Dense Gas Diagnostics: Maser Excitation and Variability

Malcolm Gray*

*Astrophysics Group, Department of Physics
University of Manchester Institute of Science and Technology
PO Box 88, Manchester M60 1QD, United Kingdom
Malcolm.Gray@umist.ac.uk

A Bestiary of Maser Diagnostics

- OH Zeeman Patterns: magnetic fields
- Proper Motions: cloud dynamics
- Velocity Gradients: rotation and gravitation
- Copropagation: density, temperature and more?
- Long-Term Variability: turbulence, pumping
- Short-Term Variability: coherence
- Future of Observations and Theory

OH Masers and Magnetic Fields

- OH is unique amongst strong-maser molcules: Zeeman effect of hyperfine structure
- Splittings larger than Doppler widths for mG fields
- Field-strength recovered directly from observations of Zeeman pairs
- Sense of field from lcp line blue or red of rcp
- Sky component of field from linear polarization (with assumptions)
- Full recovery of vector field requires modelling
- Need VLBI resolution to assign pairs unambiguously

OH Zeeman Pairs

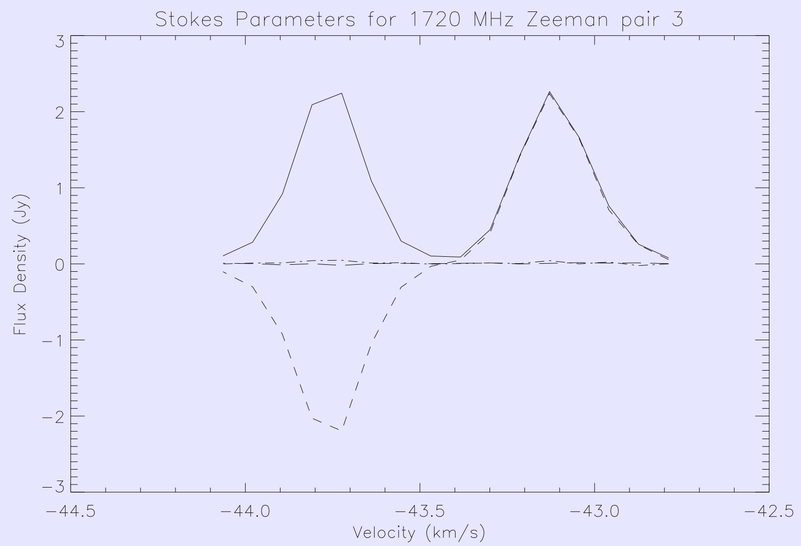


Figure 1: A single VLBA spot Zeeman pair from W3(OH)

- Theory of Zeeman effect for OH[1]
- Confirmed at VLBI resolution[2]
- Excited state lines in W3(OH)[3 4]
- Main lines have one splitting each; possible ambiguity with satellites
- Smallest measureable field ~1 mG (linewidth)
- Limits on largest field (band, linearity of effect)
- Full-polarization observations best
- Megamasers - unlikely[5]

Dousmanis et al.[1], Lo et al.[2], Baudry & Diamond[3], Desmurs et al.[4], Killeen et al.[5]

B-field Map of W3(OH)

- The map contains 211 points
- Composite of 1.7 GHz, 6 GHz and 13 GHz data
- Zeeman pairs from all four ground-state lines used
- Maximum field in map is 12.3 mG, near (0,0)
- Field centre (0,0) is at $02^{h}27^{m}03^{s}.825, +61^{\circ}52'25''.09$ (J2000)

