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on New Developments in VLBI Science and Technology

Circumstellar Masers

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Evolution beyond the main sequence for moderate mass stars (1.5 — 8 $M_\odot$)

- Stars leave the Main Sequence (MS) when exhaust H at their cores. At this point the core contracts and the mantle expands : the star enters in the Red Giant Branch (RGB) and moves up along it in the H-R diagram.
- Eventually He ignites at the core and the star moves into the Horizontal Branch (HR).
- When the He is exhausted too at the core, the core contracts and the mantle expands again. The star ascends in the H-R digram for the second time, but now along the Asymptotic Giant Branch (AGB). The C-O rich core degenerates and therefore stellar evolution can not proceed any further. While at the AGB, nuclear burning continues at the bottom of a deeply convective mantle, alternatively, in two layers :
  - a H-rich one (via CNO-cycle) surrounding and feeding . . .
  - . . . a He-rich responsible for the thermal pulses (TP-AGB).

  Along the AGB, the core grows out of the H/He-burning shells, which move outwards.

Mass-loss along at the AGB

- AGB stars are very cool (3,500 — 2,000 K) but very luminous (10^4 — 10^5 $L_\odot$), and therefore very large, $R_\star$ of the order of 1000 $R_\odot \approx 1\,\mathrm{AU}$; they are giants (or super-giants) of M/S/C spectral types.
- AGB stars are strong radial pulsators, with changes in size, as large as 50 %, and surface temperature.
- The atmosphere of the star rises and sinks alternatively, in periods of 1—2 yr., at speeds comparable to the escape velocity, of tens of km s^{-1}.
- As a result of the pulsation, a dense ($10^{10}\,\mathrm{cm}^{-3}$) and warm (1,000 K) layer develops at several stellar radii, where refractory molecules (e.g. SiO) can condense into grains.
- Once dust grains are formed, they are pushed outwards by Photon Pressure, dragging the gas along with them, forming an expanding Circumstellar Envelope (CEs), which results in a isotropic loose of mass.

CEs around AGB stars

- CEs are spherical shells around AGB stars, formed as result of their mass loss processes.

  Rich in dust grains and molecular gas

  Temperatures from 1,000 — a few 10s K

  Acceleration up to 10–30 km s^{-1} at 10^{15} cm

  Constant expansion velocity, V_∞ up to 30 km s^{-1}

  Densities as $1/r^2$ for a constant mass loss

  Mass loss rates from 10^{-8} — 10^{-4} M$_\odot$ yr^{-1}

- They are roughly spherical (at least at large scale):

  PdB/30m maps of CO in 40 AGB shells by Neri et al. (1998)

  Arcs around IRC+10216 (and many other PNe and pPNe)

  OH maser shells and SiO maser rings

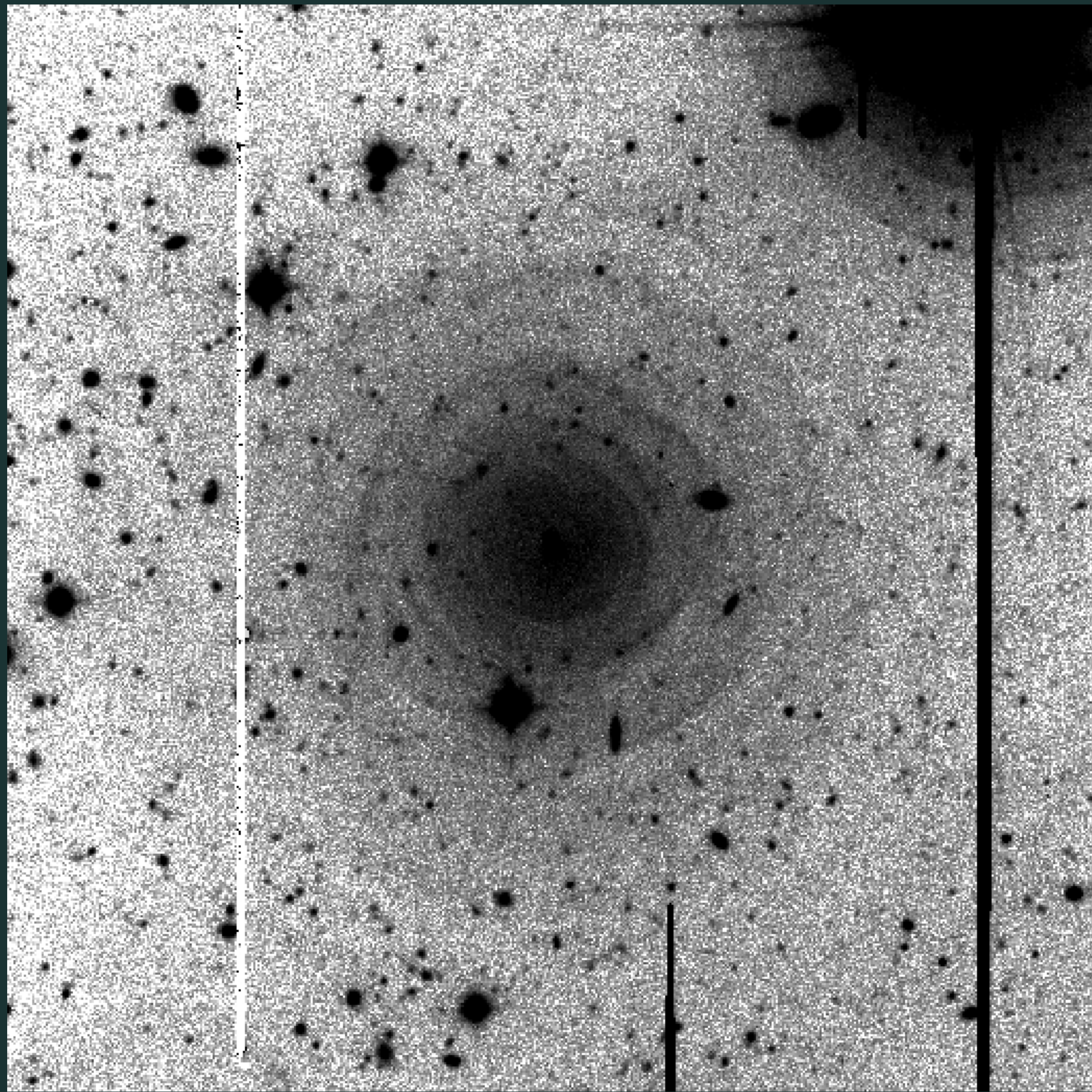
IRC +10216

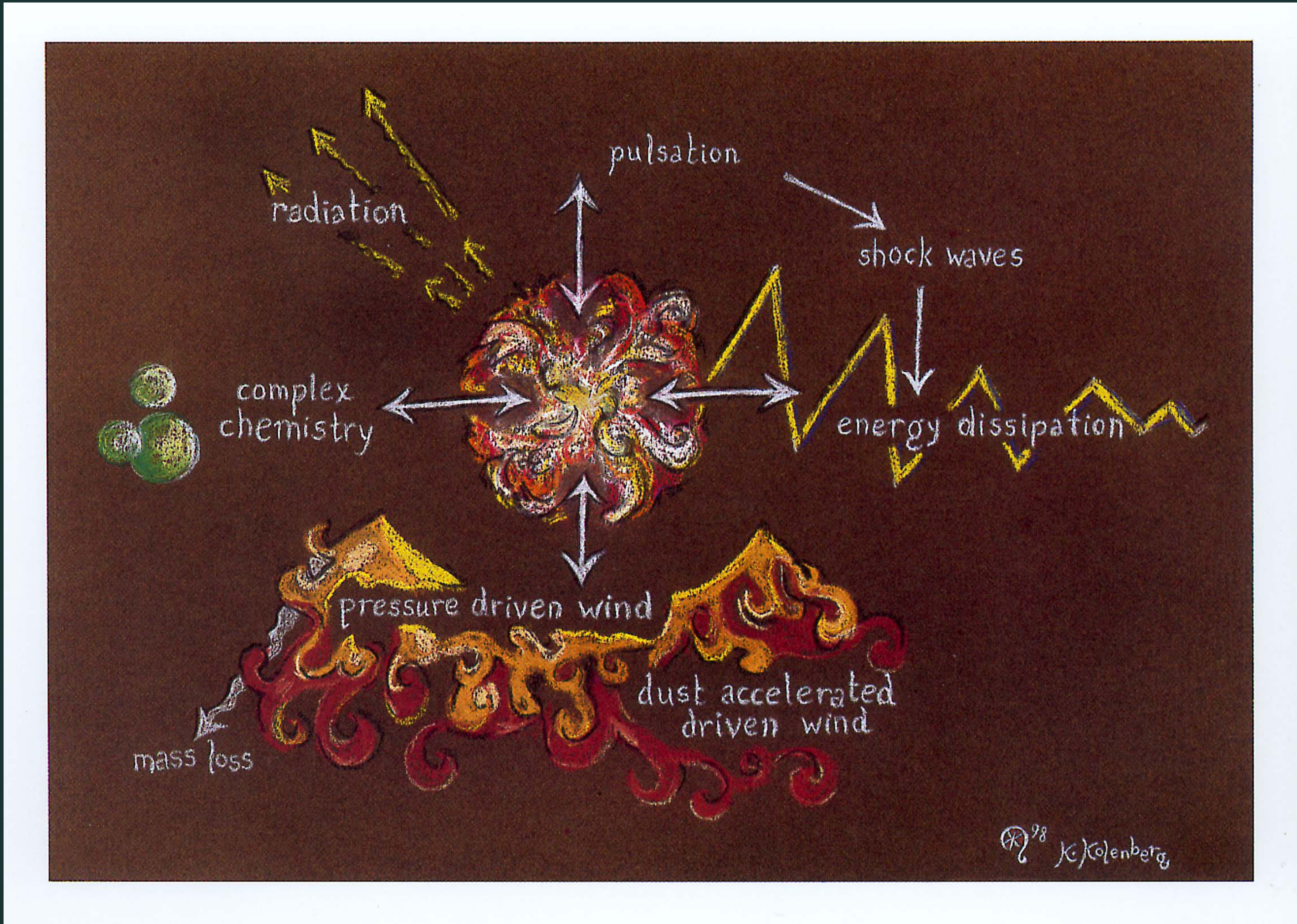
- Scattered interstellar light

  CFHT V-band image

  $223'' \times 223''$ field

- Mauron & Huggins (1999)




pulsation
radiation
shock waves
complex chemistry
energy dissipation
pressure driven wind
dust accelerated driven wind
mass loss
'98 K. Kolenberg

Chemistry of circumstellar envelopes

- In envelopes of O-rich stars, Oxygen is more abundant than Carbon, which is exhausted in the formation of CO, resulting in ...

    low abundance of other C-bearing molecules like HCN, CN, CS, etc.

    dust grains made of silicates and metallic oxides

    masers of OH, H_2O and SiO

- In envelopes of C-rich stars, Carbon is more abundant than Oxygen, which is exhausted in the formation of CO, resulting in ...

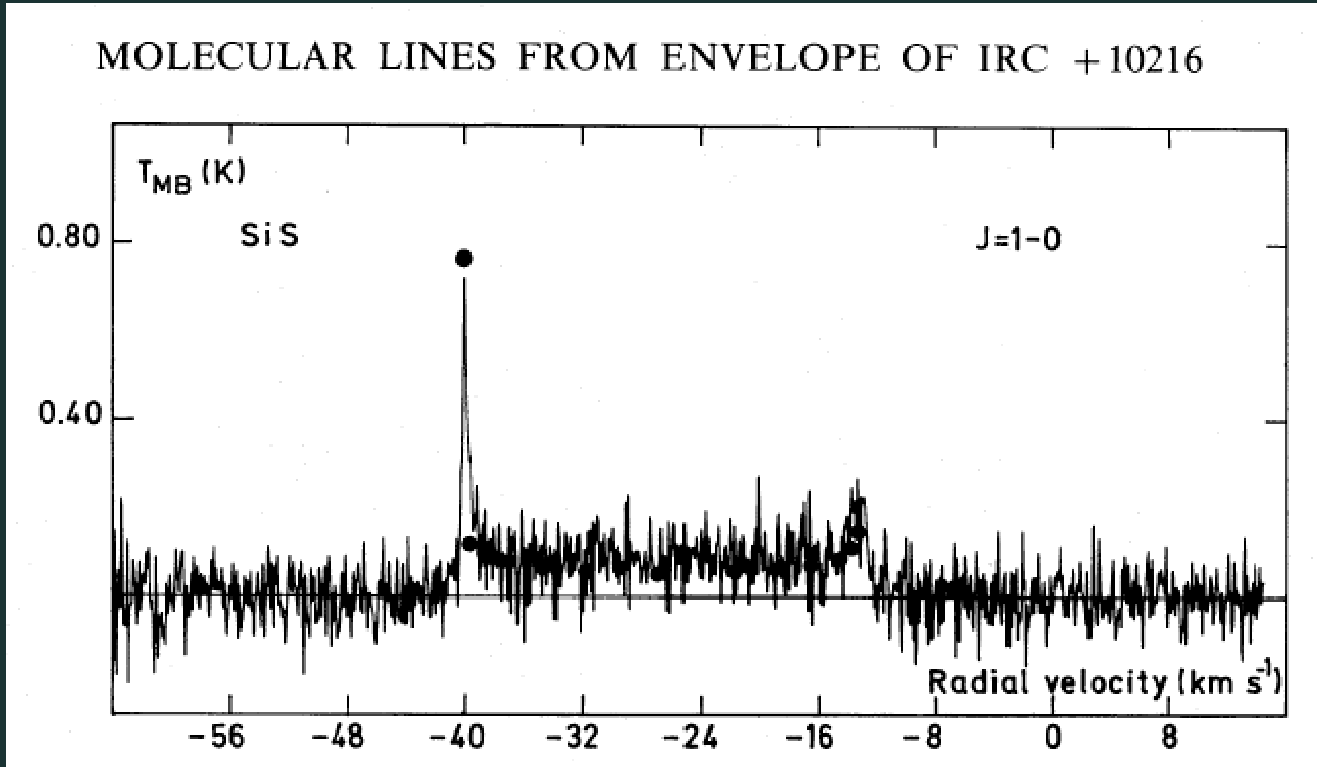
    low abundance of other O-bearing molecules like SiO, H_2O, SO, etc.

