Maser Theory: Old Problems and New Insights

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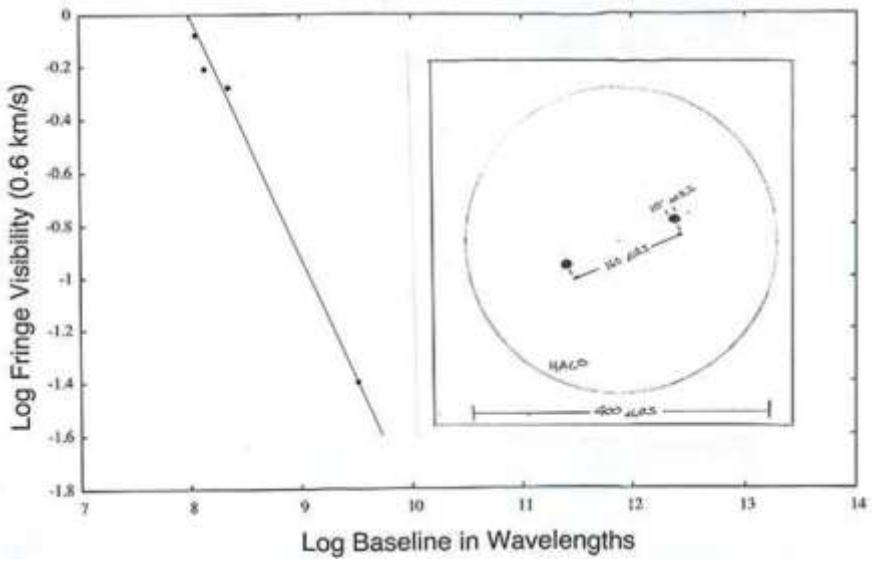
Topics

- ...in the limited time available!
- New data and coherence properties
- Polarization: a very old problem
- Molecular data (other talks)
- What are the masing objects?
- A 3-D model and variability
- The wilder shores (e.g. ASE? POAM?): another time

New Data on Coherence Properties

- Phase coherence usually ignored on grounds of source size
- 👎↗=L□❑^{2}/● (e.g. Elitzur 1992)
- H_2O maser in Cep A unresolved at 10 ❍as (10^9 m)
- 👎↗/(2□) = 3.7x10^{10} ❑^{2}



Fringe visibility amplitude for the 0.6 km/s feature in CepA observed using 3 ground-ground VLBI baselines. Including RadioAstron to Yebes data leads to the model of a pair of 10❍as features separated by 160❍as. The compact features contain 4% of the total flux (Sobolev+, in prep.)

Further Comments

The brightest H_2O masers are within a factor of order 1 of bandwidth coherence **if** $\Phi \sim 0.1$

Slysh (2003ASPC..300..239S) invokes self-Stark limit to brightness (line will split due to Stark effect by electric field of radiation)

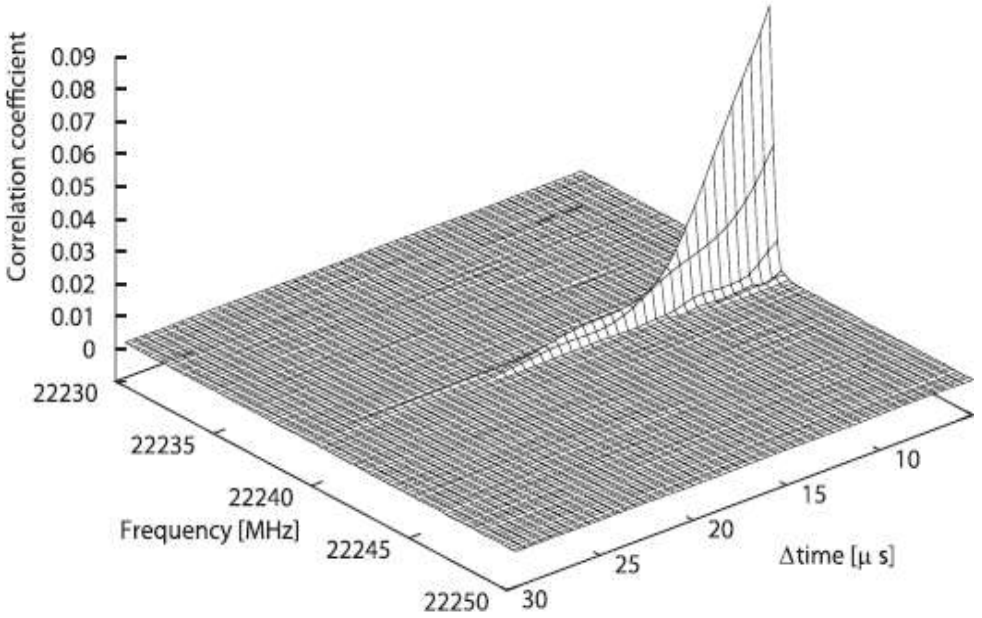
No such splitting observed: upper limit on Φ

