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

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Rotational transitions: $J=1-0, 2-1, \ldots, 8-7$ (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 ($\Delta V \sim 2 - 10 \text{ km/s}$)

**Good correlation with IR** ($8 \mu \equiv \Delta v=1$)

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

\[ v \geq 1 \text{ states populated from } v = 0 \]

+ fast radiative de-excitation, \( A \geq 5 \text{ s}^{-1} \)

\[ \tau > 1 \implies P_{\text{rad}} \sim A/\tau \sim 1/g_u \]

\[ \implies \text{selectively overpopulates levels with higher } J \]

\[ \implies \text{chain of masers (mutually reinforced)} \]

High excitation required \( \implies \text{close to the star} \)

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

Effects of line overlap ? (with lines of H$_2$O 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.
<table>
<thead>
<tr>
<th>v=1 peak area</th>
<th>v=1 peak area</th>
<th>v=2 peak area</th>
<th>v=2 peak area</th>
<th>average peak area</th>
<th>period</th>
<th>name</th>
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<td>SiO max. phase w.r.t. op. max.:</td>
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<td>0.08</td>
<td>0.11</td>
<td>0.12</td>
<td>0.10</td>
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<td>0.09</td>
<td>0.05</td>
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RELATIVE SPATIAL DISTRIBUTIONS OF THE DIFFERENT MASER LINES


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 \( \nu=1,2 \) \( J=1-0 \)

(Desmurs et al. 2000, A&A 360, 189)
IRC +10011

v=1, J=1–0: greys

v=2, J=1–0: contours

RELATIVE POSITIONS OF THE DIFFERENT MASER LINES

\[ \text{v}=1, \text{J}=1\text{–}0 \quad \text{vs} \quad \text{v}=1, \text{J}=2\text{–}1 : \]

Again, concentric rings.

But very different distributions !

\[ \text{v}=1 \quad \text{J}=2\text{–}1 \quad \text{outwards (in the few observed cases)} \]

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

$^{29}\text{SiO}$ $v=0$, $J=1-0$

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
Overlap between $^{28}\text{SiO}$ and $^{29}\text{SiO}$ ro-vibrational lines?
IRC +10011 (new epoch)

$^{28}$SiO lines

+ $^{29}$SiO $v=0$, $J=1-0$

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:

\[ H_2O \ v_2=0,12_{7,5} - v_2=1,11_{6,6} + ^{28}\text{SiO} \ v=2,J=1 - v=1,J=0 \]

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

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

Increase of photons due to emission in \( H_2O \ v_2=0,12_{7,5} - v_2=1,11_{6,6} \)

\( \Rightarrow \) overpopulation of SiO \( v=2,J=1 \) and depopulation of SiO \( v=1,J=0 \)
Predictions for H$_2$O-poor (no overlap, $\sim \chi$ Cyg) or -rich (overlap, IRC +10011) CSEs. $\sim$ explains the $v=1$ J=1–0, J=2–1; $v=1$ J=2–1 distributions and the weak $v=2$ J=2–1

SOME REMARKS ON LINE OVERLAP AND SiO MASER PUMPING

EFFECTS ON $^{29}\text{SiO}$ and $^{30}\text{SiO}$ MASERS:

- Could explain the $^{29}\text{SiO}$ $v=0$, $J=1–0$ maser, in particular its distribution
  $$^{28}\text{SiO} \ v=2, J=4 \ - \ v=1, J=3 \ + \ ^{29}\text{SiO} \ v=1, J=1 \ - \ v=0, J=0$$

- And the other $^{29}\text{SiO}$ and $^{30}\text{SiO}$ masers? At least:
  $$^{29}\text{SiO} \ v=0 \ J=1–0, J=2–1, J=4–3, J=5–4$$
  $$^{29}\text{SiO} \ v=1 \ J=1–0, J=3–2, J=4–3, J=6–5$$
  $$^{29}\text{SiO} \ v=2 \ J=6–5$$
  $$^{30}\text{SiO} \ v=0 \ J=1–0, J=2–1, J=4–3, J=5–4$$
  $$^{30}\text{SiO} \ v=1 \ J=4–3$$
  $$^{30}\text{SiO} \ v=2 \ J=4–3$$

Too many coincidences? $P \sim 1/100$ (for a given line of $^{29}\text{SiO}$, with $^{28}\text{SiO}$). Why not in other molecules?
OH 231.8+4.2: SiO MASERS IN YOUNG PNe (PPNe)

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
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
OH 231.8+4.2: ABSOLUTE POSITION MAPPING OF SiO AND H$_2$O MASERS

H$_2$O 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)
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 (≥ 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 ≤ 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