Galactic Radio Astronomy - Masers

- Masers (Microwave Amplified by Stimulated Emission of Radiation)
  - Theory
    - NH_3 (Gordon et al. 1954)
    - 1964 Nobel Prize Basov, Prokhorov, Townes
  - Cosmic Discovery
    - OH (Weaver et al. 1965)
    - H_2O and many more others
    - Properties
      - compact (e.g. 1e14 cm)
      - high brightness temperature (e.g. 1e10-1e12 K)
      - narrow line width (e.g. 0.2-0.4 km/s)
      - significant polarization
      - time variable

Galactic Radio Astronomy - Masers

- two-level (radiative + collisional)

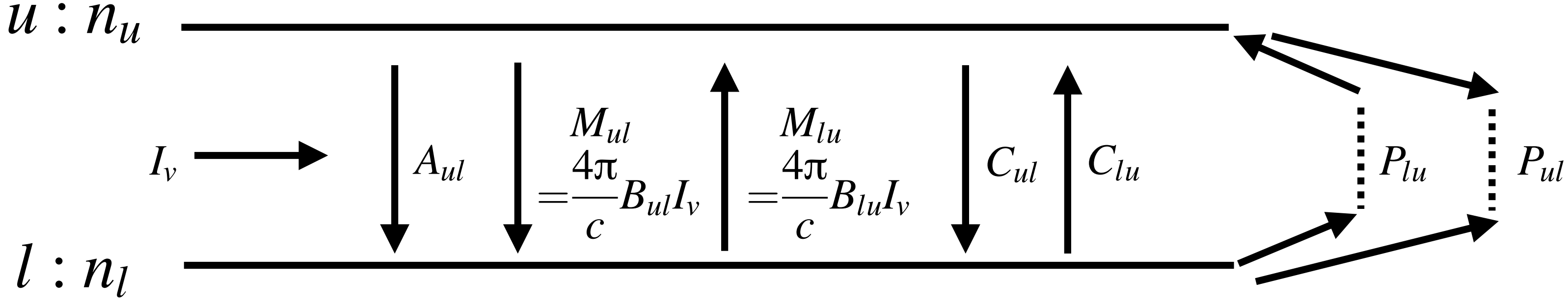
$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \varepsilon_\nu$$

$$\frac{dI_\nu}{ds} = \frac{h\nu_0}{4\pi}\big[(n_u B_{ul} - n_l B_{lu})\frac{4\pi}{c} I_\nu + n_u A_{ul}\big]\phi(\nu)$$

$$\kappa_\nu = \frac{h\nu_0}{c}\big[(n_l B_{lu} - n_u B_{ul})\phi(\nu)$$

$$= \frac{h\nu_0}{c} n_l B_{lu}\left(1 - \frac{g_l}{g_u}\frac{n_u}{n_l}\right)\phi(\nu)$$

$$\varepsilon = \frac{h\nu_0}{4\pi} n_u A_{ul}\phi(\nu)$$



$$I = B(T_b) = B(T)$$

LTE

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-h\nu_0/kT_{ex}} = \frac{g_u}{g_l} e^{-h\nu_0/kT}$$

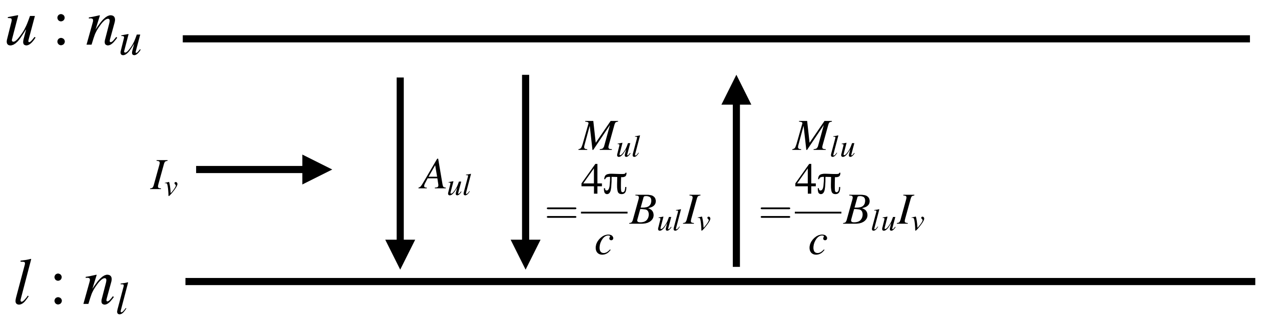
$$T_b = T_{ex} = T_K = T$$

Galactic Radio Astronomy - Masers

- two-level (radiative)