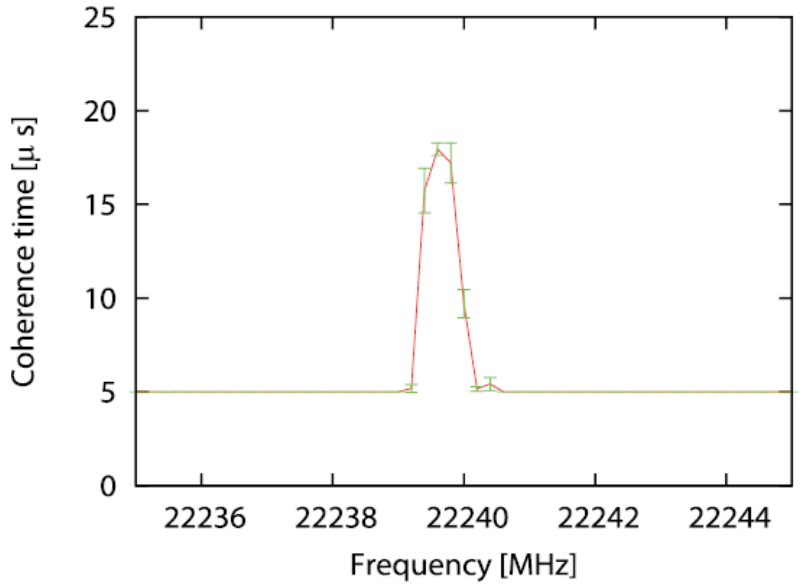
Φ_{max} for Orion-KL is 0.002, so Tb is only 1/15 of threshold for pulsation

Need for narrower lines? Restrict obs. Band?

Read Menegozzi & Lamb, 1978PhRvA.17..701M

Measured Coherence Times





New-style cross-correlation spectroscopy measures coherence times (2016PASJ...68...86T)

Typical ♦~10-30❍s

Channels 15.6kHz

👎♦~1/♦=33-100kHz

Doppler width 90kHz

Coherence across

Coherence Functions

Observational $f_{co}(t)$ does not decay like Gaussian

Please can I write on a board?!

$f_{co}(t)$ is Fourier transform of the line shape function

Intense maser radiation broadens homg. lsf

Point about Voigt profile: if homog. & inhomg. widths similar, Gaussian decay still dominates

Looks like NVR: independent subgroups so inhomog. profile not very important.

What we see is dependent on frequency binning: we must resolve the homog. profile

Polarization – many problems

Definitions: see 2014MNRAS.440.2988G.There are 4 (3 if U is uncoupled) equations, so can't write a 'formal solution'?

