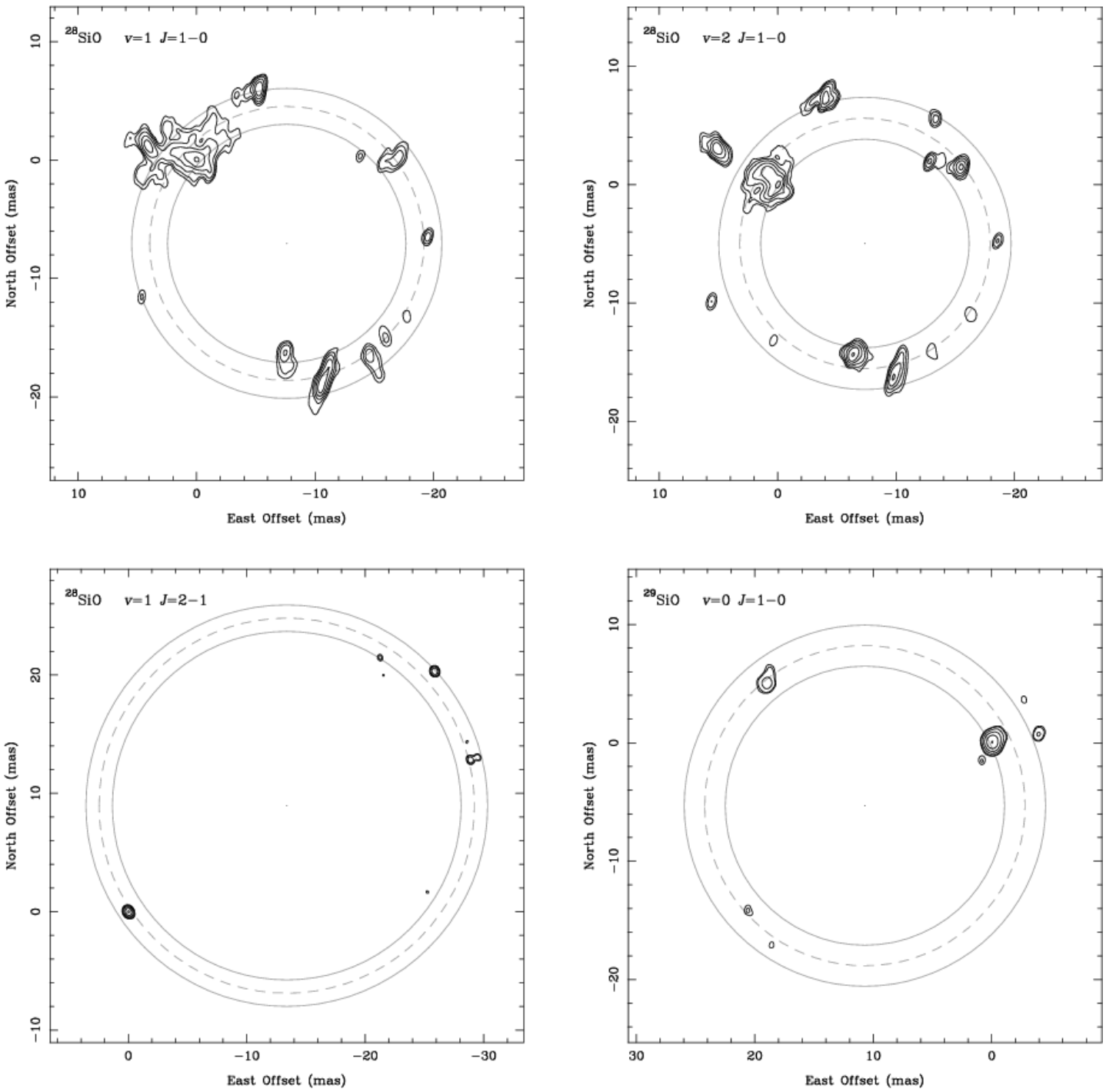
Completely unexpected from theory:

Masers at long distances, radial amplification => double-peak profiles

(Robinson & Van Blerkom ApJ, 249, 566; Deguchi & Nguyen-Q-Rieu, A&A, 117, 314)

Overlap between ^{28}SiO and ^{29}SiO ro-vibrational lines ?