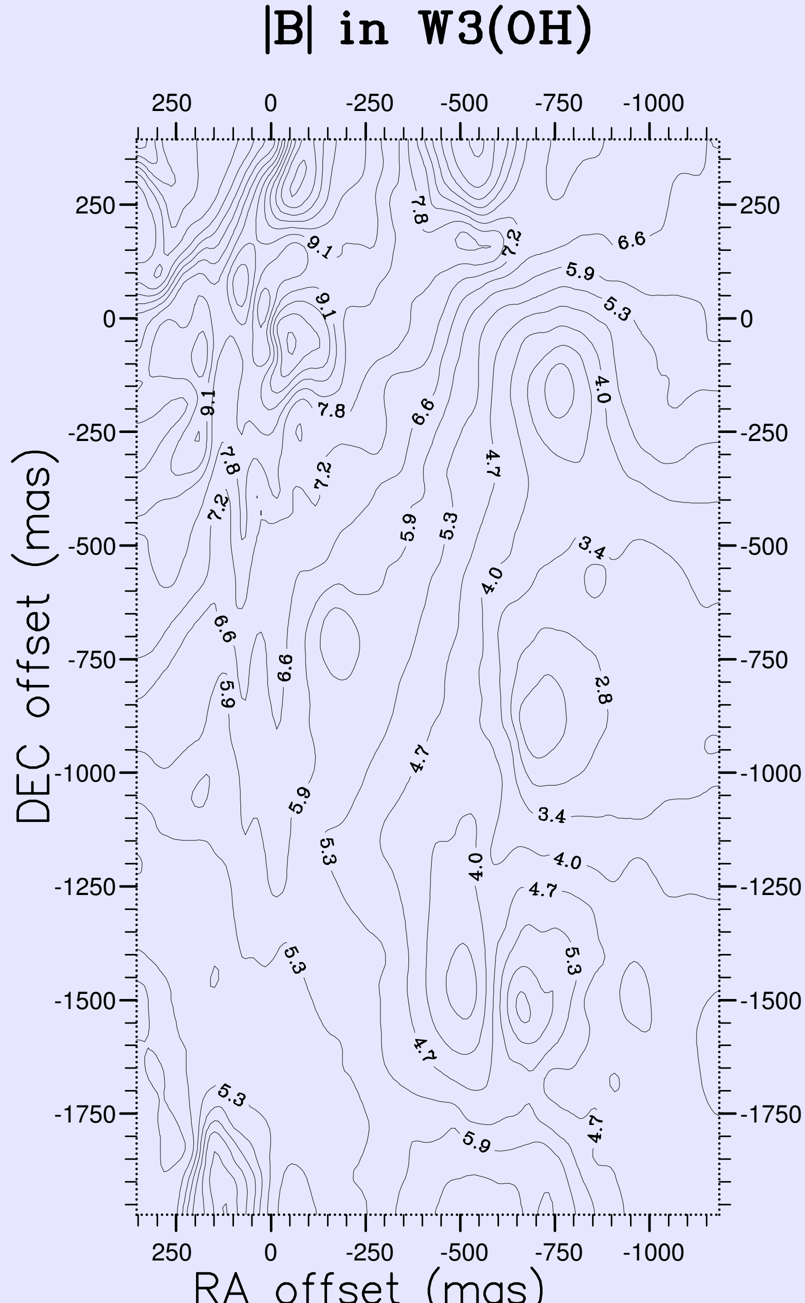


Figure 2: The magnetic field strength in mG W3(OH)