Use E. Landi Degl'Innocenti's method (1987nrt..book..265L) to write the analogue of the scalar case: the RT equation for ***i*** *=(i,q,u,v),*

$$d\boldsymbol{i}/d\tau = \eta\boldsymbol{i}$$

with Stokes matrix,

$$\eta = \begin{bmatrix} \eta_i & -\eta_q & 0 & -\eta_v \\ -\eta_q & \eta_i & 0 & 0 \\ 0 & 0 & \eta_i & 0 \\ -\eta_v & 0 & 0 & \eta_i \end{bmatrix}$$

is solved via the matrix operator, O(♦,♦'), where ♦' tends to 0 in

$$\mathrm{O}(\tau,\tau') = \mathrm{I} + \sum_{n=1}^{\infty} \frac{1}{n!} \int_{\tau'}^{\tau} d\tau_1 \int_{\tau'}^{\tau} d\tau_2 \ldots \int_{\tau'}^{\tau} d\tau_n P\left\{\eta(\tau_1)\eta(\tau_2)\ldots\eta(\tau_n)\right\}$$

$$\boldsymbol{i}(\tau) = \mathrm{O}(\tau,\tau')\boldsymbol{i}(\tau')$$

Saturation: Zeeman-split Inversions

For a CVR solution, at some node j, find the 3 inve

$$D = (1+2f^0)[1+2(g^- + h^-) + 2(g + -h^+) + 3(g^+g^- - h^+h^-) + 5(g^+h^- - g^-h^+)]$$
$$+ f^+[h^0(1+h^- + 3g^-) - g^0(1+g^- + 3h^-)] - f^-[h^0(1-h^+ + 3g^+) + g^0(1+g^+ - 3h^+)]$$

A

$$\Delta^+ = \frac{\alpha^+}{D}\left\{(1+2f^0)\left[1 - \frac{\alpha^-}{\alpha^+}(g^+ + h^+) + 2(g^- + h^-)\right] + (\frac{\alpha^-}{\alpha^+}f^+ - f^-)(g^0 + h^0)\right.$$
$$\left. + \frac{\alpha^0}{\alpha^+}\left[f^-(g^+ + h^+) - f^+(1 + 2g^- + 2h^-)\right]\right\}$$

$$\Delta^0 = \frac{\alpha^0}{D}\left\{1 + 2(g^- + h^-) + 2(g^+ - h^+) + 3(g^+g^- - h^+h^-) + 5(g^+h^- - g^-h^+)\right.$$
$$\left. - \frac{\alpha^+}{\alpha^0}\left[g^0(1 + g^- + 3h^-) - h^0(1 + 3g^- + h^-)\right] - \frac{\alpha^-}{\alpha^0}\left[g^0(1 + g^+ - 3h^+) - h^0(1 + 3g^- + h^-)\right]\right\}$$

$$f^{0,\pm} = \frac{1}{4\pi}\oint 2(\bar{i}^{0,\pm} - \bar{q}^{0,\pm})\sin^2\theta d\Omega \qquad g^{0,\pm} = \frac{1}{4\pi}\oint \left[(1+\cos^2\theta)\bar{i}^{0,\pm} + \bar{q}^{0,\pm}\sin^2\theta\right] d\Omega$$

$$h^{0,\pm} = \frac{1}{4\pi}\oint 2\bar{v}^{0,\pm}\cos\theta d\Omega$$

with

Physical Nature of Masing Objects

We would probably say 'clouds'?

Shocked layers, condensations from instabilities, turbulent eddies, cometary comae, ?