(González-Alfonso & Cernicharo, 1997, A&A, 322, 938)



IRC +10011 (new epoch)

^{28}SiO lines

+ ^{29}SiO v=0, J=1–0

(Soria-Ruiz et al. 2005, A&A 432, L39)

SOME REMARKS ON LINE OVERLAP AND SiO MASER PUMPING

LINE OVERLAP

Two lines, perhaps of different molecules, coincide in frequency.

The external photon field 'seen' by one of the lines can be strongly affected.

In SiO: always ro-vibrational lines affected

OBSERVATIONAL FACTS THAT COULD BE EXPLAINED BY LINE OVERLAP:

H_2O v_2=0,$12_{7,5}$ – v_2=1,$11_{6,6}$ + ^{28}SiO v=2,J=1 – v=1,J=0

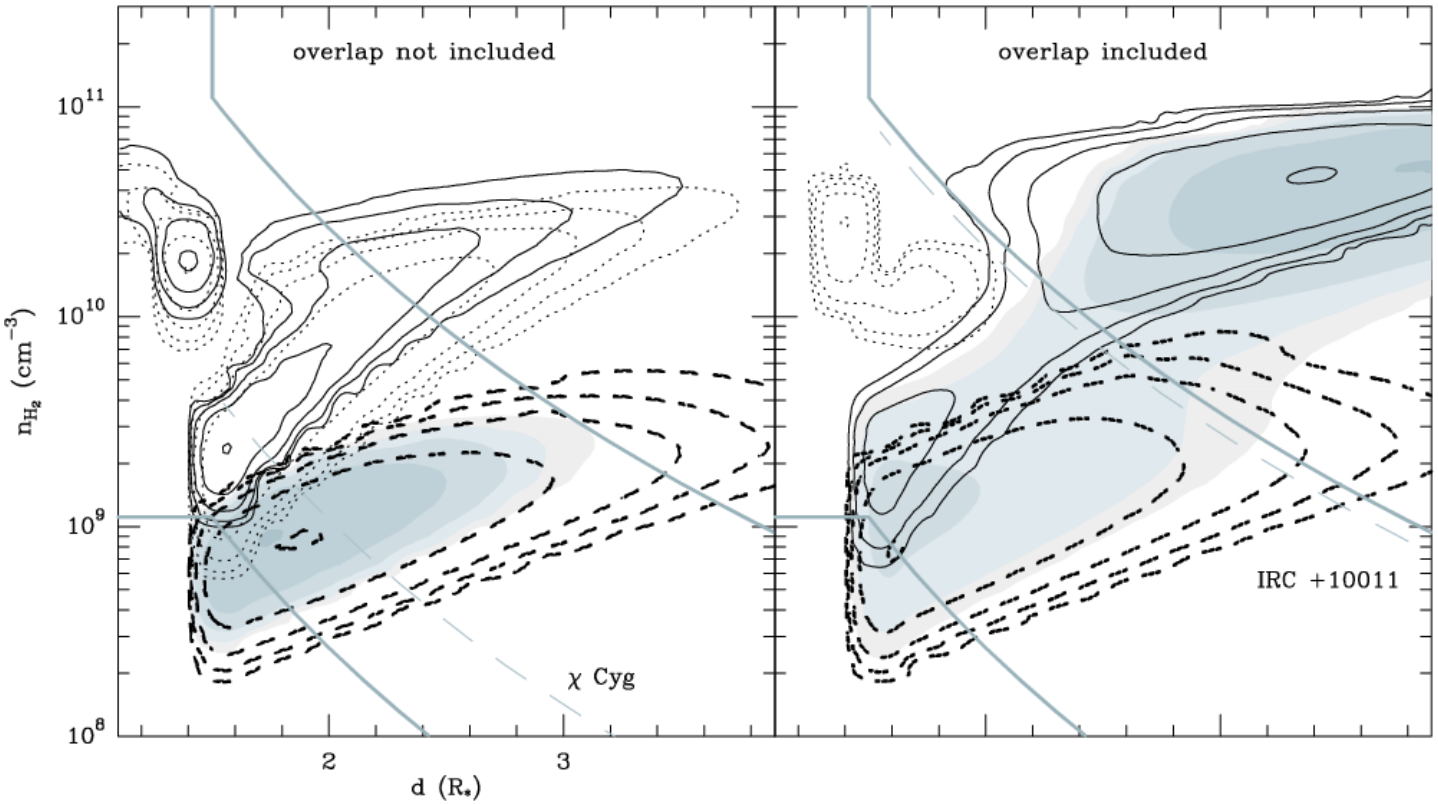
- Anomalously weak emission in v=2 J=2–1 (in O-rich stars)