Magnetic Field Information with Modelling

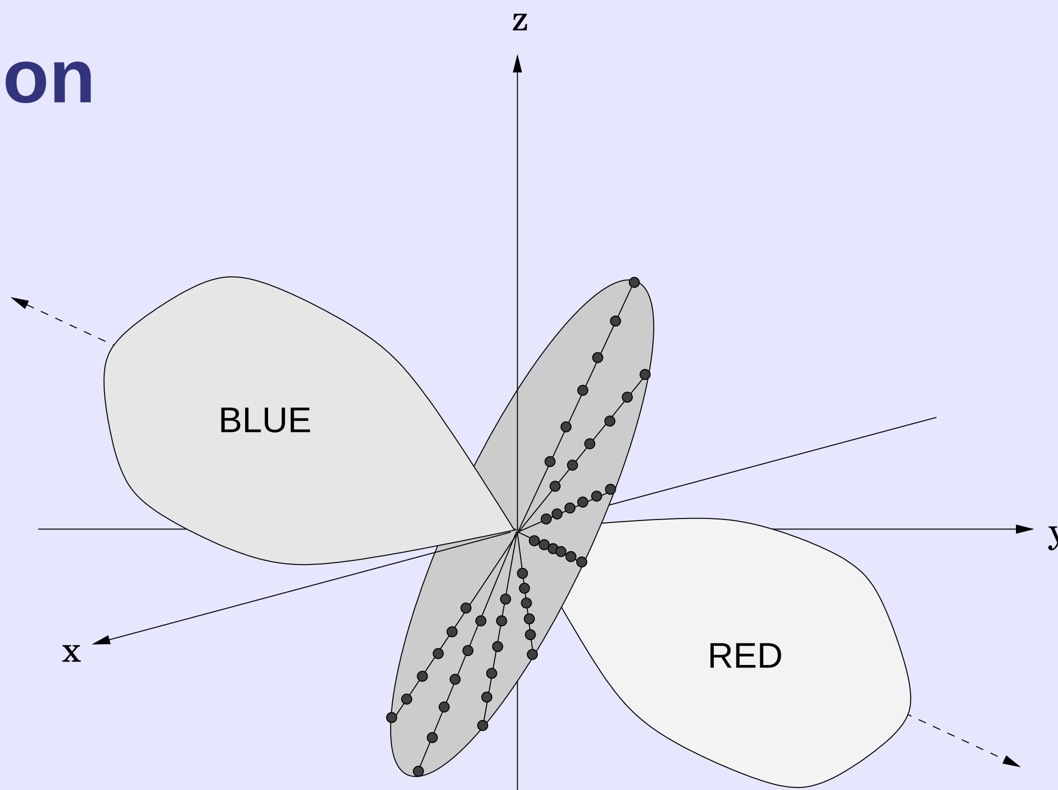


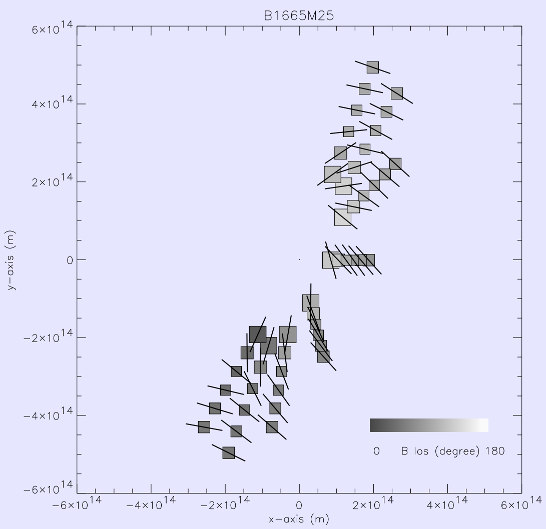
Figure 3: Model maser positions for W75N

- Field reversal through disc
- Uses linear polarization information
- Full polarization observation and disc + outflow model[6]
- (i) G35.2-0.74N[7]
- (ii) W3 IRS5, H_2O linear poln.[8]
- (iii) W75N with detailed maser model[9]

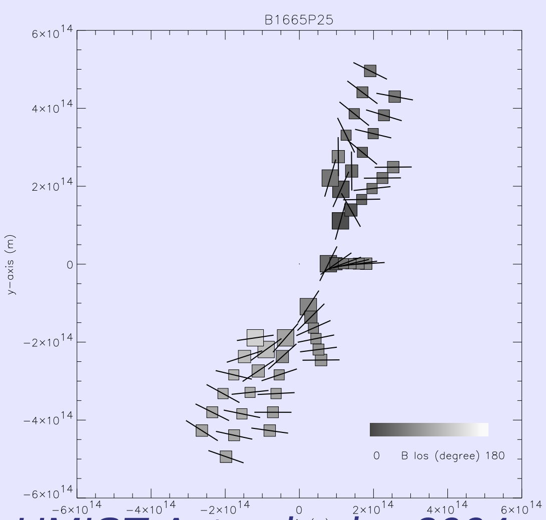
Uchida & Shibata[6], Hutawarakorn & Cohen[7], Gray et al.[9], Imai et al.[8]

Model of W75N

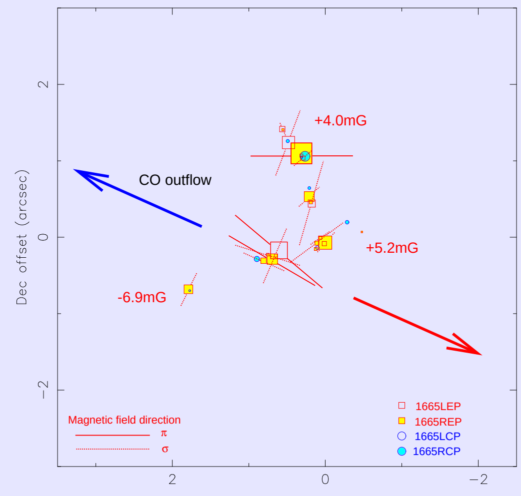
Field orientations: 25 AU below disc



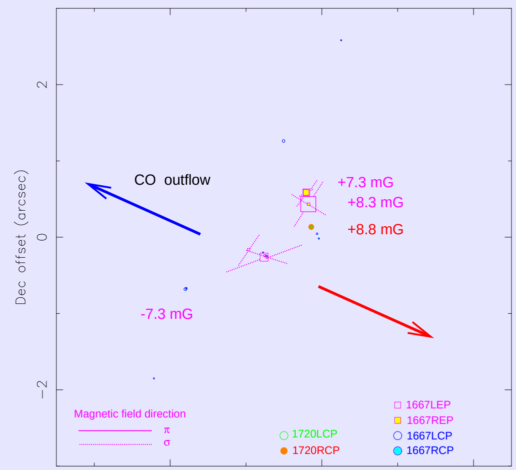
Field orientations: 25 AU above disc



Field orientations in W75N from full polarization observations



(a)



Proper Motion Observations

- You may have to wait quite a long time!
- Annual motion is 210 $v_k/d_{pc}\,\mu$as
  for object at d_{pc} parsecs with tangential velocity v_k km s^{-1}
- Include radial velocity information for detailed analysis of kinematics
- Use statistics of motions to confirm/eliminate models
- Total duration limited by variability (H_2O)
- OH in W3(OH); $>$2 epochs