In most cases, we don't really know

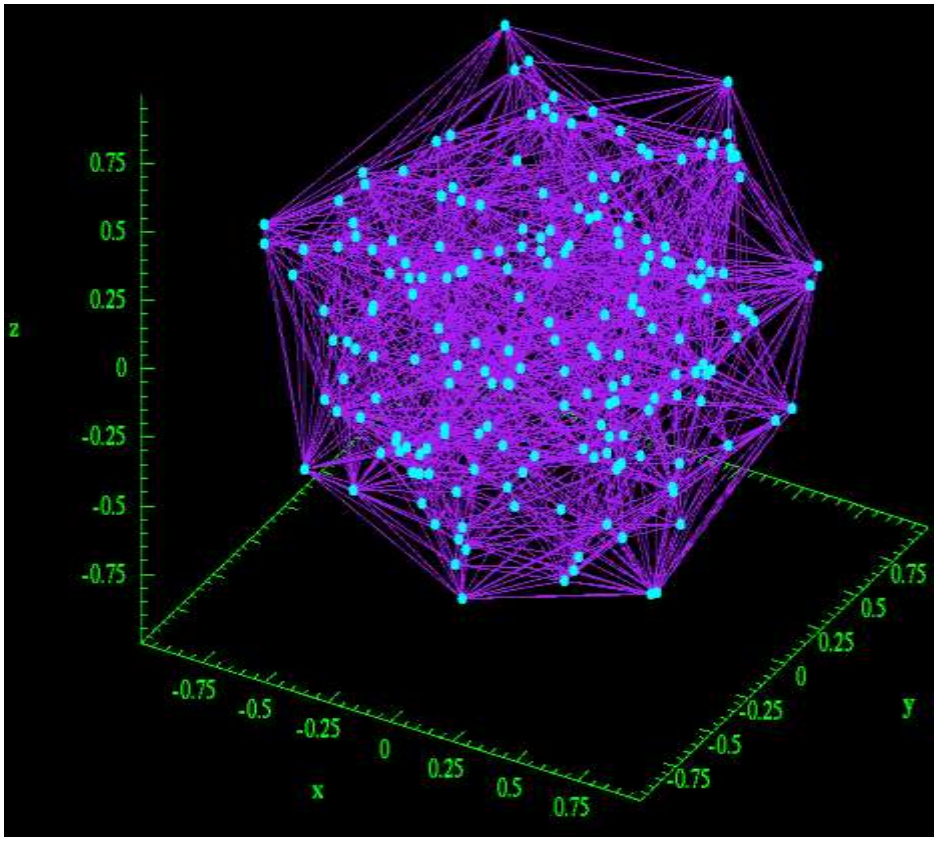
Probably irregular shapes

Typically have a surrounding medium that emits far less brightly, at least in our direction

Almost certainly move as physical objects (not wave phenomena) from proper motion distances