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \varepsilon_\nu$$

$$\frac{dI_\nu}{ds} = \frac{h\nu_0}{4\pi}\big[(n_u B_{ul} - n_l B_{lu})\frac{4\pi}{c} I_\nu + n_u A_{ul}\big]\phi(\nu)$$



$u : n_u$

$l : n_l$

I_ν

A_{ul}

$M_{ul} = \frac{4\pi}{c} B_{ul} I_\nu$

$M_{lu} = \frac{4\pi}{c} B_{lu} I_\nu$

$$\kappa_\nu = \frac{h\nu_0}{c}\big[(n_l B_{lu} - n_u B_{ul})\phi(\nu)$$

$$= \frac{h\nu_0}{c} n_l B_{lu}\left(1 - \frac{g_l}{g_u}\frac{n_u}{n_l}\right)\phi(\nu)$$

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- two-level (radiative + collisional)

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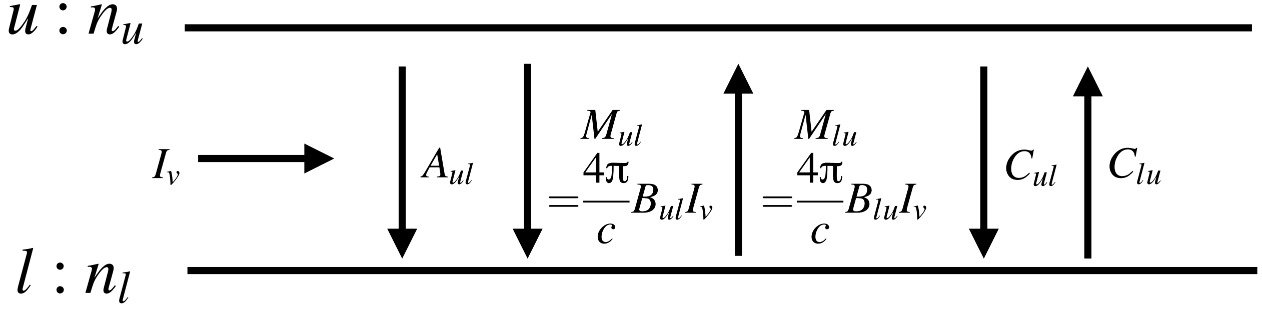


$u : n_u$

I_ν

A_{ul}

$M_{ul} = \frac{4\pi}{c} B_{ul} I_\nu$

$M_{lu} = \frac{4\pi}{c} B_{lu} I_\nu$

C_{ul}

C_{lu}

$l : n_l$

$$n_u(A_{ul} + C_{ul} + M_{ul}) = n_l(C_{lu} + M_{lu})$$

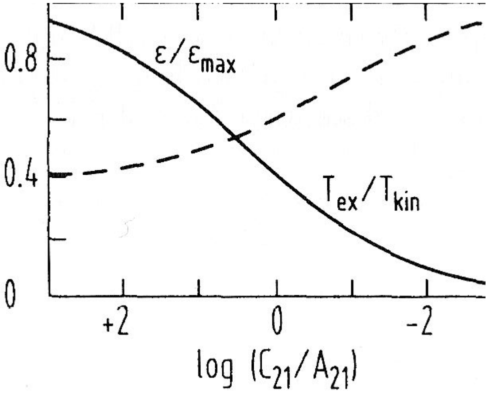
$$\varepsilon_\nu = \frac{h\nu_0}{4\pi}\frac{n_l(C_{lu} + M_{lu})}{(A_{ul} + C_{ul} + M_{ul})}\phi(\nu)$$