    dust grains made of carbonaceous compounds, PAHs

    masers of SiS and HCN

- And the S-type stars are just in between ($[O]/[C] \approx 1$)

Circumstellar masers of C-rich stars : SiS



- Only the v=0 J=1–0 line in IRC +10216 (Nguyen-Q-Rieu et al. 1984)
- U-shaped with blue peak stronger than red one (amplification of the stellar continuum).
- A case similar to OH masers (we will see later on)

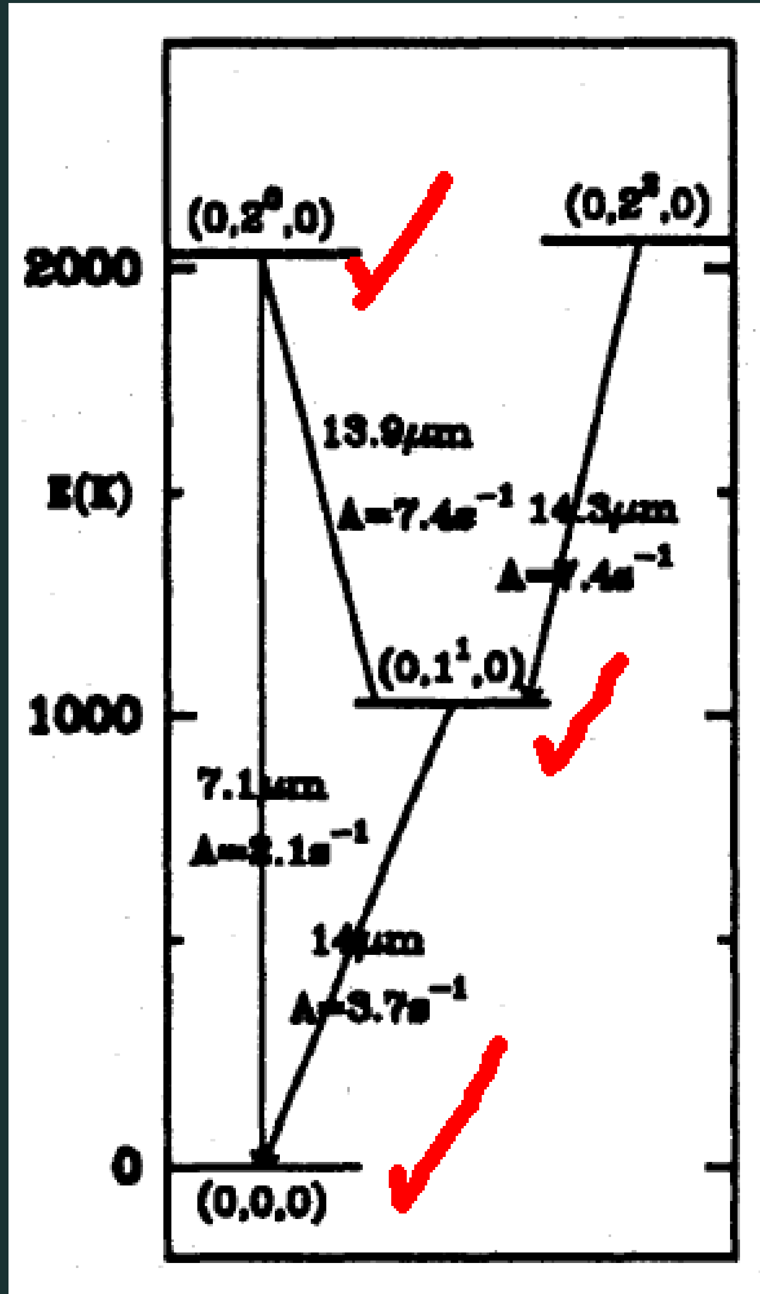
Circumstellar masers of C-rich stars : HCN

- Always detected in just a few sources (< 10)
- Ground state (000) J=1–0 (@ 89 GHz) masers of HCN & $H^{13}CN$
- Vib. excited masers of HCN

  (02^00) J=1–0 (@ 89 GHz)

  ($01^{1c}0$) J=2–1 (@ 178 GHz)

Izumiura et al. (1985), Lucas & Cernicharo (1989), and references therein



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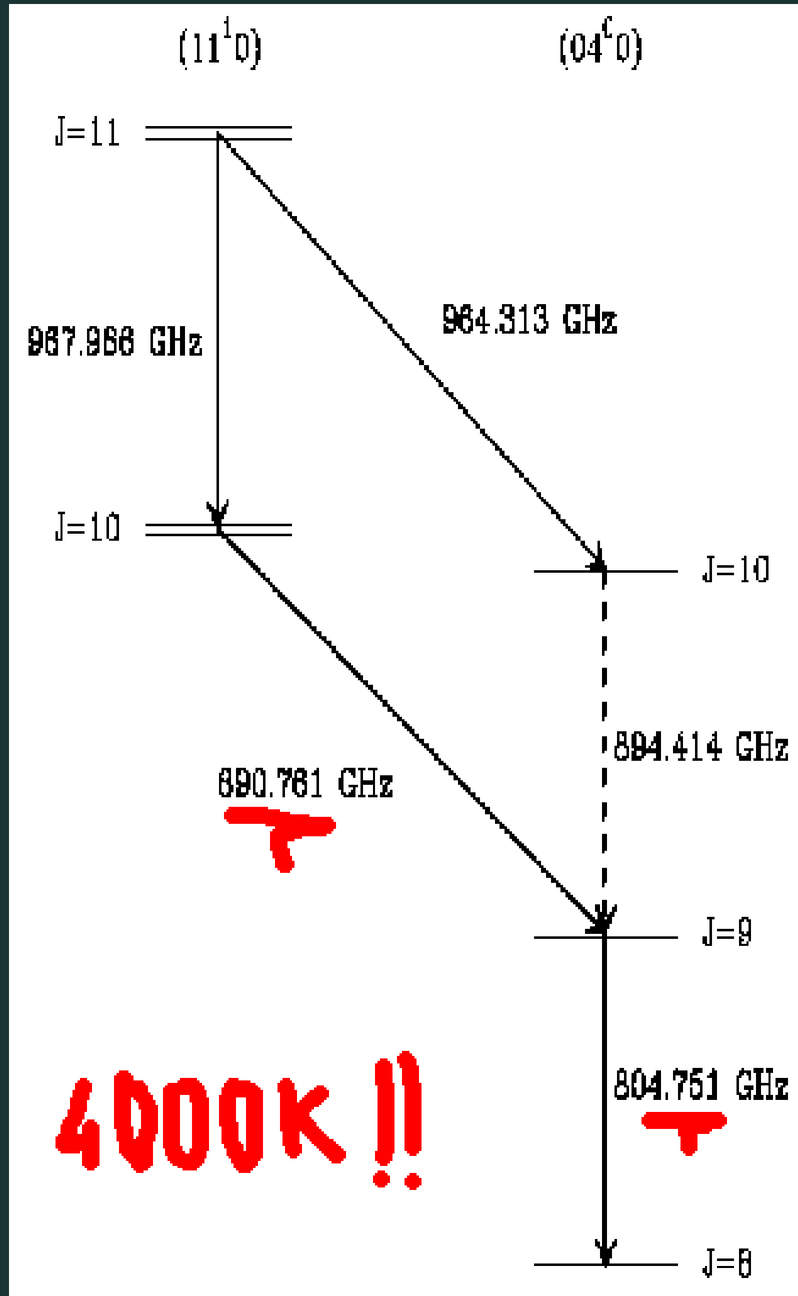
  (02^00) J=1–0 (@ 89 GHz)

  ($01^{1c}0$) J=2–1 (@ 178 GHz)

  (04^00) J=9–8 (@ 805 GHz)
- Cross-ladder (11^10)–(04^00) J=10–9 (@ 891 GHz)

Izumiura et al. (1985), Lucas & Cernicharo (1989),
and references therein

Schilke & Menten (2003), and references therein



Circumstellar masers of O-rich stars

- Three masing species : OH, H_2O (ortho & para), & SiO (^{28}SiO, ^{29}SiO, & ^{30}SiO).
- For the strong and low-frequency lines : OH, 22 GHz H_2O, & ^{28}SiO

  Detected in hundreds of sources

  Many high spatial resolution images (VLA, MERLIN, EVN, VLBA)
- They probe the three main regimes in the envelope :

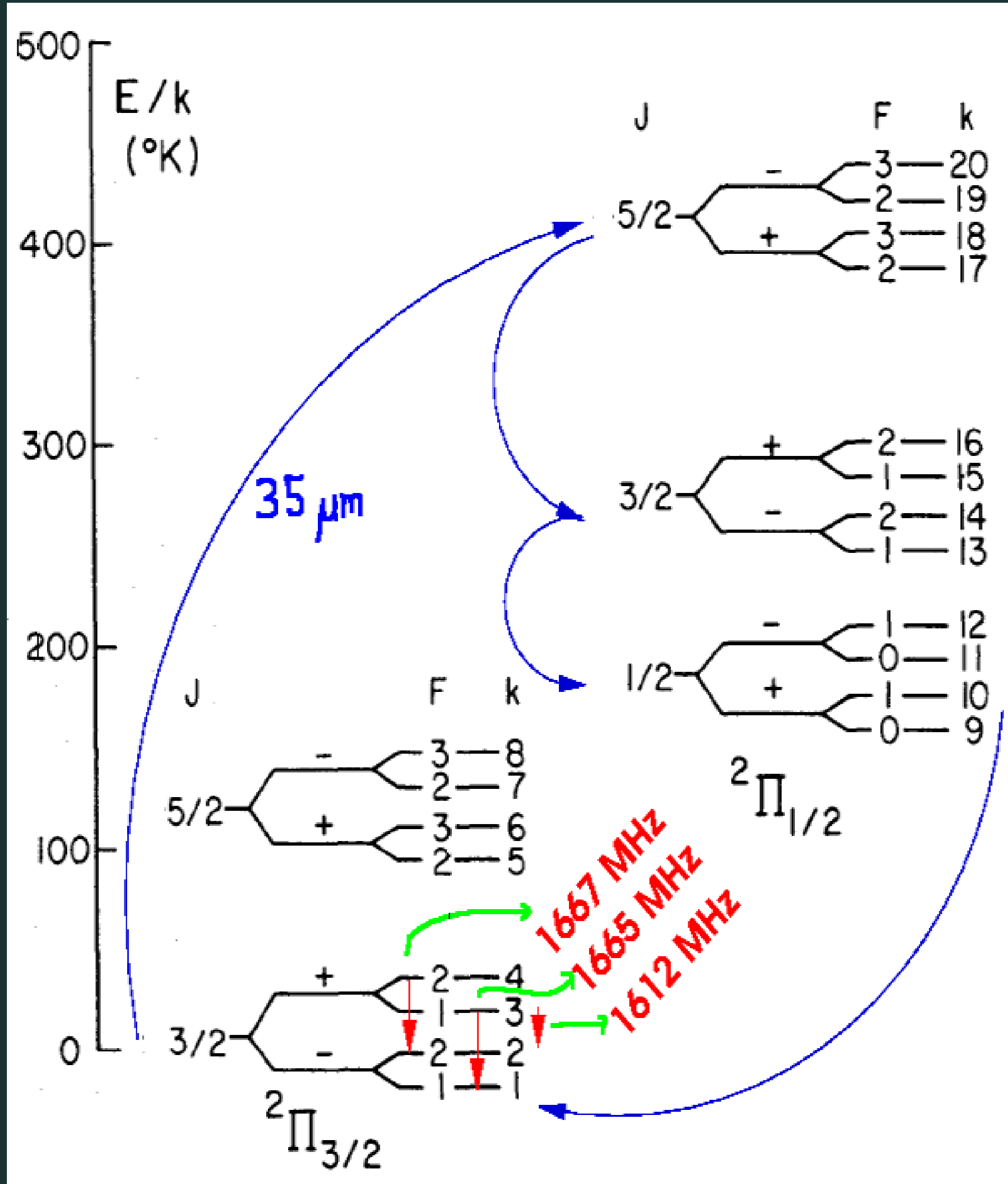
  OH masers : outer parts (radius of 10^{16} cm), constant velocity expansion, photo-dissociation processes, low density, cool gas