  Olofsson et al. (1985, A&A, 169, 179)

- Anomalous distribution of ^{28}SiO v=1, J=2–1

Increase of photons due to emission in H_2O v_2=0,$12_{7,5}$ – v_2=1,$11_{6,6}$

=> overpopulation of SiO v=2,J=1 and depopulation of SiO v=1,J=0



———	v=2, J=1–0
.....	v=2, J=2–1
greys :	v=1, J=1–0
– – – –	v=1, J=2–1

Predictions for H_2O-poor (no overlap, ∼ χ Cyg) or -rich (overlap, IRC +10011) CSEs.

∼ explains the v=1 J=1–0, J=2–1; v=1 J=2–1 distributions and the weak v=2 J=2–1

(Soria-Ruiz et al., A&A, 426, 131; Bujarrabal et al., A&A, 314, 883)

SOME REMARKS ON LINE OVERLAP AND SiO MASER PUMPING

EFFECTS ON ^{29}SiO and ^{30}SiO MASERS:

- Could explain the ^{29}SiO v=0, J=1–0 maser, in particular its distribution

  ^{28}SiO v=2,J=4 – v=1,J=3 + ^{29}SiO v=1,J=1 – v=0,J=0

- And the other ^{29}SiO and ^{30}SiO masers? At least :