Calls for 3D modelling of irregular clouds

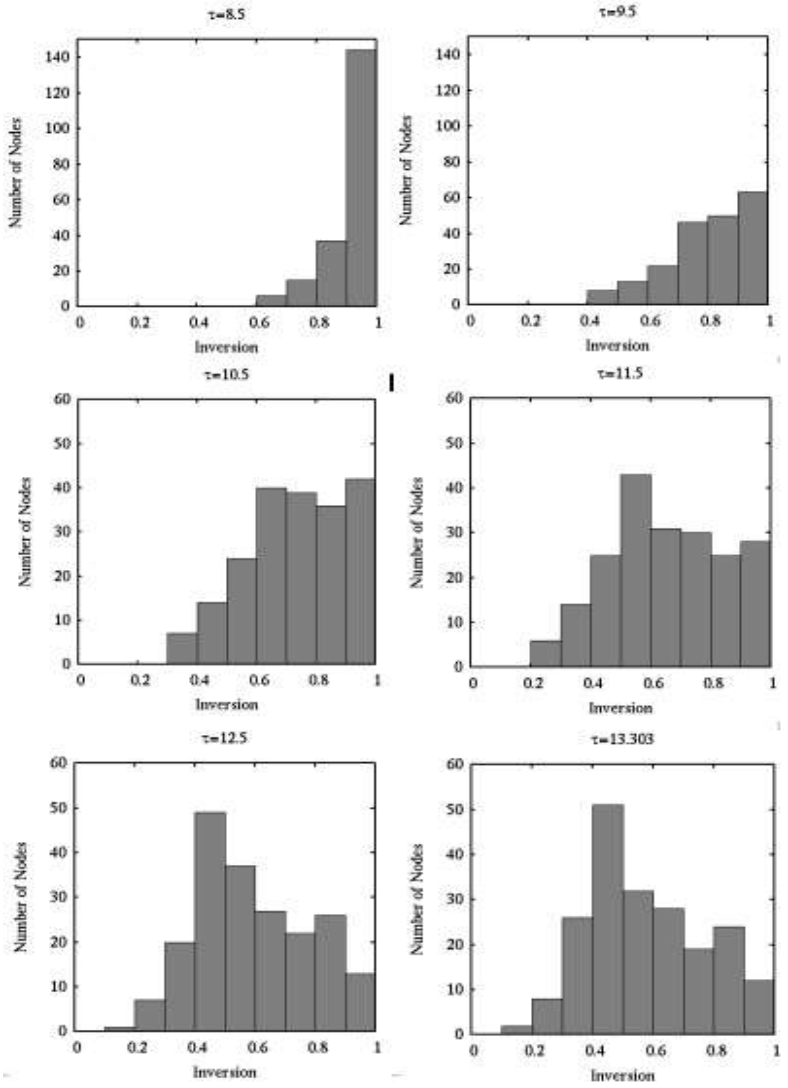
A 3-D Maser Model with Saturation

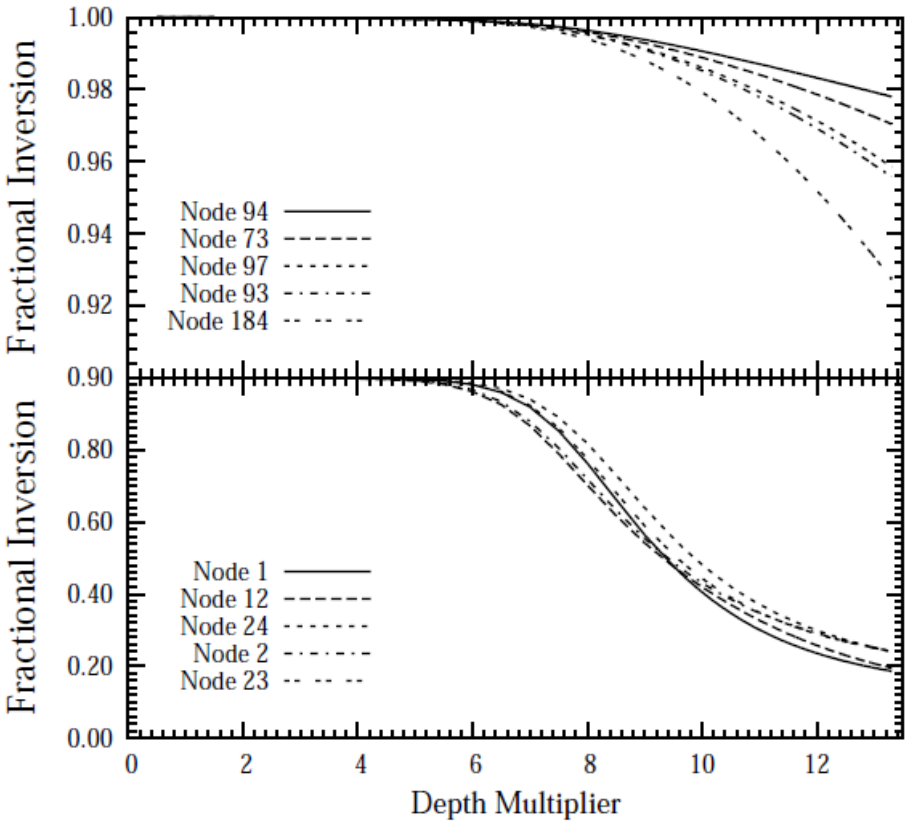


$$\Delta_i - \left[1 + \frac{i_{BG}}{4\pi} \sum_{q'=1}^{Q'} \frac{a_{q'}}{s_{q'}^2} \sum_{n=0}^{\infty} \frac{1}{n!(n+1)^{1/2}} \left(\sum_{j=1}^{J} \Phi_{j,q'} \Delta_j \right)^n \right]^{-1} = 0$$