  22 GHz H_2O masers : mid envelope (radius of 10^{15} cm), acceleration of the envelope, grain growth, intermediate densities, warm gas

  SiO masers : extended atmosphere (radius of 10^{14} cm), pulsation, no grains yet formed, high densities, hot gas

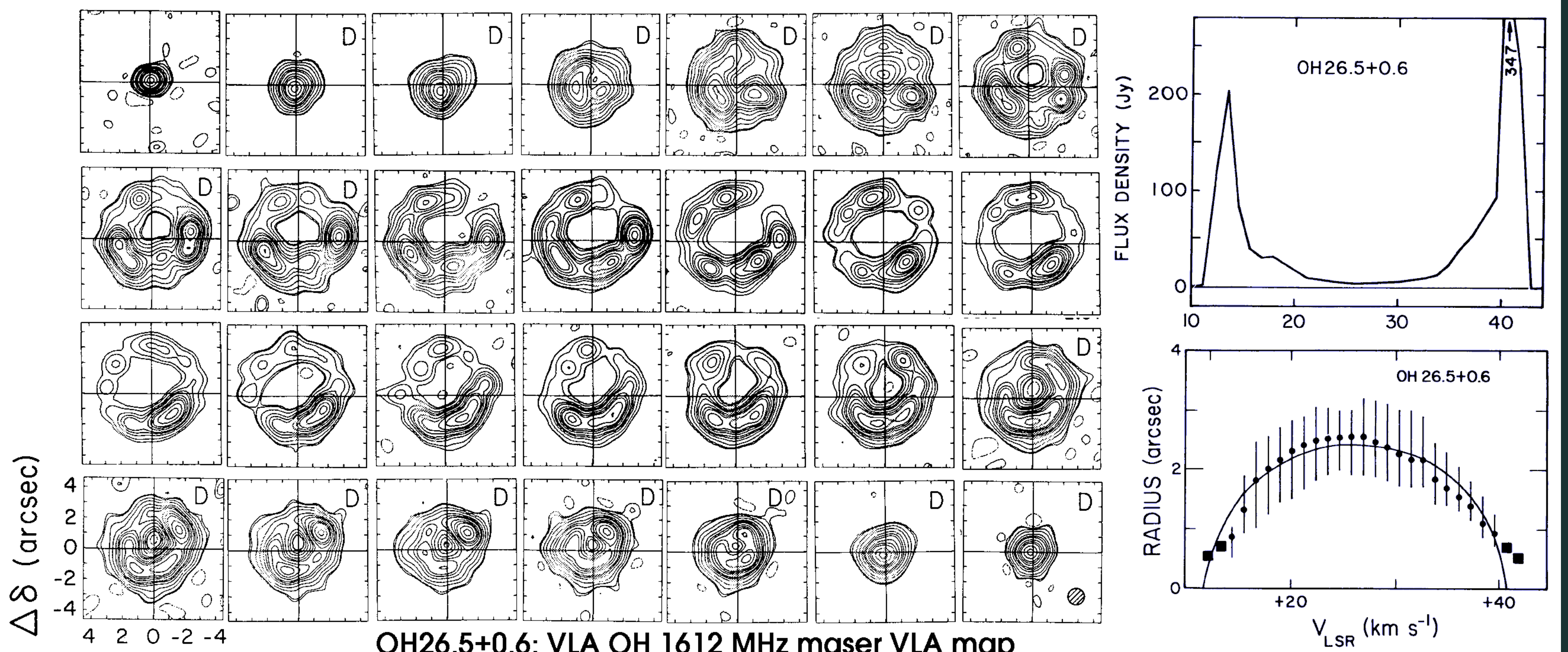
OH masers

- Detected in the 1665 and 1667 MHz main lines, and the 1612 MHz satellite line, between the hyperfine components of the ground $^2\pi_{3/2}$ J=3/2 state.
- Located in the outer parts of the envelope (at distances about 10^{16} cm), where OH is formed from the photolysis of H_2O by interstellar UV photons (which penetrate because the dust envelope is thin enough).
- Pumped through IR lines at 35 μm between $^2\pi_{3/2}$–$^2\pi_{1/2}$ J=3/2–5/2 states.



The thin shell model of OH masers

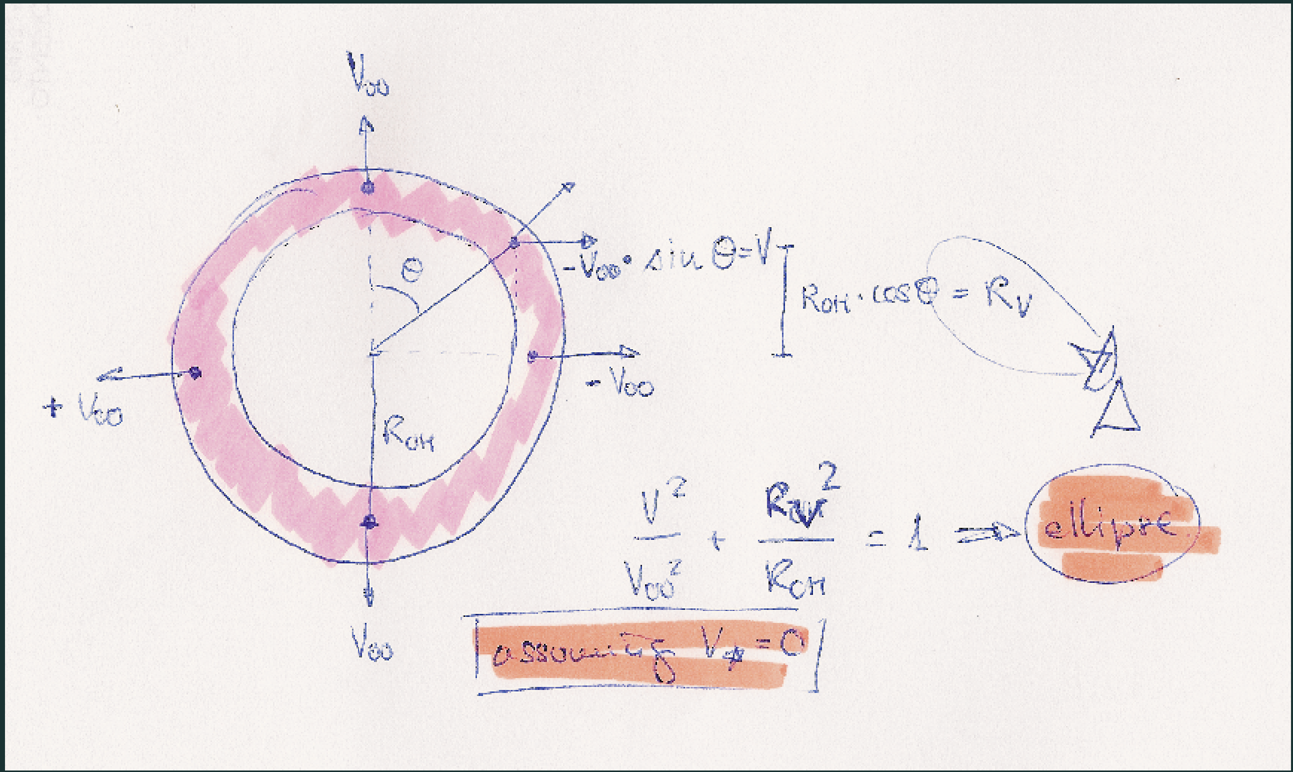
- OH maser profiles are often U-shaped, implying radial amplification of both the front and rear parts of the envelope.
- VLA/MERLIN maps and velocity vs. distance to the star diagrams can be fitted to ellipses.



OH26.5+0.6: VLA OH 1612 MHz maser VLA map
Bowers & Johnston 1990, ApJ 354, 676

The thin shell model of OH masers

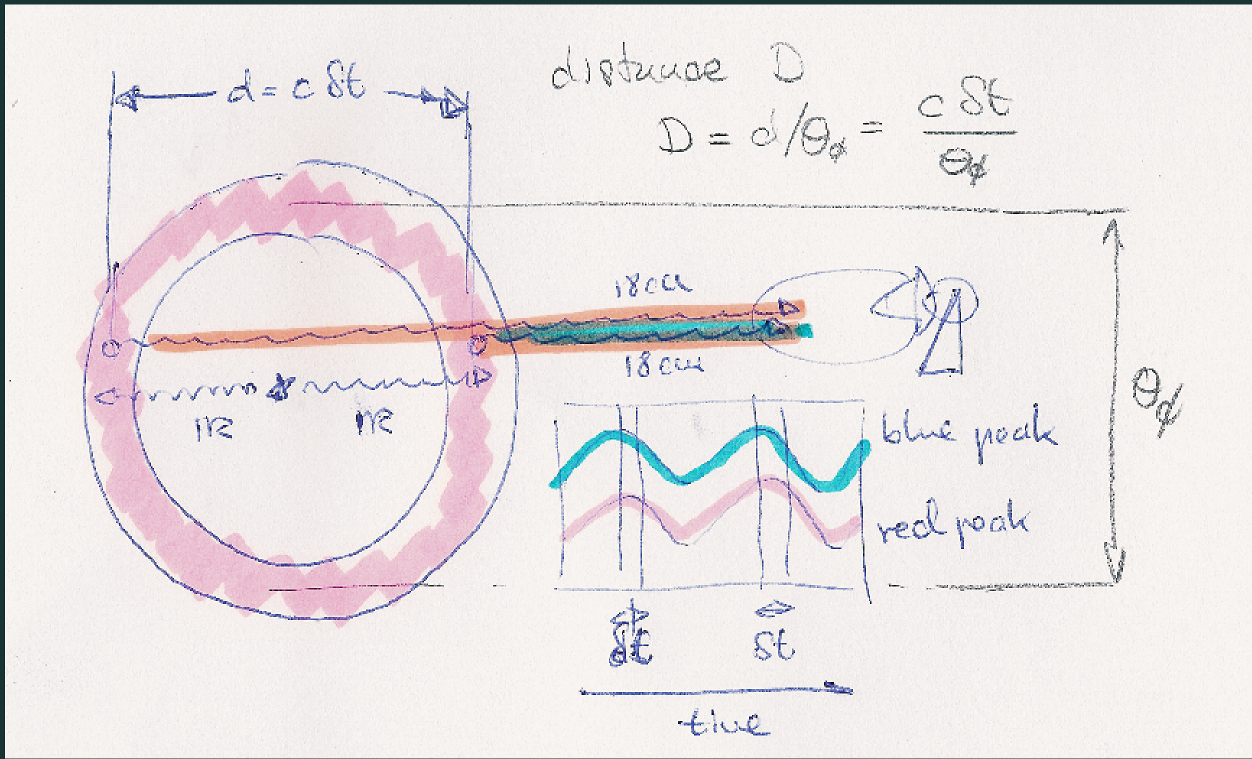
- OH maser profiles are often U-shaped, implying radial amplification of both the front and rear parts of the envelope.
- VLA/MERLIN maps and velocity vs. distance to the star diagrams can be fitted to ellipses.
- These properties indicate that maser emitting region is thin, roughly spherical, and radially expanding at constant velocity.



Distance estimation using OH masers : past

- OH masers in regular variables vary with the same period of the star (due to the pumping).
- There is a delay, δt, of the light curve of the red peak w.r.t. that of the blue one, simply because the extra path travel by red peak photons : the diameter of the envelope $d = c\,\delta t$.
- Knowing the angular diameter of the shell Θ_ϕ, and assuming spherical symmetry, the distance to the source D is given by the expression :

$$D = \frac{d}{\Theta_\phi} = \frac{c\delta t}{\Theta_\phi}$$



Distance estimation OH masers : present

- The most blue-shifted spot of the OH masers can amplify the stellar continuum at 18 cm. If this is the case, the position of this spot on the sky tell us the position of the star itself.
- Vlemmings et al. (2003) performed phase-referenced VLBI observations of such spots in two objects, U Her & W Hya, for several years, obtaining

  the proper motion of the star in the plane of the sky

  the annual parallax and distance to the objects

- These authors also did a similar job using the most red-shifted OH maser spot in R Cas and S CrB.
- See also Vlemmings et al. (2002) for the same technique applied to the 22 GHz H_2O masers in U Her.