  ^{29}SiO v=0 J=1–0, J=2–1, J=4–3, J=5–4

  ^{29}SiO v=1 J=1–0, J=3–2, J=4–3, J=6–5

  ^{29}SiO v=2 J=6–5

  ^{30}SiO v=0 J=1–0, J=2–1, J=4–3, J=5–4

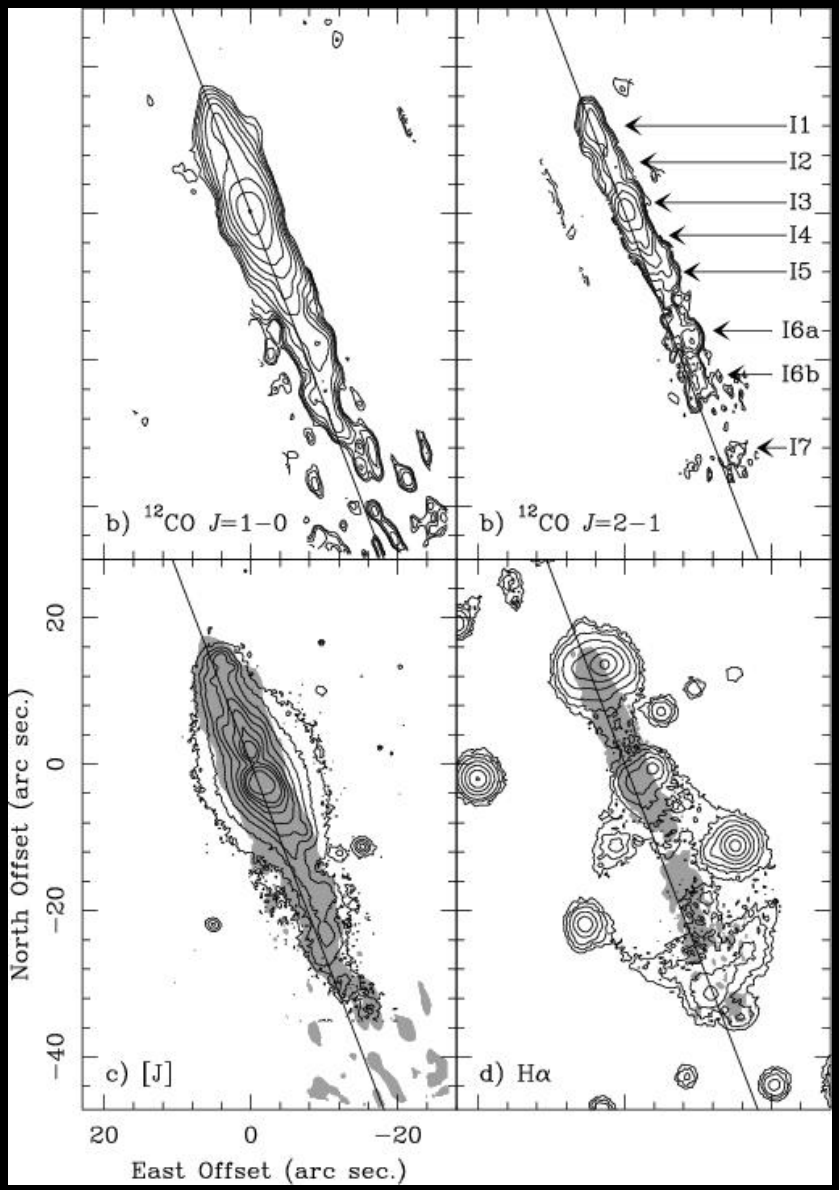
  ^{30}SiO v=1 J=4–3

  ^{30}SiO v=2 J=4–3

Too many coincidences? P $\sim$ 1/100 (for a given line of ^{29}SiO, with ^{28}SiO).

Why not in other molecules?

OH 231.8+4.2: SiO MASERS IN YOUNG PNe (PPNe)



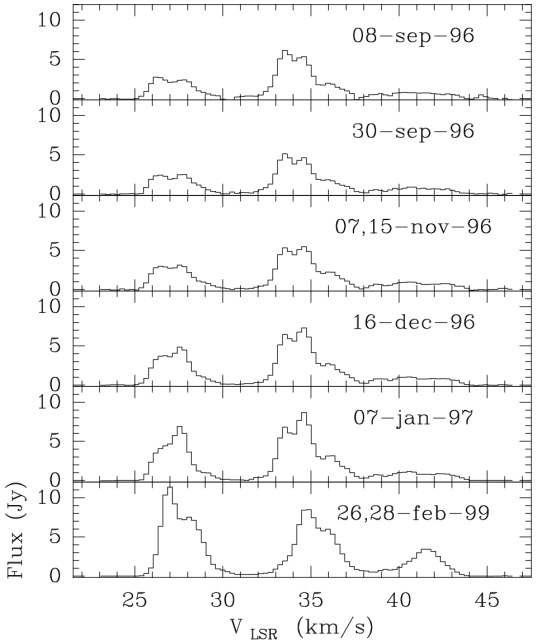
Alcolea et al. (2001, A&A 373, 932), Bujarrabal et al. (2002, A&A 389, 217)

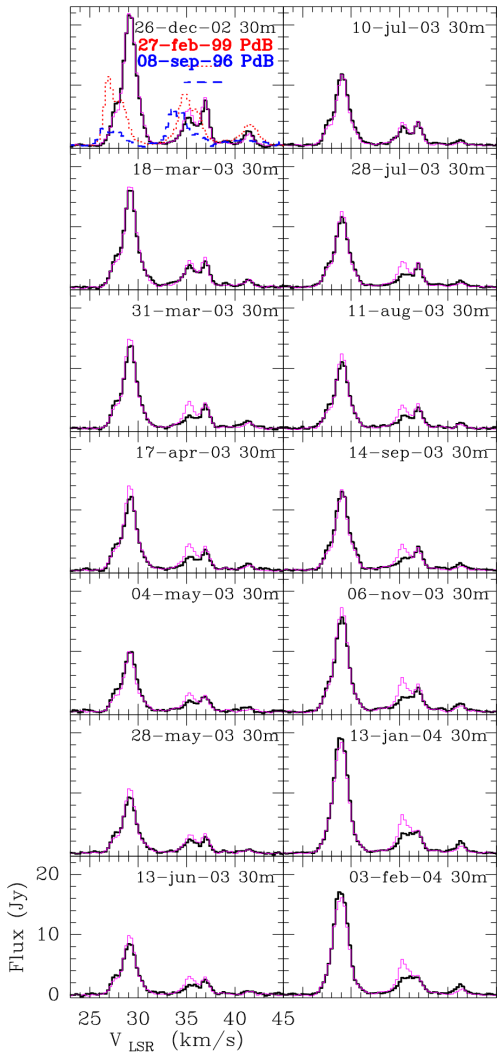
SiO v=1, J=2–1 MASER (86 GHz) IN OH 231.8+4.2

Remarkably stable three-peak structure.