Some Maser Proper Motion Measurements

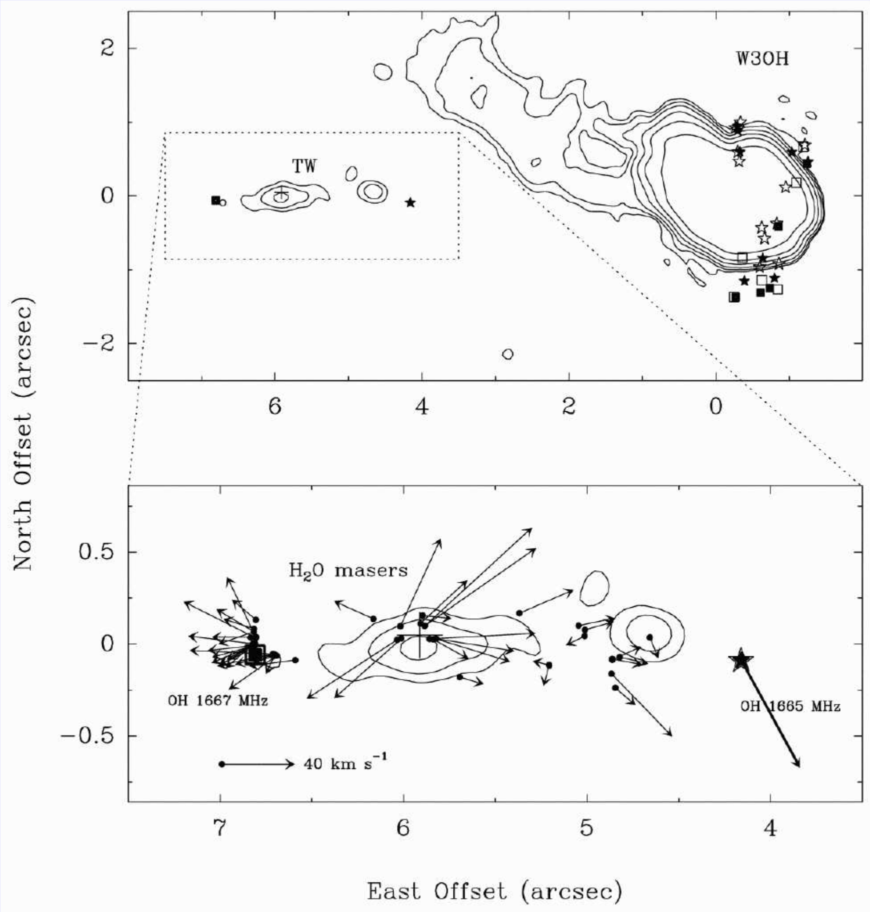
Object	Species	Freq. (GHz)	Interval (yr)	Notes
W3(OH)	CH_3OH	12.2	6[10,12]	Keplerian disc?
W3(OH)	OH	1.7	Note[13]	can't be just rotation
Ceph A	H_2O	22.2	7[31,14]	exp. into rotating disc
W51-IRS2	H_2O	22.2	19[16,15]	bow shock
W75N	H_2O	22.2	1[11]	jet + shell
W3(OH)TW	OH	1.7	8[18]	OH linked to H_2O
NGC2071IR	H_2O	22.2	0.33[17]	outflows $\perp$ to disc

Note: there are several epochs of high-resolution maser observation for W3(OH) at 1.7 GHz, spanning at least the years 1976[13]-1996[29].

Discovery of microstructures (Torrelles et al. 2001)

Menten et al.[10], Moscadelli et al.[12], Reid et al.[13], Torrelles et al.[31], Gallimore et al.[14], Schneps et al.[16], Eisner et al.[15], Torrelles et al.[11], Argon et al.[18], Seth et al.[17], Wright et al.[29]

Proper Motion Example



- Shown are OH and H_2O proper motions in W3(OH)TW (Argon et al.[18])
- Water masers form outflow
- OH masers follow H_2O
- Not typical behaviour for OH
- Younger object than W3(OH): HII region still obscured
- New type of OH maser which follows cometary shocks?

Maser Groups with Velocity Gradients

- Effect well known in Class II methanol masers in star-forming regions[19]
- Also found in H_2O and OH megamasers
- OH masers in star-forming regions
  - MUST be properly demagnetised velocities
- Use the masers to map the velocity field
- With additional assumptions, it is possible to weigh the central enclosed mass M
- Keplerian formula $dv/dx = (GM/r^3)^{1/2} \cos i$

Norris et al.[19]