218 W. H. T. Vlemmings et al.: VLBI astrometry of circumstellar OH masers

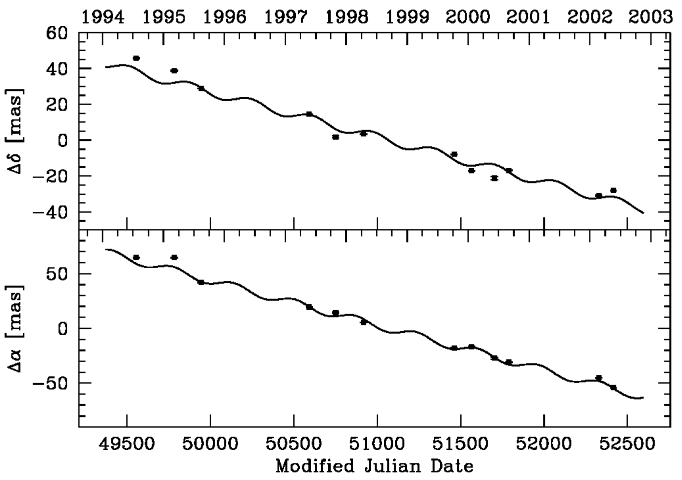


Fig. 6. The position of the most blue-shifted 1667 MHz maser spot of U Her with respect to J1630+2131. The error bars on the positions indicate the formal position fitting errors. The solid line is the best fitting parallax and proper motion trajectory for the 12 epochs of observations. Note that the scales are different for declination and right ascension.

An inventory of (000) H_2O masers

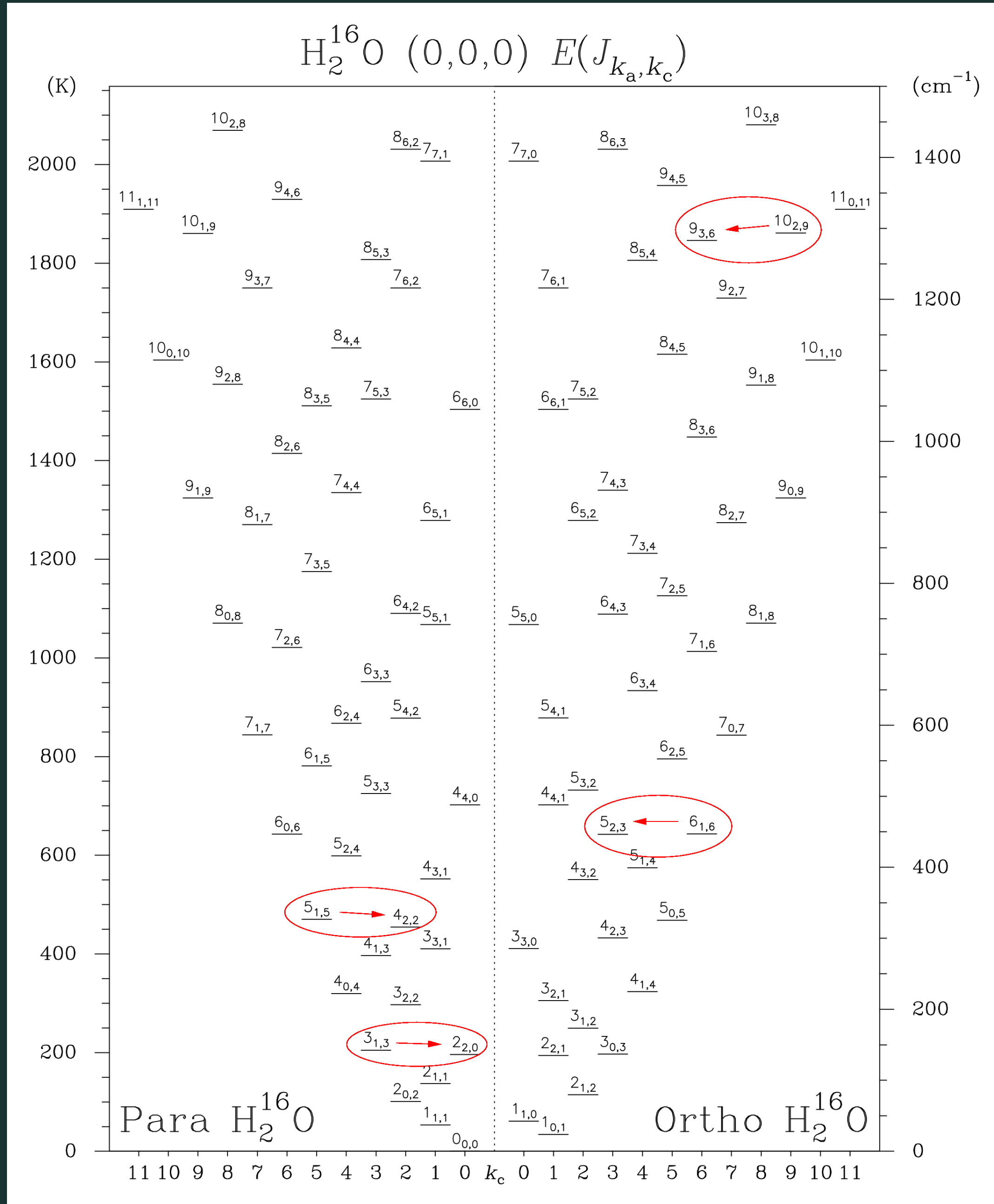
- In addition to the $6_{1,6}$–$5_{2,3}$ @ 22 GHz, we also have H_2O masers from the ground estate in the transitions :

  $3_{1,3}$–$2_{2,0}$ @ 183 GHz

  $10_{2,9}$–$9_{3,6}$ @ 231 GHz

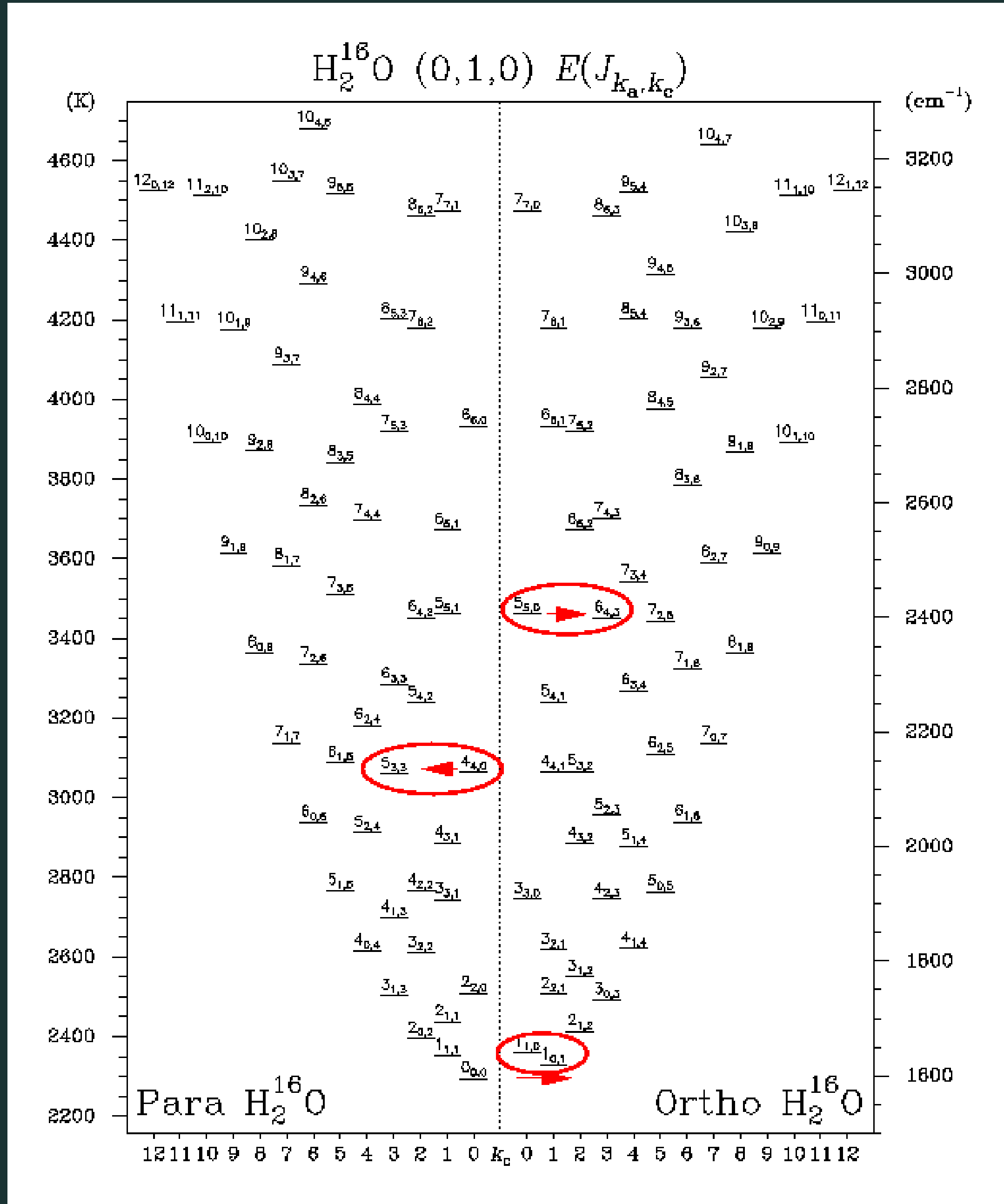
  $5_{1,5}$–$4_{2,2}$ @ 325 GHz

- Upper level always in/near the *backbone*
- Collisional excitation at similar conditions, except for the 231 GHz line which requires higher densities and temperatures.



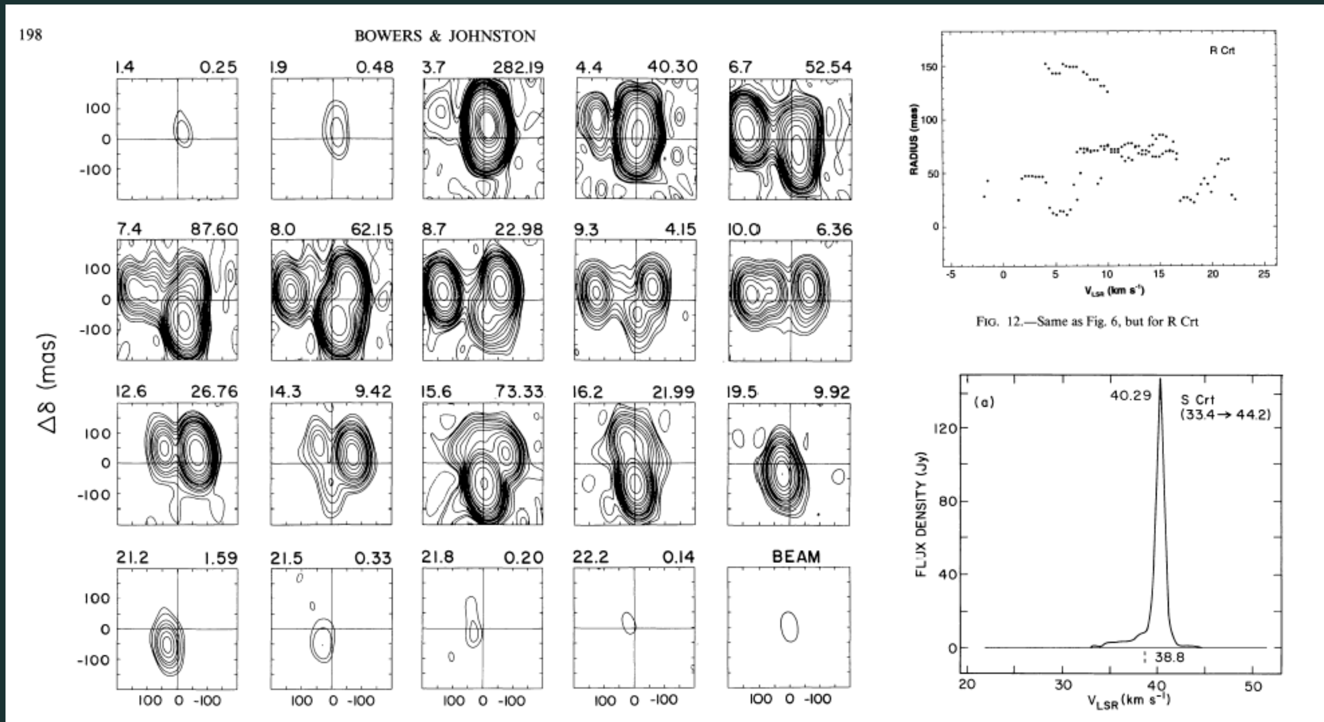
An inventory of (010) H_2O masers

- H_2O masers detected also in the 1st vib. excited estate of the bending mode, (010), in few sources showing strong SiO maser emission (like VY CMa)
- Upper level always in the *transposed backbone* $4_{4,0}$–$5_{3,3}$ @ 96 GHz, $5_{5,0}$–$6_{4,3}$ @ 233 GHz, & $1_{1,0}$–$1_{0,1}$ @ 685 GHz
- They probably arise from the innermost shells of CEs (like SiO masers, since they have similar excitation). No valid model yet. We probably need to include the next excited levels, (100), (020) & (001).



