IAU Symp. 242: Summary

• Progress since 2001 meeting in Brazil
• What do we think we understand?
• What don’t we understand?
Masers: Complexity

- Chemistry (Temp, dens, ionization, evaporation, dissociation, …)
- Amplification (limited by clumping or Vel/B-field gradients, saturation, beaming, pumping)
  
  Pump: concept of single pump path naïve: 10-100s routes contribute to OH
  
  Ampl.: OH line wing variability ~10^3 s puzzling
  
  Polarization: pure π components (100% linear) not seen! Why?
  
  OH stimulation of σ by π radiation in aligned clouds

- Lifetimes (dynamic cloud formation)
- Projections (3-D observed as 2-D)
- Extinction (eg, visible, IR images)

OH masers in H2O outflow
Interstellar Masers: Characteristics

• \( \text{H}_2\text{O} \)
  Power-law position correlations...no clustering scale...fractal/turbulence
  outer scale ~ injection of energy via jet wind (~\(10^{17}\) cm)
  inner scale ~ dissipation of energy at maser spot scale (~\(10^{13}\) cm)

• \text{OH}
  OH: strong clustering scale (not power-laws like \( \text{H}_2\text{O} \)) ~ 100 AU
  Both form lines/arcs on sky & worms in P-V space
  Are maser “worms” Strelnitski’s cascading vorticity?

• \( \text{CH}_3\text{OH} \) (unknown)
  Class II: expect similar to OH
  Class I: perhaps like H2O
Interstellar Masers: Variability

- **CH$_3$OH Periodic Variability**

  Clear quasi-sinusoidal variations in ~10% surveyed
  VLBA maps show spot “pulsation”, nothing else changing
  Periods between 133 to 504 days…similar to Miras
  While chance meeting of MSF cloud & Mira variable very low…
  embedded pulsating PMS star (eg, lower mass VY CMa) intriguing =>
  pulsation lifetime ~ 10% of maser lifetime
Masers Pumps

- **SiO**
  Collisions and/or radiation

- **H$_2$O**
  Collisional: doesn’t correlate well with IR; but does with outflows/shocks

- **CH$_3$OH**
  Class-I collisional: shocks at interface of MC
  Class-II radiative: associated with IR dark clouds and hot molec cores of MSFRs

- **OH**
  Radiative: OH correlates well with MIR; not with fast outflow

- **H$_2$CO**
  Radio Continuum and IR pumps probably doesn’t work;
  by default (possibly e$^-$ if n$_H$~10$^3$) collisions if n$_H$~10$^6$

Does intrinsic complexity of the pumping or ignorance of atomic/molecular cross-sections dominate?
Mm/submm Masers

• Lots of new mm/submm masers,
  
  Even though (as Strelnitski pointed out at the last meeting),
  it is harder for Nature to invert populations at higher frequencies
Interstellar Masers: YSO disk/jets

- Fast outflows: H$_2$O
- Slow outflows: H$_2$O, CH$_3$OH, SiO
- Disks: ? (H-recomb masers in MWC349)
  - disk hard differentiate from bipolar jets
    - often rely on other jet indicators:
      - H$_2$ 2.1 um
      - thermal SiO
      - radio continuum, but not always…

- HII expansion: OH, CH$_3$OH Class II
- Shocks: CH$_3$OH Class I, OH/SNRs
Interstellar Masers: B-fields

• **OH**
  
  typically 1 – 10 mG…but up to 40 mG seen!
  
  Always ordered: either 0 or 1 reversal across source

• **H₂O**
  
  typically 10 – 100 mG

• **B ∼ n(H₂)⁰.⁵**
  
  suggests n(H₂O) only ~100 x n(OH)…
  
  but uncomfortable for B(OH) > B(H₂O)
Interstellar Masers: Age Sequence

Possible Interstellar Maser Chronology

- OH in H$_2$O outflow
- Class I very young, but will form star?
- H$_2$O first gen/Class II 2nd generation
- H$_2$O maser
- H$_2$O 2x OH...longer lived or lower mass star
- mm-only cores
- Protostar
- NH$_3$-only cores

Other dimensions: stellar mass, external ionization & shocks, etc.
AGB Masers: Standard Model

Note: asymmetry in radio photospheres (green)
AGB Masers: Standard Model
### Stellar Masers: Magnetic Fields

<table>
<thead>
<tr>
<th>Maser</th>
<th>$B$(Zeeman) (G)</th>
<th>$R$ (cm)</th>
<th>$B^2/8\pi$</th>
<th>nkT</th>
<th>$\rho v^2$</th>
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<td>$10^{+1}$</td>
<td>$1\times10^{-3}$</td>
<td>$10^{-2}$</td>
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</table>
## Stellar Masers: Magnetic Fields