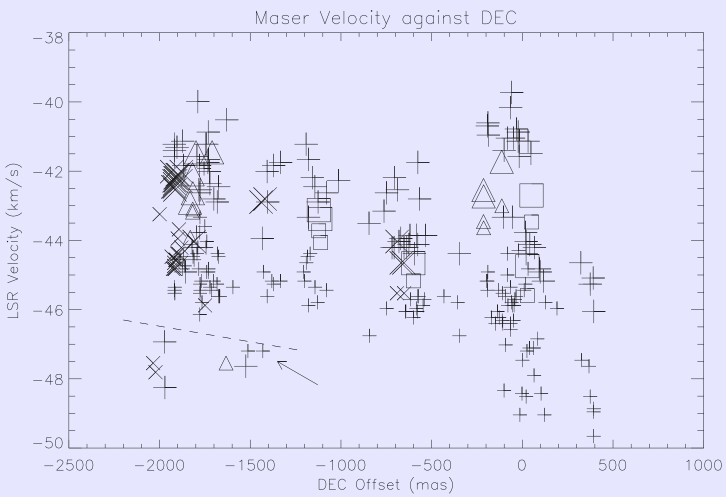
Masses from Maser Velocity Gradients

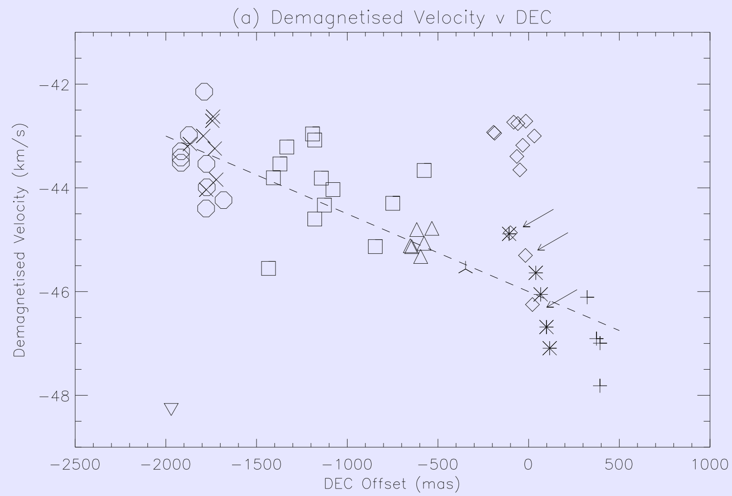
Object	Object Type	Species	Freq. (GHz)	Mass (M⊙)
NGC4258	megamaser	H_2O	22.2	2.2×10^7 from[20]
NGC4258	megamaser	H_2O	22.2	3.9×10^7 from[21]
IIIZw35	megamaser	OH	1.667	5.2×10^6 from[22]
IIIZw35	megamaser	OH	1.667	1.0×10^7 from[23]
MKN273	megamaser	OH	1.7	1.5×10^8 from[24]
NGC7538	massive SFR	CH_3OH	12.2/6.7	31 from[27]
NGC6334F	massive SFR	OH	1.7	25 from[26]
W3(OH)	massive SFR	OH	1.665	27 from[29]
W75N	massive SFR	CH_3OH	12.2/6.7	4.4 from[25]
MonR2	massive SFR	CH_3OH	12.2/6.7	74.6 from[25]
G29.95-0.02	massive SFR	CH_3OH	12.2/6.7	30.8 from[25]
NGC7538-IRS1	compact HII	H_2CO	4.83	~1 from[28]
NGC2071	protoplanetary	H_2O	22.2	1 from[31]
Orion	protoplanetary	H_2O	22.2	15 from[30]

Notes: Data from Minier et al.[25] assume Case 2.
Mass for NGC7538-IRS1 computed from gradient in Hoffman et al.[28]

Haschick et al.[20], Herrnstein et al.[21], Diamond et al.[22], Pihlström et al.[23], Yates et al.[24], Minier et al.[25], Hoffman et al.[28], Zheng[26], Wright et al.[29], Torrelles et al.[31], Abraham & Vilas Boas[30]