Water vapor : 22 GHz masers (I)

- VLA observations do not resolve them but show that the OH thin shell model does not apply : It occurs at radius of 10^{15} cm. No radial amplification. No constant velocity, the gas is still being accelerated by the *photon pressure*.
- See e.g. Bowers & Johnston (1994), Colomer et al. (2000).



Water vapor : 22 GHz masers (II)

- These results have been confirmed and improved by proper motion measurements made at higher resolution with MERLIN and VLBA, in the super-giants NML Cyg, VY CMa, S Per & VX Sgr (Richards et al. 1996, 1998; Marvel 1996, Murakawa 2003).
- The expansion velocity increases by a factor of two along the H_2O maser region, implying logarithmic velocity gradients of 0.5–1.0.

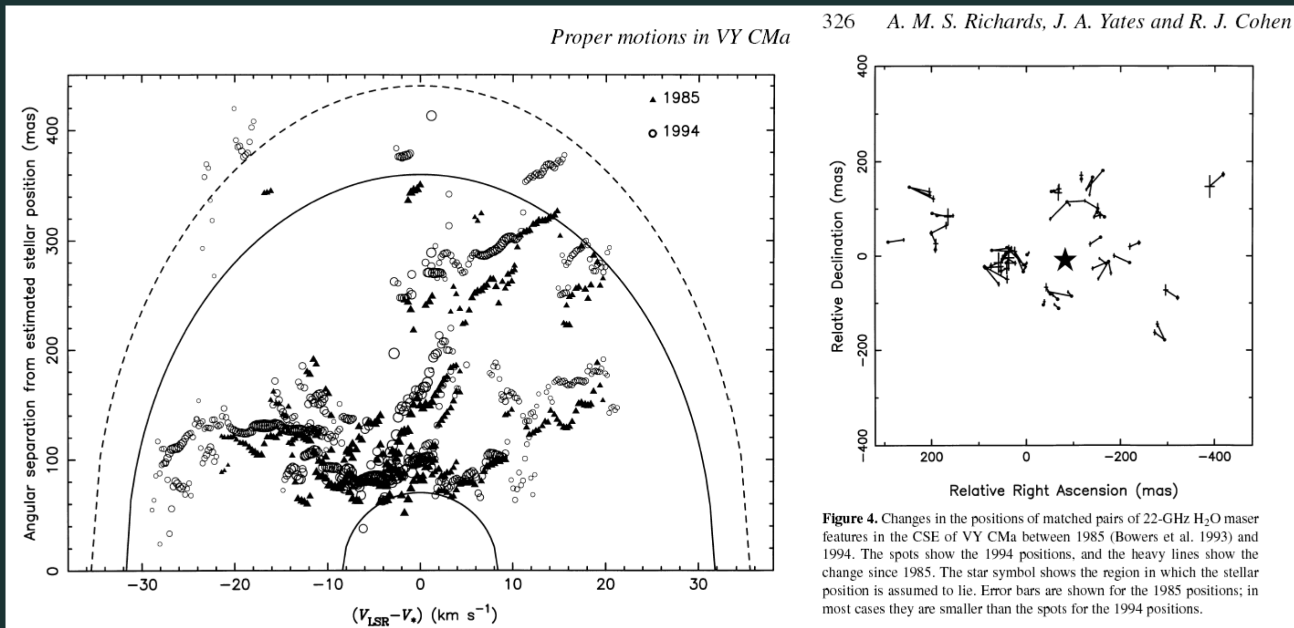


Figure 4. Changes in the positions of matched pairs of 22-GHz H_2O maser features in the CSE of VY CMa between 1985 (Bowers et al. 1993) and 1994. The spots show the 1994 positions, and the heavy lines show the change since 1985. The star symbol shows the region in which the stellar position is assumed to lie. Error bars are shown for the 1985 positions; in most cases they are smaller than the spots for the 1994 positions.

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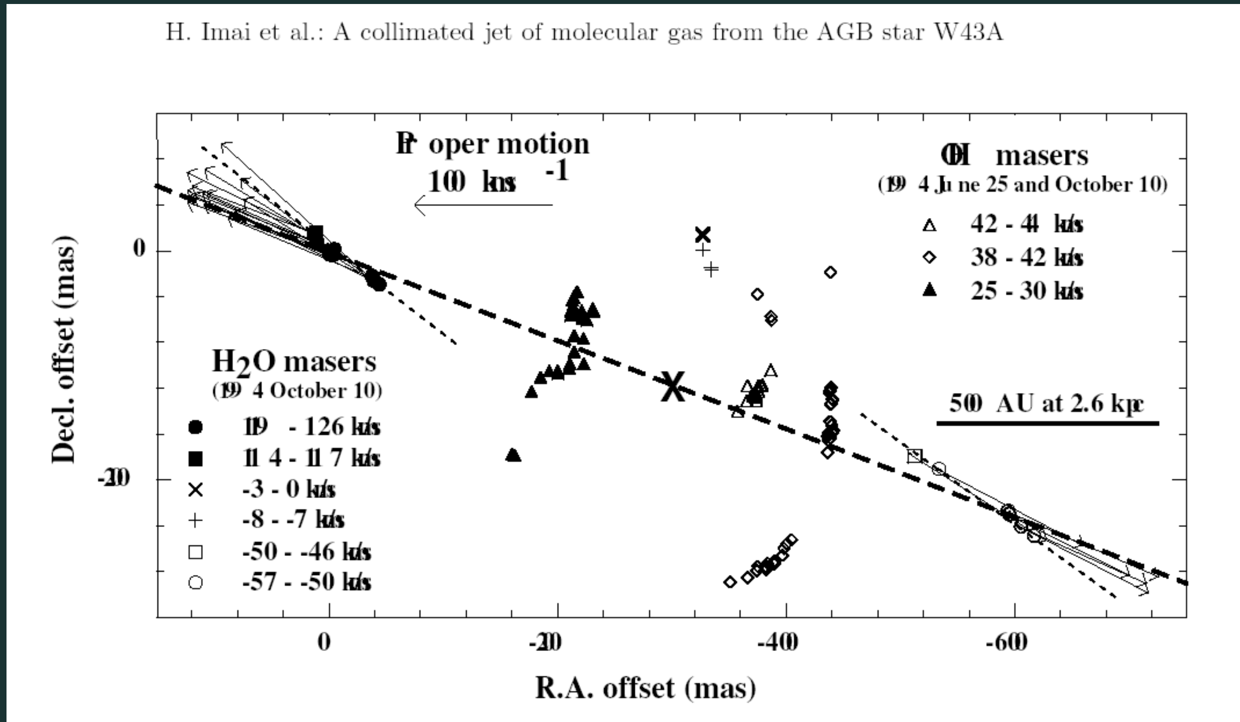
- The expansion velocity increases by a factor of two along the H_2O maser region, implying logarithmic velocity gradients of 0.5–1.0.
- Bains et al. (2003a) obtain similar results just from velocity vs. distance to the center plots. They have observed three Mira variables, U Her, U Ori & IK Tau, and the semi-regular RT Vir.
- See also the proper motion studies by Sudou et al. (2002) and Imai et al. (2003) in the Mira variable IRC +60169 (AP Lyn) & RT Vir.

Water vapor : 22 GHz masers (end)

- Imai et al. (2002, 2004) have also measured proper motions of 22 GHz H_2O masers but in two post-AGB sources (with pre-PN surrounding them), W43A and IRAS 19134+2131.
- In these cases the water masers trace (very young) bipolar outflows that characterize this type of sources.



SiO masers

- SiO masers in CEs are detected in the three main species, ^{28}SiO, ^{29}SiO & ^{30}SiO (with relative abundances of 1/20/30).
- We have maser lines in rotational lines from the J=1–0 (@ 43 GHz) up to the J=8–7 (@ 350 GHz) of the ground v=0 and v=1, 2, 3 & 4 vibrational excited estates (@ 1770, 3530, 5260 & 6970 K).
- The main observed lines are : v=1 J=1–0 and J=2–1, and v=2 J=1–0,
- They arise from the innermost circumstellar layers :

  Because of excitation requirements

  Silicon Monoxide is strongly depleted after grain formation

  VLBI observations show rings of spots with diameters of 10^{14} cm, 2–5 stellar radii (Diamond et al. 1994).

  VLA observations in o Cet place the star at the center of SiO maser ring (Reid & Menten 2002)

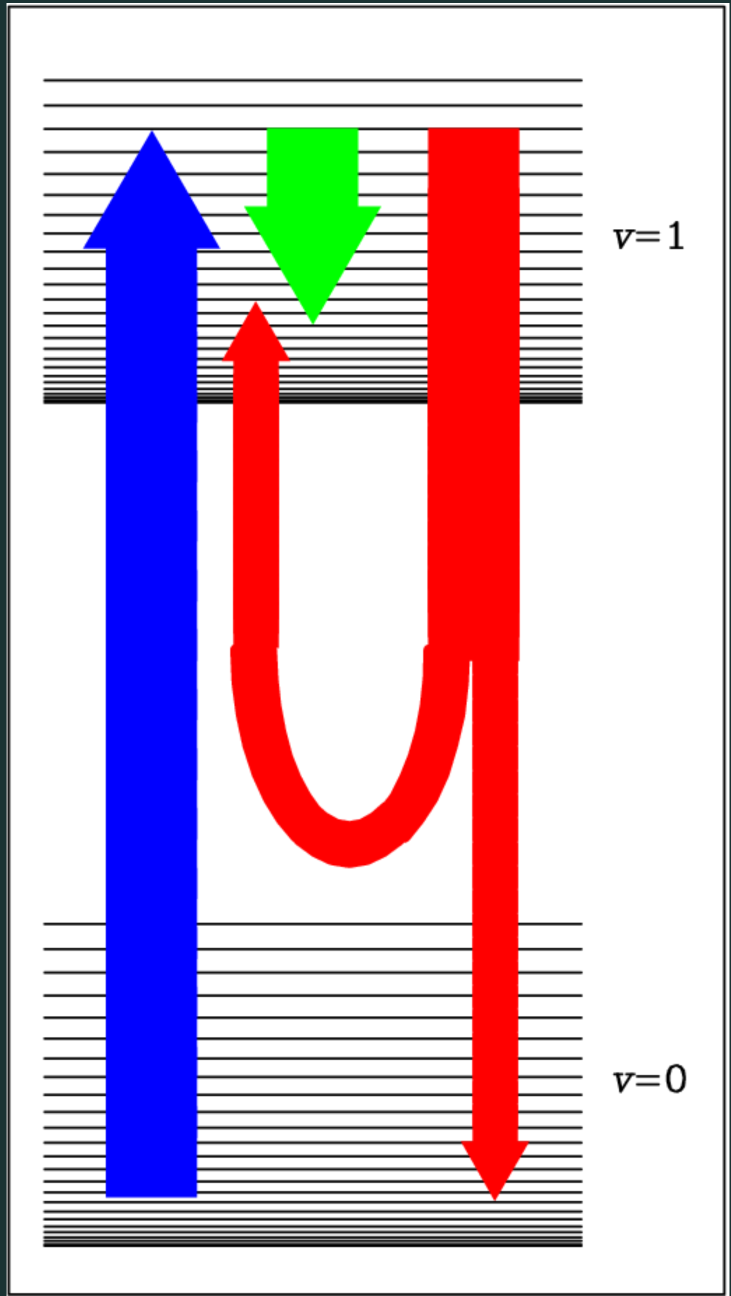
Inversion mechanism for SiO masers

- The inversion of $v \geq 1$ masers is based on *self-trapping* mechanism (Kwan & Scoville 1974).

  When $v \longrightarrow v$–1 transitions are optically thick, the higher the J value the less probable the de-excitation via those transitions, resulting in a chain of inverted populations along the v state.

- On top of this we have the effects of the overlaps of the IR lines of SiO and H_2O.

  The (010)–(000) $11_{6,6}$–$12_{7,5}$ IR line of H_2O quenches off the v=2 J=2–1 ^{28}SiO maser in O-rich sources. (Bujarrabal et al. 1996).