<table>
<thead>
<tr>
<th>Maser</th>
<th>$B_{\text{Zeeman}}$ (G)</th>
<th>$R$ (cm)</th>
<th>$B^2/8\pi$</th>
<th>$nkT$ (dynes/cm²)</th>
<th>$\rho v^2$</th>
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<td>$10^{-3}$</td>
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<td>Radio/Molec</td>
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<td>$4 \times 10^{-1}$</td>
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<tr>
<td>Star</td>
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<td>$5 \times 10^0$</td>
<td>$5 \times 10^{+1}$</td>
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</table>

Assume $B \sim 1/R^2$

20 km/s shocks
Stellar Masers: Post AGB Stars

Eg, SiO “disk” + fast H2O “outflow”

Synchrotron emission

Cat’s Eye PN (HST)
Stellar Masers: Super & Hypergiant Stars

• **VY CMa**

In SF region, but has no Li, so post-main-seq star

\[ L \sim 5 \times 10^5 L_{\text{sun}} \left( \frac{D}{1.5 \text{ kpc}} \right)^2 \sim \text{maximum allowed L} \]

Parallax needed!

Losing mass extremely rapidly over past \(10^3\) yr

Complex asymmetric structures seen, but an axis at PA~50 deg seen in OH, H$_2$O, SiO, IR

• **S Per**

H$_2$O projected to same R as main-line OH: problem.

co-spatial or projection effect (H$_2$O f-b caps)?

OH main-line Zeeman B-field 3 mG,
H$_2$O B-field 150 mG suggests not co-spatial

“Onion model dead” …too early to claim this.
Galactic Structure

• Spiral Structure

Parallaxes are here, parallaxes are here!

~10 MSFRs & 10 evolved stars
(~25 Pulsars also)

Large kinematic anomalies found

VERA and VLBA will soon provide ~100
mapping spiral arms (finally)
determining (dark) mass distribution of M.W.
measuring $\Theta_o$ & $R_o$ (+/-few%)

• Inner Galaxy

Surveys of evolved stars tracing the Bar

• Magnetic Field

Some tantalizing correlations of Pulsar RM B-fields
with OH maser B-field…definitive results must
await many parallaxes
H$_2$O AGN Masers

- Sub-pc scale disks and jets

  Clear understanding that masers populate both disk and jets
types: thin disks, thick disks, jets, winds
Learning details of accretion disks (warps, B-fields, n, T, $M_{BH}$, spiral arms...)
NGC 4258: archetypal AGN maser
  Thin, warped, accretion disk well established
  Periodicity in high vel data real
disk thinness $\sim 5 \mu$as $\sim \sim 10$ AU measured $\Rightarrow$ hydrostatic equil $T=600$ K
accel vs $V_{sys}$ changes may be caused by spiral arms
H$_2$O AGN Masers

• **Precision Cosmology**

  Maser Cosmology Project: GBT + VLBA

  direct, geometric distance + redshift

  goal: $H_0$ accurate to 3%

  Eq. of state of dark energy …

  Cosmological constant vs. quintessence

UGC3789 excellent “NGC4258-like” candidate
OH Megamasers

Associated with star bursts (result of major mergers)…
not associated with the AGNs, but…
183 GHz AGN H$_2$O masers found in Arp220 (which doesn’t have 22 GHz!)

Very dense gas is key: specifically n(H$_2$) $\sim$ 10$^{5.6}$ cm$^{-3}$,
but if large B-fields measured are correct, might imply n(H$_2$) >10$^{6-7}$

Associated, but weak, H$_2$CO and 1720 MHz OH “megamasers”

Why 1667 MHz compact & 1665 MHz extended?
Torus filled with clouds (each with low gain);
chance alignments (both along l.o.s. and in Vel) can give high gain spots
Aligned, well-separated clumps produces high beaming…unsaturated

Origin of arcs with V-gradients unclear: M $\sim$ r V$^2$ / G $>$ 10$^{5}$ M$_{\odot}$ if gravitational
Next Meeting?

- $H_0$ measured to 3% accuracy... $w=1$ (and the Universe will end)
- Constancy of Fundamental “Constants” further tested
- mm/submm maser observations will be as common as cm-wave masers
- Blind surveys (of at least the Plane) will be completed for all major classes of molecular masers
- Milky Way mapped with ~200 parallaxes/proper motions
- H-recombination line maser from EOR
- ...
Where Should the Next Meeting be?

Washington DC (North America)
Rio de Janeiro (South America)
Alice Springs (Australia)
?

(Europe, Asia, or Africa)

7’th meeting would logically be in the Antarctic in ~2030!