Not due to lucky clump combination in the inner envelope ($V\Delta t/R > 1$) .

Expected from masers in rotating disks (e.g. Deguchi et al. 1983, ApJ, 264, L65)

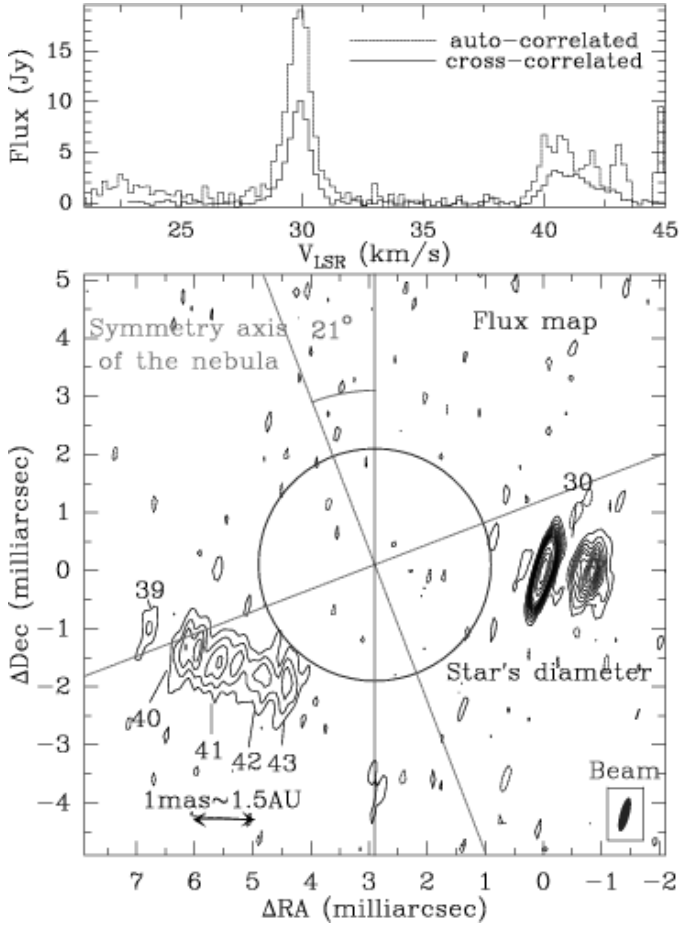




unpublished data from Sánchez Contreras et al.,

in preparation

OH 231.8+4.2: VLBI MAPPING OF SiO v=2 J=1–0 (43 GHz)



Spatial distribution and velocities compatible with rotation for a reasonable stellar mass (plus infall?)