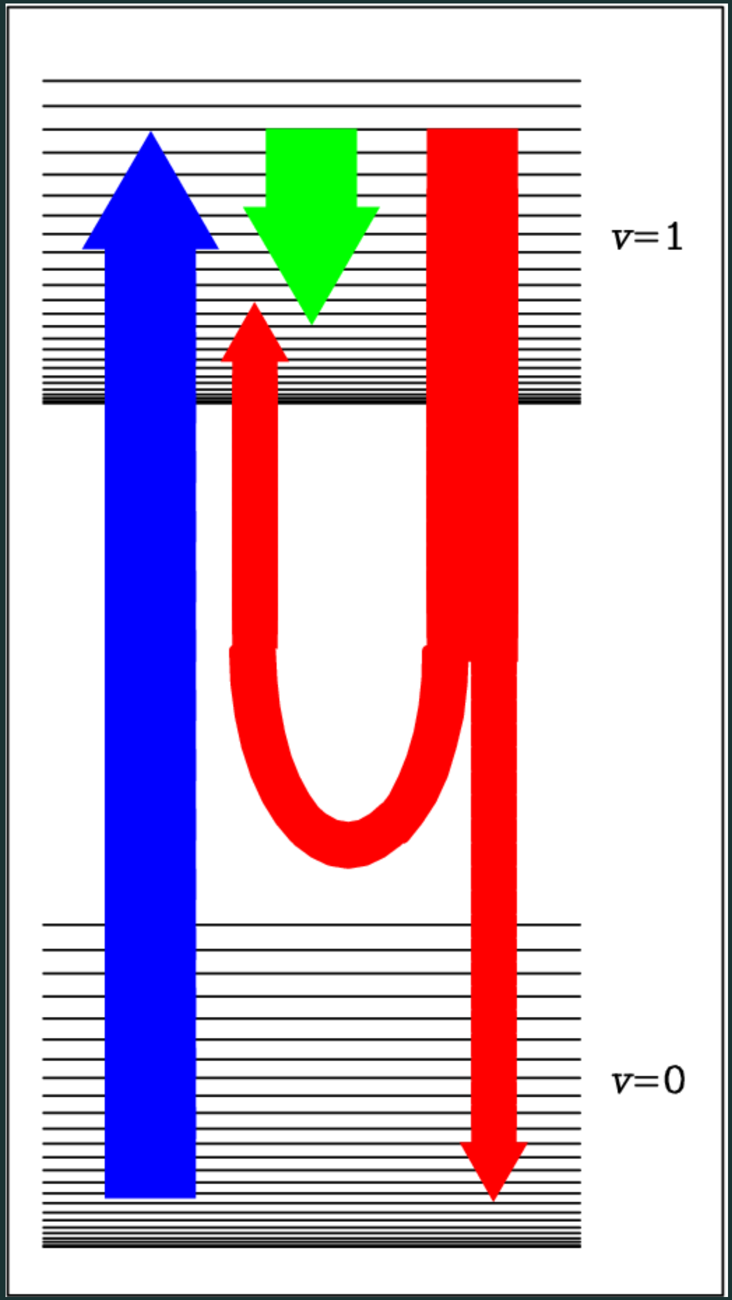


Pumping of SiO masers

- There is still debate on the source of the pumping energy.
- Radiative models (Bujarrabal 1994). SiO masers are pumped thanks to the 8 μm stellar radiation via $v \longrightarrow v{+}1$ transitions, that are optically thin.

  It requires: a thin shell emitting region and/or radial strong accelerations.

  It Explains: the observed rings because of the tangential amplification, the observed linear polarization, the correlation of the SiO maser and IR stellar fluxes, and the variation in phase of both SiO and IR light curves.



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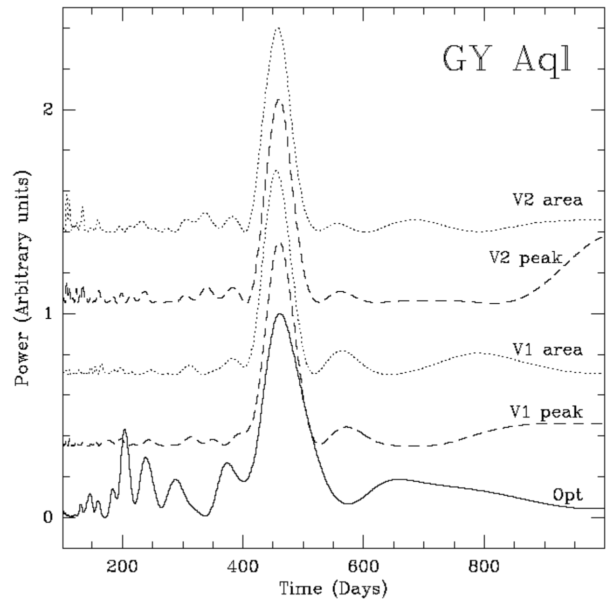
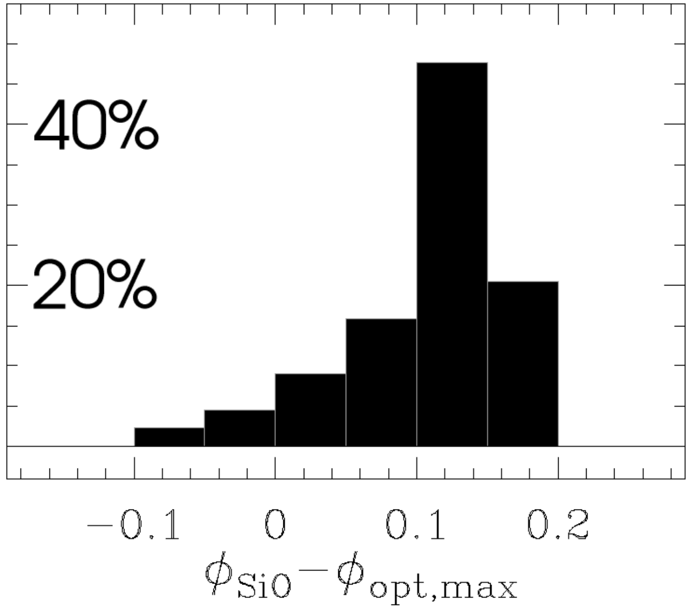


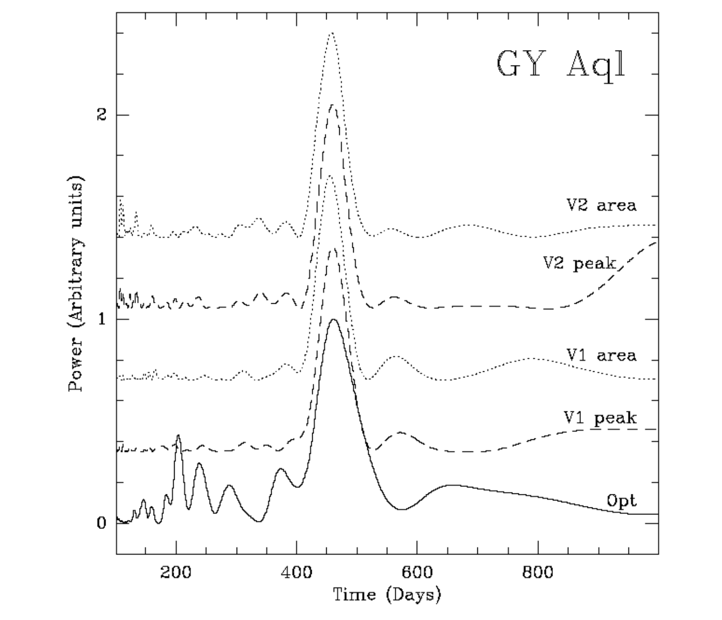


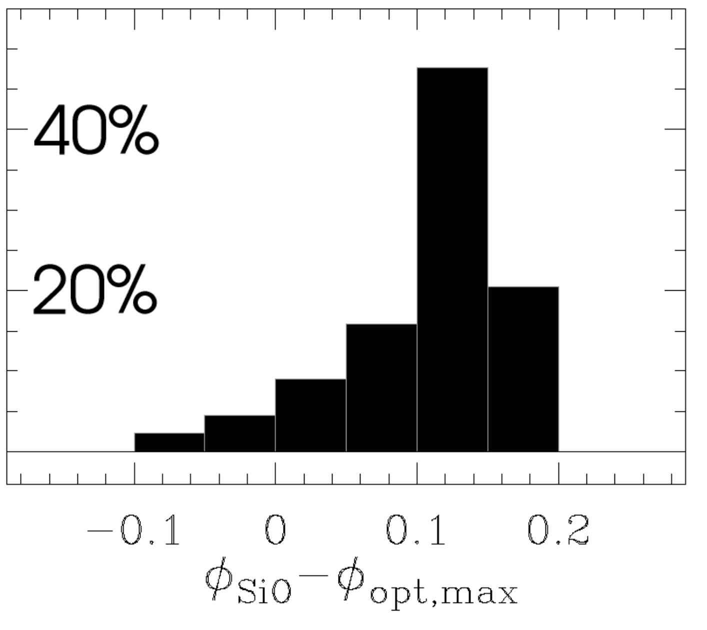
Pumping of SiO masers

- There is still debate on the source of the pumping energy.
- Collisional models (Humphreys et al. 2002). SiO masers are pumped thanks to collisions with H_2, due to the thermal energy of the gas and also the shocks induced by the stellar pulsation.

  It does not requires any special velocity field or geometry for the maser emitting region.

  It is very difficult to explain how the SiO maxima is attain always at the same optical phase for al maser spots in all stars. Propagation at speeds of $\sim 100\,\mathrm{km\ s^{-1}}$ are required.





Pumping of SiO masers

- For better constraining models, simultaneous VLBI maps of several SiO maser lines are required.
- Today we have firm results on the ^{28}SiO v=1 and v=2 masers @ 43 GHz (J=1–0 lines). Both lines show ring-like structures, the v=2 spots being always shifted by 1 m.a.s. inwards (Desmurs et al. 2000, Cotton et al. 2004).
- Particularly useful is the comparison of the v=1 J=1–0, v=1 J=2–1 and v=1 J=1–0 lines

  v=1 J=1–0 and v=1 J=2–1 are adjacent transitions with similar excitation

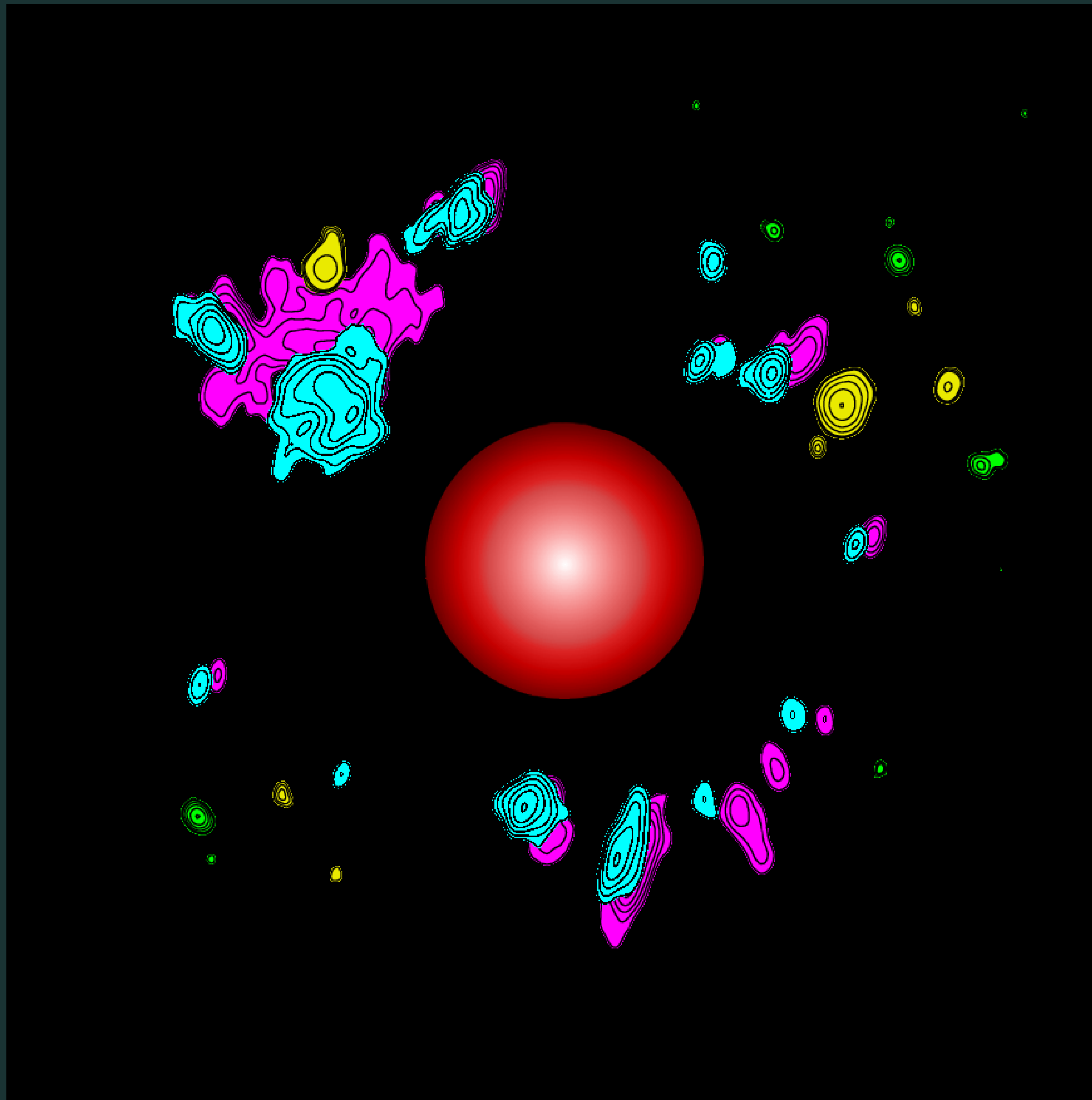
  v=1 J=1–0 and v=2 J=1–0 are lines about the same frequency but with very different excitation, 1770 & 3530 K respectively
- So far, we have simultaneous observations of these three lines in three sources : IRC +10011, χ Cyg and R Cas.