Velocity Gradient Example





Maser velocities in W3(OH)
after demagnetisation

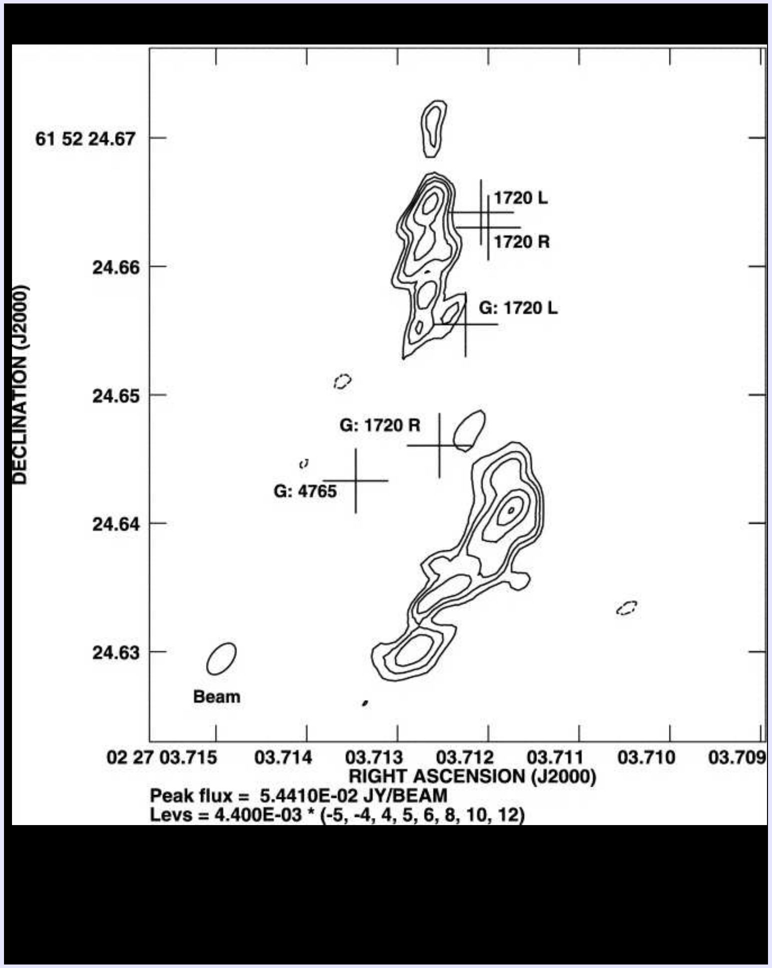
Maser velocities in W3(OH)
before demagnetisation

Copropagation and Line Ratios

- Can we use intensity ratios of maser lines like other spectral lines to derive physical conditions?
- Only if the maser lines copropagte from a resolved spot
- May be copropagation of lines of different species, for example OH and methanol.
- Interpretation requires radiation transfer theory unless the masers are unsaturated.
- Unsaturated case: need to know backgrounds

Copropagation Examples

- 1720 and 4765 MHz in W3(OH)
- MERLIN, 2 spots[32]
- Better resolution: VLBA[33]
- CH_3OH 4.6 & 12.2 GHz in W3(OH)
- Various theories required for inverse problem
- Most theories do something well, but are weak on other points
- Multi species theory[34]
- Need more than 2 lines
- Optimisation for inverse problem



Gray et al.[32], Palmer et al.[33], Cragg et al.[34]

Long Term Variability

- In star-forming regions, maser gain length often assumed to be a chain of velocity-coherent blobs
- May be magnetic compensation[35]
- Less evidence for change in pumping scheme than in late-type stars
- Gain modified by bulk-flows and turbulence
- Match variability timescales to theoretical predictions for particular turbulence spectrum
- Link to age/evolution of SFRs

Cook[35]

Low Resolution Observations

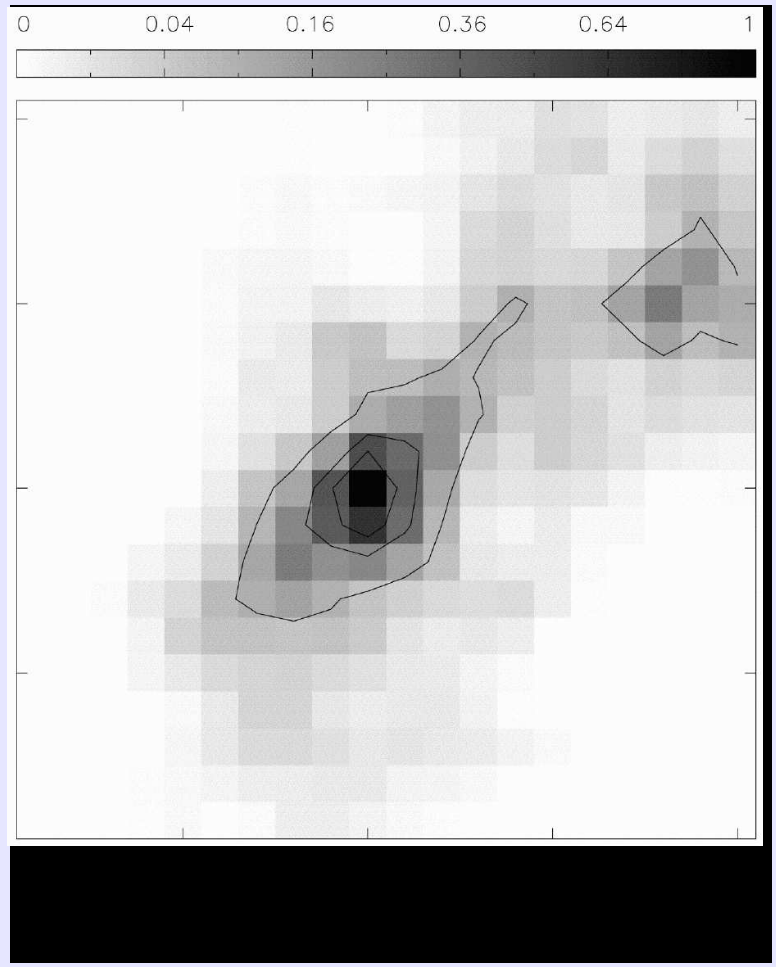
- Observations of H_2O masers in 14 SFRs[36]
- Duration 13 yr; interval 2-3 months
- Objects with higher L_{FIR} have stronger and more stable masers
- Lower luminosity limit for masers $\sim$430 $L_\odot$