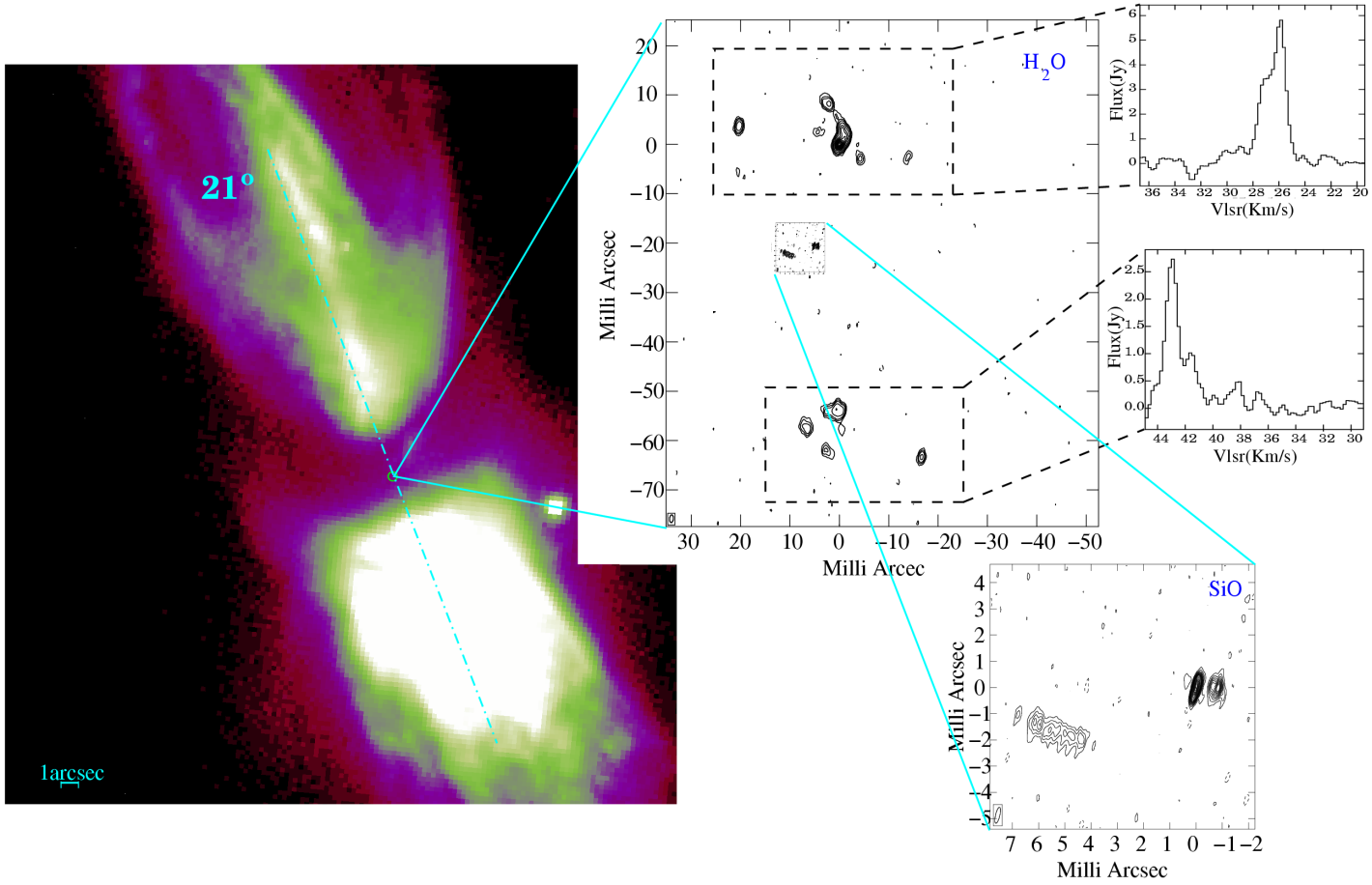
Perpendicular to the nebular axis!

But, unfortunately the central peak was undetected

Single-dish monitoring plus maps => rotating tiny disk

Sánchez Contreras et al. (2002, A&A, 385, L1)

OH 231.8+4.2: ABSOLUTE POSITION MAPPING OF SiO AND H_2O MASERS



H_2O placed along the axis => supports the rotating disk – axial structure interpretation

Desmurs et al. (2007, A&A, in press; SEE ALL DETAILS IN POSTERs)

SEARCH FOR ROTATING DISKS IN YOUNG PNe

INNER ROTATING DISKS IN PPNe: IMPORTANT FEATURES !

- Explain the ubiquitous bipolar ejections in PPNe :
  - implying enormous amounts of momentum (radiation pressure not enough)
  - leading the shaping of PNe (systematically axial)
- Explain other observational results :
  - NIR excess due to hot dust in stable reservoirs (i.e. keplerian disks)
  - Anomalous atmospheric abundances probably due to reaccretion
  - ...

But only well detected in one PPN: the Red Rectangle
(from CO mapping, A&A, 441, 1031)

SEARCH FOR ROTATING DISKS IN YOUNG PNe

Inverse angular momentum problem:

Gas ejected by an AGB star must win momentum from a companion!

Detection in thermal emission require big disks ($> 1''$), like in the Red Rectangle.

But such big disks require a stellar companion with a relatively high mass ($\geq 0.5\ M_\odot$)

Substellar companions or planets cannot accelerate so strongly the circumstellar gas

=> the disk sinks to a small size ($R \propto M^2$)

Companion $\lesssim 0.1\ M_\odot$ => very small disks

=> VLBI observations of masers

Observations of SiO masers around post-AGB stars may be the key

... work in progress