SiO masers in IRC +10011

- Similar results in two epochs (Soria-Ruiz et al. 2004, this proceedings). Three concentric SiO maser rings :

^{28}SiO v=2 J=1–0 (@ 3530 K)
just 1 m.a.s. inside the
^{28}SiO v=1 J=1–0 (@ 1770 K).

^{28}SiO v=1 J=2–1 (@ 1770 K)
4 m.a.s. !!! outside the
^{28}SiO v=1 J=1–0 (@ 1770 K).



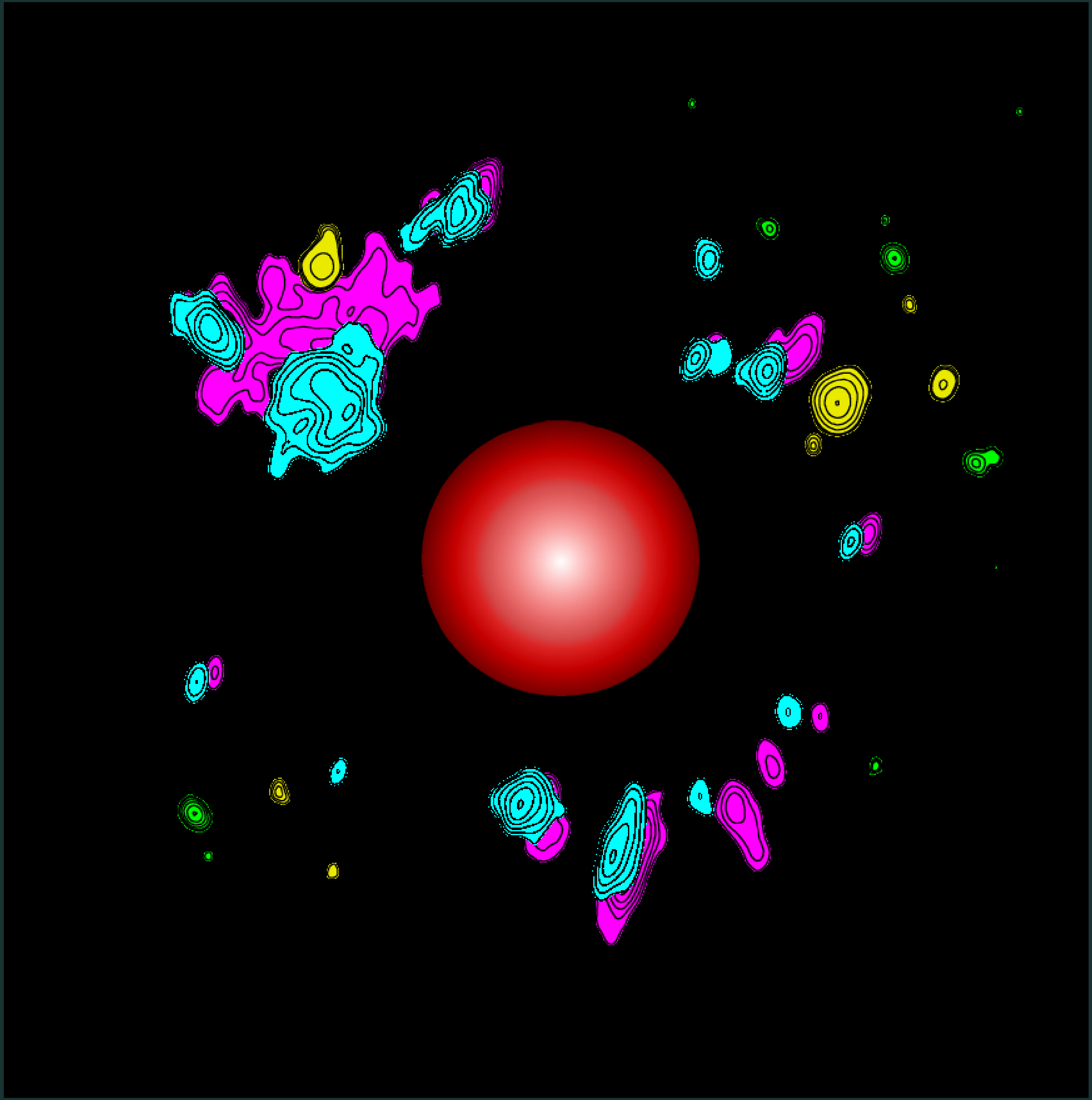
SiO masers in IRC +10011

- Pumping models on the contrary predict :

  ^{28}SiO v=1 J=2–1 (@ 1770 K) and
  ^{28}SiO v=1 J=1–0 (@ 1770 K).
  are very much the same.

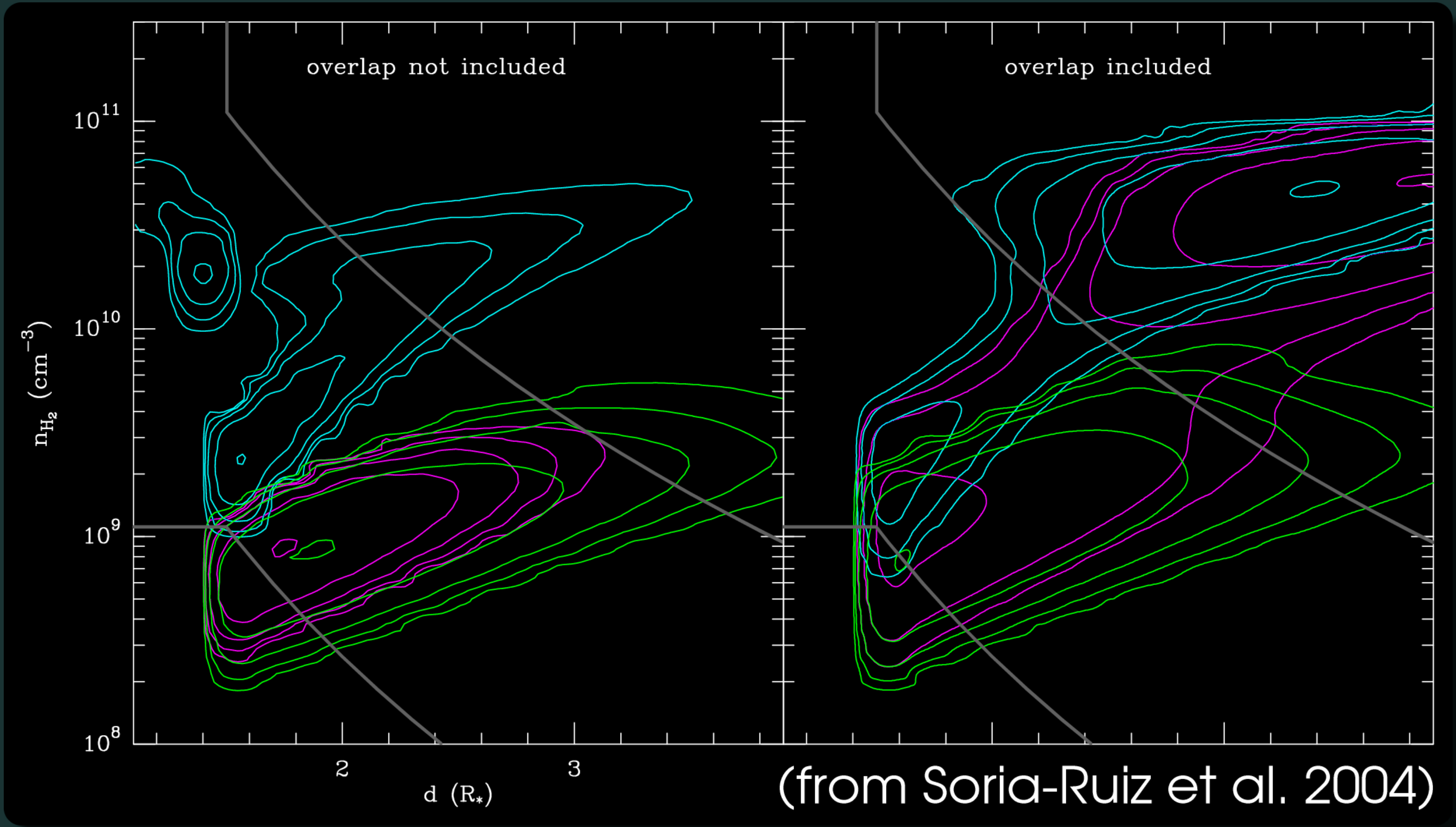
  ^{28}SiO v=2 J=1–0 (@ 3530 K)
  requires different conditions than
  ^{28}SiO v=1 J=1–0 (@ 1770 K).

- Similar results on R Cas ? (Winter et al. 2002, see also Phillips et al. 2003)



The effects of water on SiO

- The overlap between the (010)–(000) $11_{6,6}$–$12_{7,5}$ line of H_2O nad the v=2–1 J=1–0 one of ^{28}SiO may explain IRC +10011's results.



(from Soria-Ruiz et al. 2004)

The effects of water on SiO

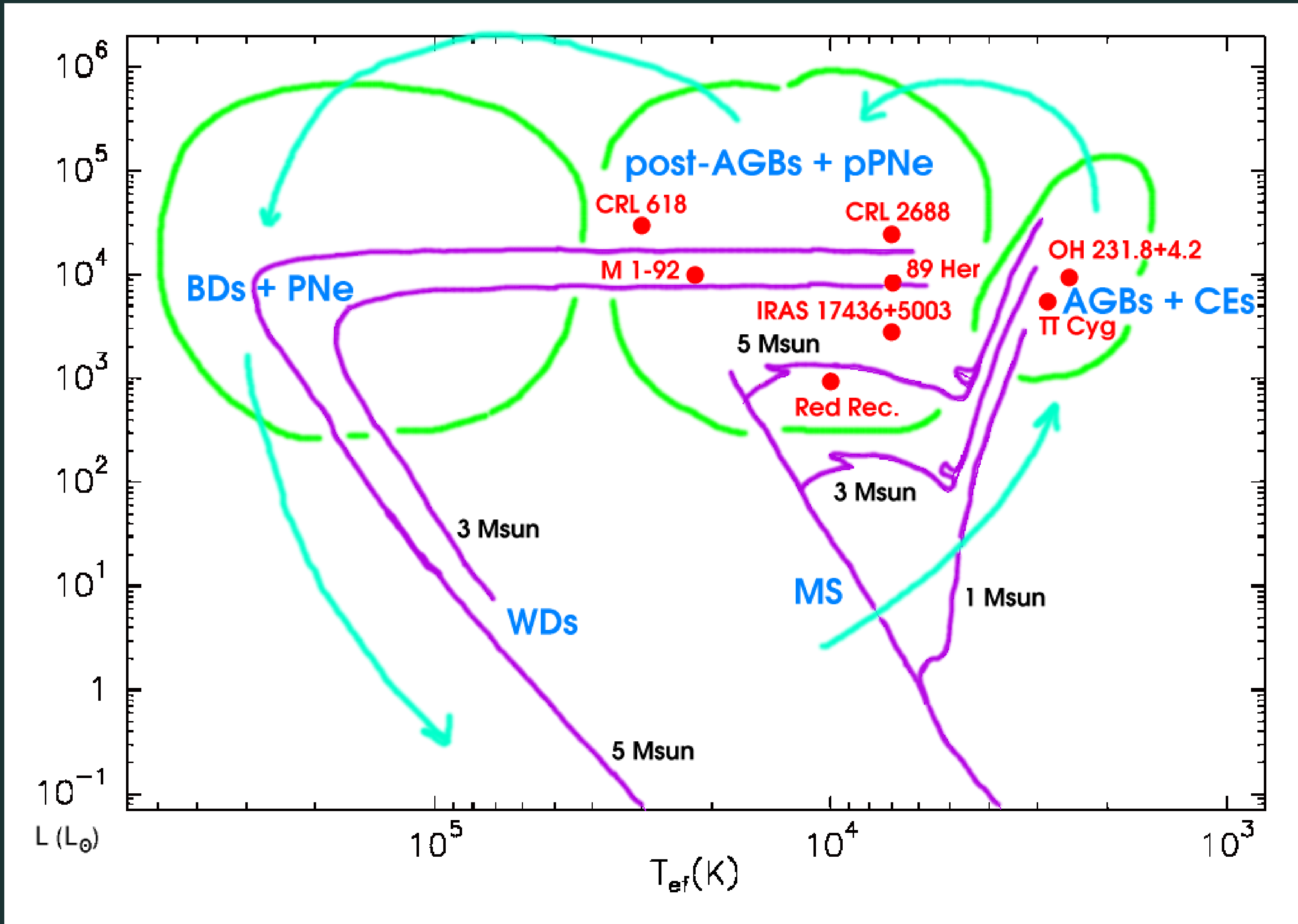
- The overlap between the (010)–(000) $11_{6,6}$–$12_{7,5}$ line of H_2O and the v=2–1 J=1–0 one of ^{28}SiO may explain IRC +10011's results.
- The theory is supported by the results of χ Cyg (v=2 J=2–1 ^{28}SiO maser also detected, Soria-Ruiz et al. 2004)

  Similar sizes for the J=1–0 & J=2–1 emitting regions in both v=1 and v=2 states.

  v=2 masers are much less extended than v=1 ones.
- This is just what pumping models predict. However χ Cyg is a S-type star with much less water abundance (H_2O/OH masers not detected) than O-rich stars (IRC +10011 & R Cas).
- The proposed overlap is anyhow required to explain the weakness of the v=2 J=2–1 line in O-rich sources. This line is normal in S-type stars.
- Still too few data, but more sources and more epochs are yet to come.