- Irregular DeLaunay triangulated domain
- Initial test is uniform, 2 level, CVR
- Simulation of rotation
- Can be made much more general
- Population solution at nodes (202 here): finite element implementation of CEP

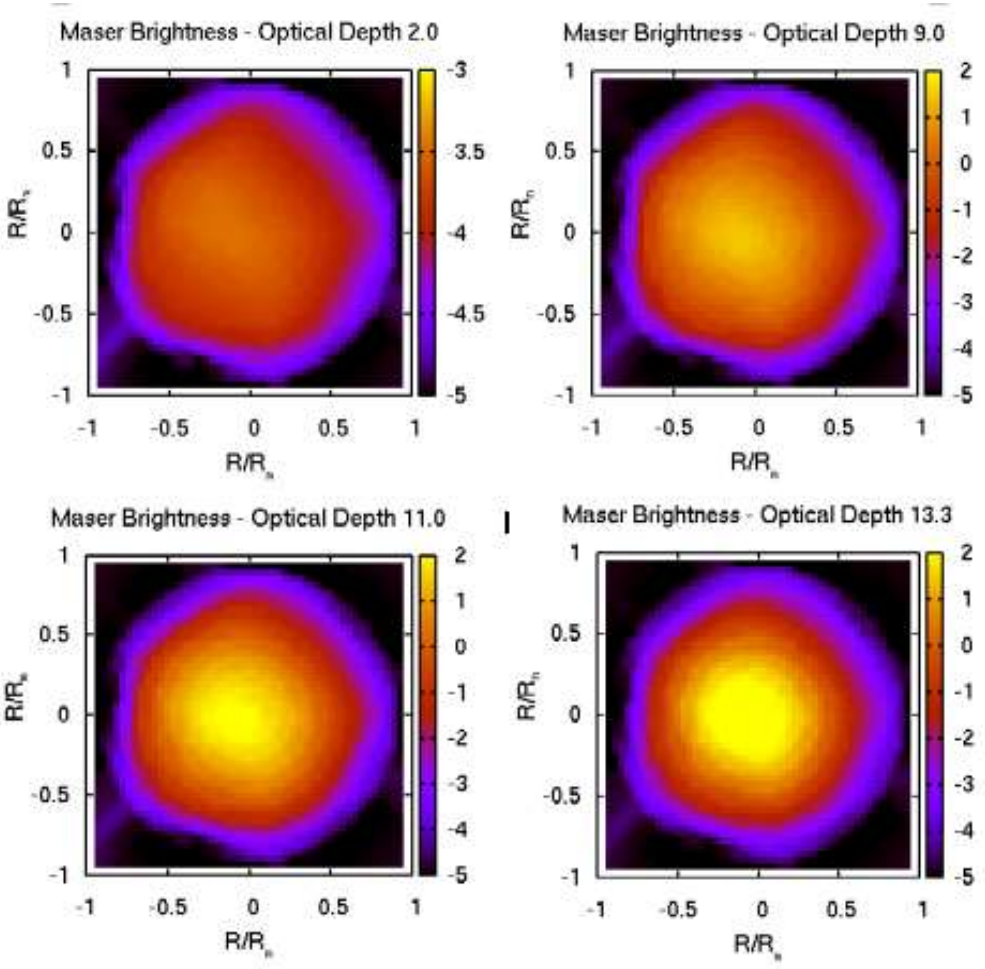
Saturated Populations





Formal Solutions

- Test behaviour against expectations for spherical models
- Amplify background through **known** nodal solution
- Unsaturated core versus saturated shell
- Maser looks smaller than physical cloud
- Size and beam angle



Simulations of Rotation

Rotation axis selected so long axis of domain passes through line of sight