- Flare variability, e.g. G9.62-0.20[37], MonR2

Brand et al.[36], Goedhart & Gaylard[37]

High Resolution Observations

- Tell us about physics of an individual maser column
- Observations of 25 GHz CH_3OH[38]
- Modelled in terms of turbulence[39,40]
- Parameters: Kolmogorev intensity index; Gaussian amplitude width
- Model spot looks very realistic



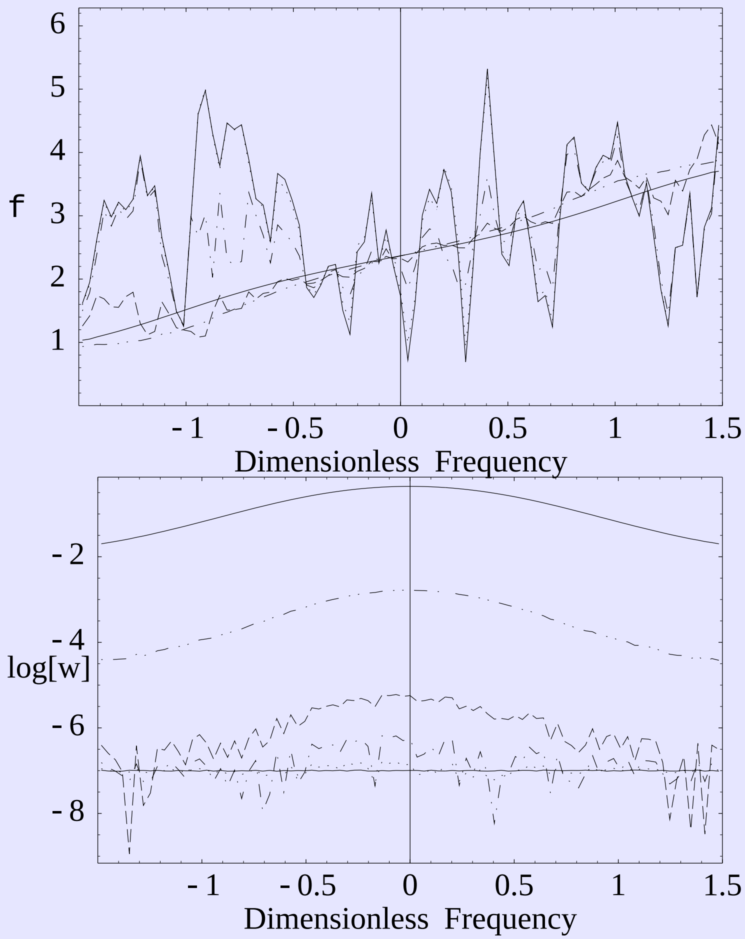
Johnston et al.[38], Sobolev et al.[39],[40]

Short Term Variability

- Define as variability on timescales shorter than the light-crossing time for the maser
- Effects predicted for water masers[41]
- Instabilities in Radiative transfer equation on timescale L/c
- Narrow-band observations - phase effects
- Early observation[42] used too large a bandwidth
- What do we measure? What are we diagnosing?

Scappatici & Watson[41], Evans et al.[42]

Amplitude and Phase Propagation



- Model amplifies photon number and phase[43]
- There are 90 bins, with 9 per homogeneous profile
- Phases lock as maser saturates
- Timescale ~ 1/(homogeneous width)
- Destroyed to some extent by IR cross-relaxation
- Needs intensity correlation experiments

Gray & Bewley[43]

Future of Observations and Theory

- Bright future for maser tracers: information on smallest scales
- Alma - routine high-resolution observations
- e-MERLIN & e-VLA - sensitivity
- SKA
- More epochs for proper motions
- High resolution + continuum correlation: distances?
- VLBI at more (& higher?) frequencies