Evolution beyond the AGB

- Due to the mass loss along the AGB, mainly during the Superwind Phase, the convective mantle shrinks and finally disappears, almost leaving the H-burning shell exposed. The AGB phase ends, the copious mass loss ends, and the star moves to the right in the H-R diagram becoming a blue dwarf very rapidly (in a few thousand yr).
- At some point in this evolution, the star is hot enough ($> 30{,}000\,\mathrm{K}$) that it can start photo-dissociating and ionizing the former AGB CE, which becomes a Planetary Nebula (PN): and so the former AGB star is called a Planetary Nebula Nucleus (PNN).
- PNe are the result not only of the strong ionizing radiation from their hot central stars, but also of the interaction of a wind released by the PNN (faster and more tenuous) with the former AGB wind (slow but massive). This Interacting Stellar Wind (ISW) model was proposed by Kwok et al. 1978 (ApJ 219, L125) to explain the structure of spherical PNe.


10^6
10^5
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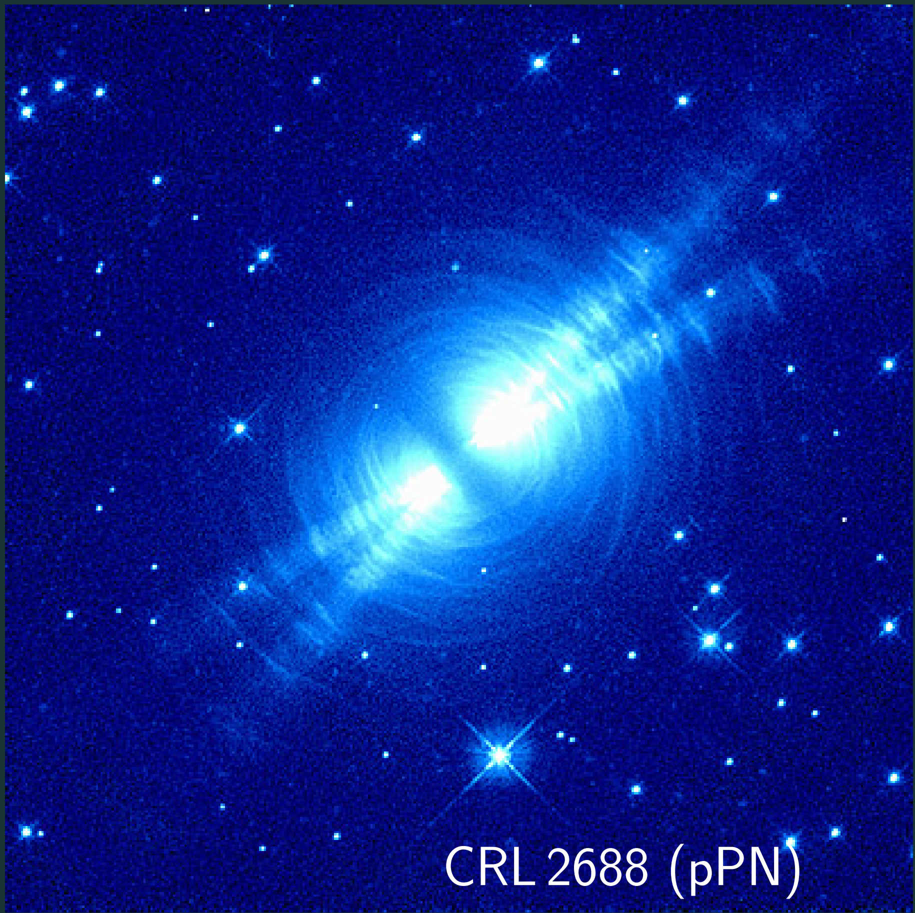
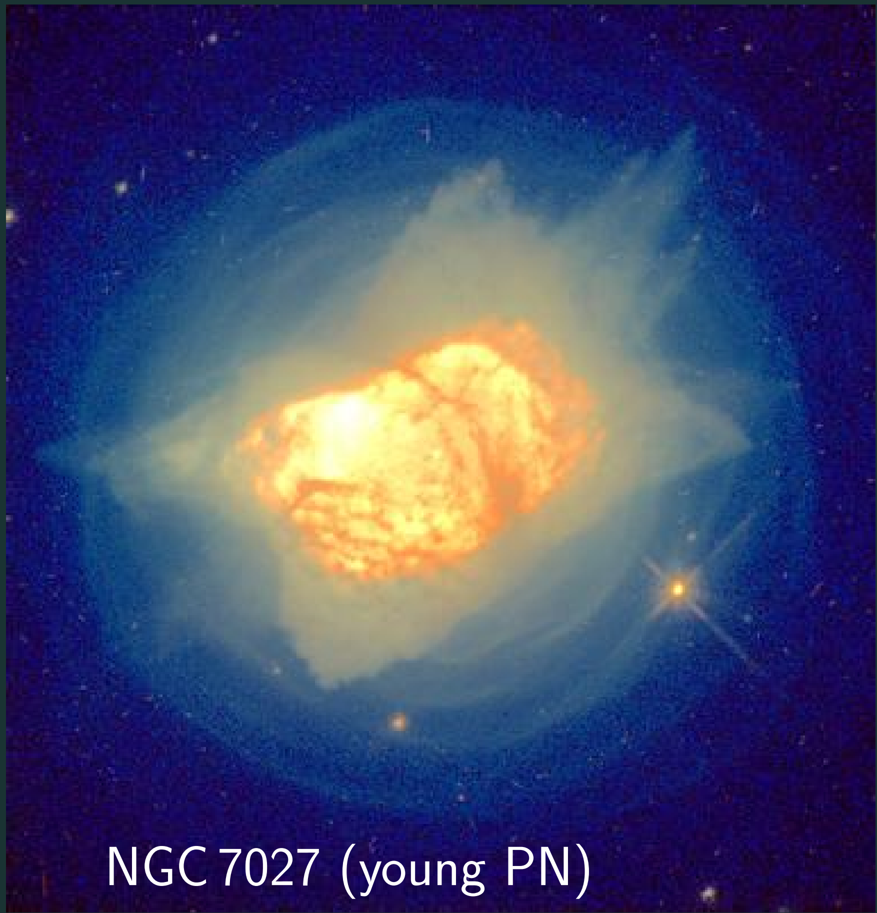
10^3
10^2
10^1
1
10^{-1}
L (L$_\odot$)
10^5
10^4
10^3
T_{ef}(K)
post-AGBs + pPNe
CRL 618
CRL 2688
M 1-92
89 Her
OH 231.8+4.2
BDs + PNe
AGBs + CEs
IRAS 17436+5003
TT Cyg
5 Msun
Red Rec.
3 Msun
3 Msun
MS
1 Msun
WDs
5 Msun

On the shaping of non spherical PNe

- However, not all PNe are spherically symmetric, especially after the HST.



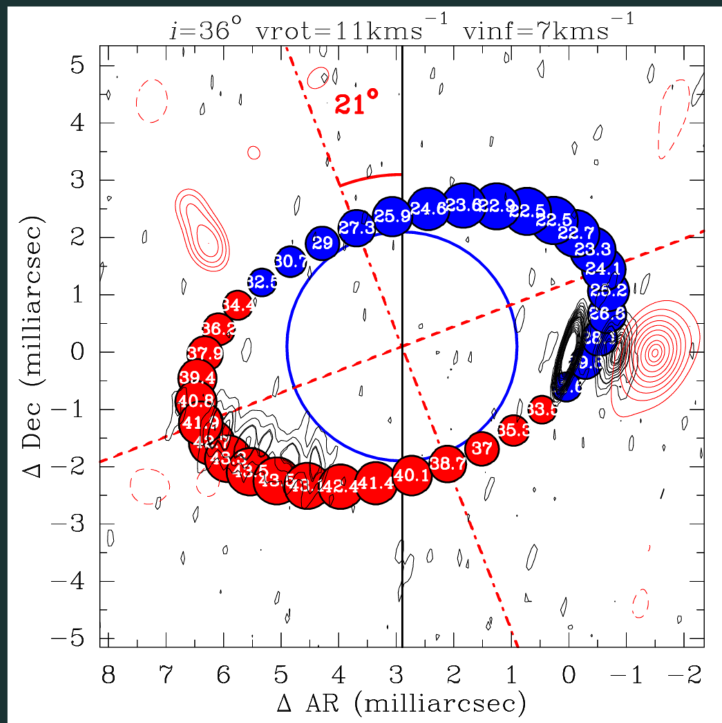


On the shaping of non spherical PNe

- However, not all PNe are spherically symmetric, especially after the HST.
- Today we believe that the symmetry breakup results from the sudden interaction of the slow expanding spherical CE, with some fast bipolar jets released by the star at the end of the AGB.
- These outflows are observed in thermal (CO) and maser lines (H_2O) in the so called pre-PNe (pPNe), objects around post-AGB sources that have not yet attained the PN phase.
- We know for sure that *radiation pressure* is unable to power these bipolar ejecta. Some authors have suggested that some sort of magneto-centrifugal launching must be at work, as it happens in many other bipolar flows in Astrophysics (from AGNs to nano-QSOs and proto-stars).
- This asks for the investigation of the existence of fast rotation and the measurements of magnetic field strengths in envelopes around AGB and post-AGB sources.

Circumstellar rotation as seen by SiO masers

- The closer to the star the better for finding signatures of circumstellar rotation. This makes VLBI observations of SiO masers an ideal test for the existence of rotation at the AGB phase.
- Desmurs et al. (poster session, see also Sánchez-Contreras et al. 2002) found a disk of SiO masers probably orbiting around the central star. However this is a very peculiar case : a strongly bipolar pre-PN with a AGB-like star.



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- Hollis et al (2001) found that SiO masers in R Aqr are in Keplerian rotation, but again this a very peculiar case since it is a symbiotic system (it has compact hot companion).
- Boboltz & Marvel (2000) claimed the detection of rotation at speeds of $\sim 10\,\mathrm{km\ s^{-1}}$ in the super-giant NML Cyg. (However they assumed a systemic velocity that disagrees with that from thermal CO by $\sim 5\,\mathrm{km\ s^{-1}}$.)
- In addition to R Aqr, Cotton et al. (2004) reported indications of rotation only in S CrB (out of nine targets observed).

Maser polarization and the circumstellar magnetic field

- The polarization properties of the different circumstellar masers can be used to probe the strength of stellar magnetic field across the envelope.
- SiO masers show strong linear polarization but perpendicular to the radial direction. This is a natural consequence for radiative pumping models.
- Kemball & Diamond (1997) reported the detection of small circular polarization in TX Cam, implying magnetic field values of 5–10 G in the SiO maser region.
- Circular polarization measurements of 22 GHz H_2O masers by Vlemmings et al. (2002) give values of 100-500 mG in three super-giants and of 1 G in the Mira variable U Her.
- And from the polarization of OH masers, Bains et al. (2003 & 2004) and Szymczak & Gérard (2004) find magnetic field strengths of a few mG in some pre-PNe.

Prospects for the future

- The HSA, and the combination of the EVLA+VLBA will improve the sensitivity and dynamic range of the arrays at 7 mm : weak SiO masers (^{28}SiO v=3, ^{29}SiOv=1, ^{30}SiO v=0, etc.). Same for the 3 mm band thanks to the GMVA : HCN masers, SiO J=2–1 masers. The new 40 m dish in Yebes should play a role in these arrays.
- eEVN will certainly allow to organize more frequent VLBI sessions, from which proper motion studies will greatly benefit.
- The VERA will provide multi-epoch maps of 43 GHz SiO & and 22 GHz H_2O masers for numerous AGB envelopes, in addition to providing accurate positions and distances.
- ALMA will be able to provide 6 m.a.s. resolutions at 700 GHz, being an ideal complement to VLBI studies of both SiO and H_2O masers.

Prospects for the future (end)

- The observations of the H_2O thermal lines in CEs, to be carried out with the HIFI instrument on the Herschel satellite (formerly known as FIRST), would greatly benefit from the accurate knowledge of the geometry and kinematics provided by VLBI observations of circumstellar masers.
- VLTI-VINCI will monitor the changes in size and temperature of AGB stars. VLTI-MIDI will do a similar job on the dust formation layers. Simultaneous high spatial resolution observations of H_2O and SiO masers are mandatory to have a complete picture of these inner shells of the envelopes.
- And finally, we should be prepared for the SKA when it comes.