- Full polarization models - computing power
- ‘Intelligent’ optimisation

References

[1] Dousmanis G. C., Sanders T. M., Townes C. H., 1955, Phys. Rev., 100, 1735
[2] Lo K. Y., Walker R. C., Burke B. F., Moran J. M., Johnston K. J., Ewing M. S., 1975, ApJ, 202, 650
[3] Baudry, A., Diamond, P. J., 1998, A&A, 331, 697
[4] Desmurs, J.-F., Baudry, A., Wilson, T. L., Cohen, R. J., & Tofani, G., 1998, A&A, 334, 1085
[5] Killeen, N. .E. B., Staveley-Smith, L., Wilson, W. E., & Sault, R. J., 1996, MNRAS, 280, 1143
[6] Uchida Y., Shibata K., 1985, PASJ, 37, 515
[7] Hutawarakorn B., Cohen R.J., 1999, MNRAS, 303, 845
[8] Imai H.,, Horiuchi S., Deguchi S., Kameya O., 2003, ApJ, 595, 285
[9] Gray M. D., Hutawarakorn B., Cohen R. J., 2003, MNRAS, 343, 1067
[10] Menten, K.-M., Reid, M. J., Moran, J. M., Wilson, T. L., Johnston, K. J., & Batrla, W., 1988, ApJ, 333, L83
[11] Torrelles J. M., et al., 2003, ApJ, 598, L115
[12] Moscadelli, L., Menten, K. M., Walmsley, C. M., & Reid, M. J., 1999, ApJ, 519, 244
[13] Reid M. J., Haschick A. D., Burke B. F., Moran J. M., Johnston K. J., Swenson G. W., 1980, ApJ, 239, 89
[14] Gallimore J. F., Cool R. J, Thornley M. D., McMullin J., 2003, ApJ, 586, 306
[15] Eisner J. A., Greenhill L. J., Herrnstein J. R., Moran J. M., Menten K. M., 2002, ApJ, 569, 334
[16] Schneps M. H., Lane A. P., Downes D., Moran J. M., Genzel R., Reid M. J., 1981, ApJ, 249, 124
[17] Seth A. C., Greenhill L. J., Holder B. P., 2002, ApJ, 581, 325
[18] Argon A. L., Reid M. J., Menten K. M., 2003, ApJ, 593, 925

[19] Norris, R.-P., et al., 1998, ApJ, 508, 275
[20] Haschick A. D., Baan W. A., Peng W., 1994, ApJ, 437, 35
[21] Herrnstein J.R., et al., 1999, Nature, 400, 539
[22] Diamond, P.-J., Lonsdale, C. J., Lonsdale, C. J., & Smith, H. E., 1999, ApJ, 511, 178
[23] Pihlström Y.M., Conway J.E., Booth R.S., Diamond P.J., Polatidis A.G., 2001, A&A, 377, 413
[24] Yates J.A., Richards A.M.S., Wright M.M., Collett J.L., Gray M.D., Field D., Cohen R.J., 2000, MNRAS, 317, 28
[25] Minier V., Booth R.S., Conway J.E., 2000, A&A, 362, 1093
[26] Zheng X.-W., 1989, ChJSS, 9, 87
[27] Minier V., Booth R. S., Conway J. E., 1998, A&A, 336, 5
[28] Hoffman I.M., Goss W.M., Palmer, Richards A.M.S., 2003, ApJ, 598, 1061
[29] Wright M. M., Gray M. D., Diamond P. J., 2004, MNRAS, in press
[30] Abraham Z., Vilas Boas J. W. S., 1994, A&A, 290, 956
[31] Torrelles J. M., Gómez J. F., Rodrq́uez L. F., Curiel S. & Anglada G., 1998, ApJ, 505, 756
[32] Gray M.D., Cohen R.J., Richards A.M.S., Yates J.A., Field D., 2001, MNRAS, 324, 643
[33] Palmer P., Goss W. M., Devine K. E., 2003, ApJ, 599, 324
[34] Cragg D. M., Sobolev A. M., Godfrey D., 2002, MNRAS, 331, 521
[35] Cook A. H., 1966, Nature, 211, 503
[36] Brand J., Cesaroni R., Comorretto G., Felli M., Palargi F., Palla F. , Valdettaro R., 2003, A&A, 407, 573
[37] Goedhart S., Gaylard M.J., 2002, IAUS, 206, 131
[38] Johnston K. J., Gaume R. A, Wilson T. L., Nguyen H. A., Nedoluha G. E., 1997, ApJ, 490, 758
[39] Sobolev A. M., Wallin B. K., Watson W. D., 1998, ApJ, 498, 763
[40] Sobolev A. M., Watson W. D., Okorokov V. A., 2003, ApJ, 590, 333

[41] Scappatici G. A.& Watson W. D., 1992, ApJ, 400, 351
[42] Evans N. J, Hills R. E, Rydbeck O. E. H., Kollberg E., 1972, Phys. Rev. A., 6, 1643
[43] Gray M.D., Bewley S.L., 2003, MNRAS, 344, 439

This presentation has been typeset from a TEX / LATEX file prepared by the author.