Galactic Radio Astronomy - Masers

- two-level (radiative + collisional)

$$\varepsilon_\nu=\frac{h\nu_0}{4\pi}\frac{n_l(C_{lu}+M_{lu})}{(A_{ul}+C_{ul}+M_{ul})}\phi(\nu)$$

$$\varepsilon_\nu = \frac{h\nu_0}{4\pi}\frac{g_u n_l}{g_l}\frac{\left(\frac{I_\nu}{2h\nu_0^3/c^2}+\frac{C_{ul}}{A_{ul}}e^{-h\nu_0/kT_K}\right)}{\left(1+\frac{I_\nu}{2h\nu_0^3/c^2}+\frac{C_{ul}}{A_{ul}}\right)}\phi(\nu)$$



$$\frac{n_u}{n_l}=\frac{g_u}{g_l}e^{-h\nu_0/kT_{ex}}$$

$$\frac{C_{lu}}{C_{ul}}=\frac{g_u}{g_l}e^{-h\nu_0/kT_K}$$

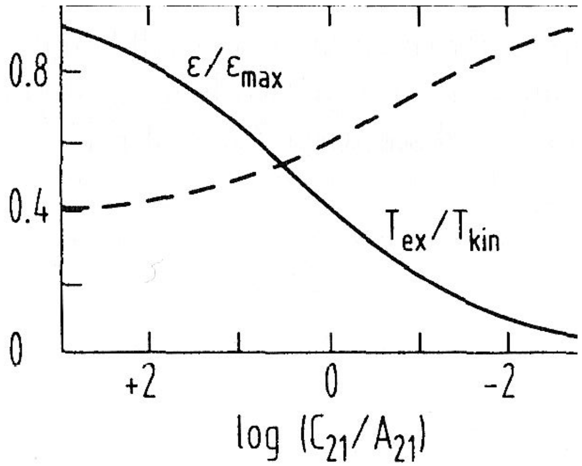
$$\frac{I_\nu}{I_\nu+\frac{2h\nu_0^3}{c^2}}=e^{-h\nu_0/kT_b}$$

$$T_{ex} = T_K\frac{T_b A_{ul}+T_0 C_{ul}}{T_K A_{ul}+T_0 C_{ul}}$$

$$(T_{ex}\ ,\ T_K\ ,\ T_b\ \gg\ h\nu_0/k)$$

Galactic Radio Astronomy - Masers

- two-level (radiative + collisional)



LTE

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$$T_b = T_{ex} = T_K = T$$

in general
Non-LTE

$$T_b < T_{ex} < T_K$$

(but,) no masing

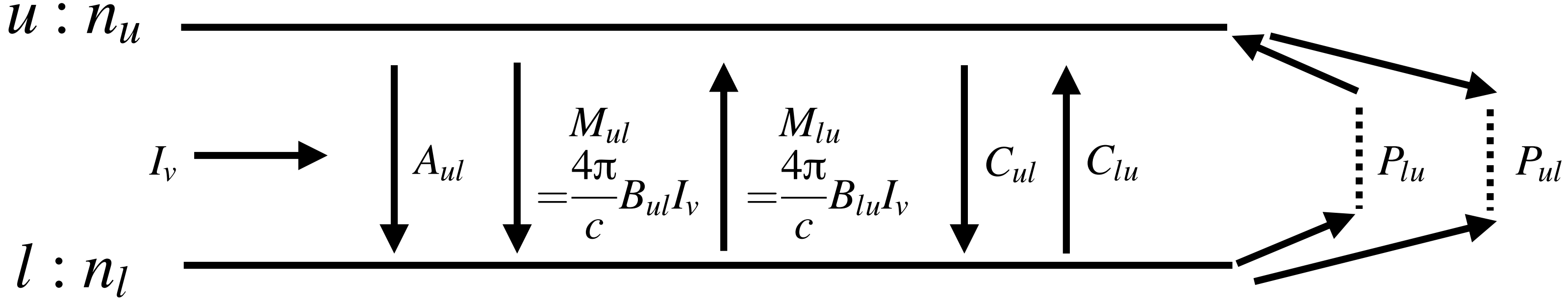
What is critical density?

Galactic Radio Astronomy - Masers

- three-level (radiative + collisional) or “two-level” + “pumping”

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \varepsilon_\nu$$

$$\frac{dI_\nu}{ds} = \frac{h\nu_0}{4\pi}\left[(n_u - n_l)B\frac{4\pi}{c}I_\nu + n_u A\right]\phi(\nu)$$



LTE $$\frac{n_u}{n_l} = \frac{g_u}{g_l}e^{-h\nu_0/kT_K}$$

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- three-level (radiative + collisional) or “two-level” + “pumping”

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \varepsilon_\nu$$

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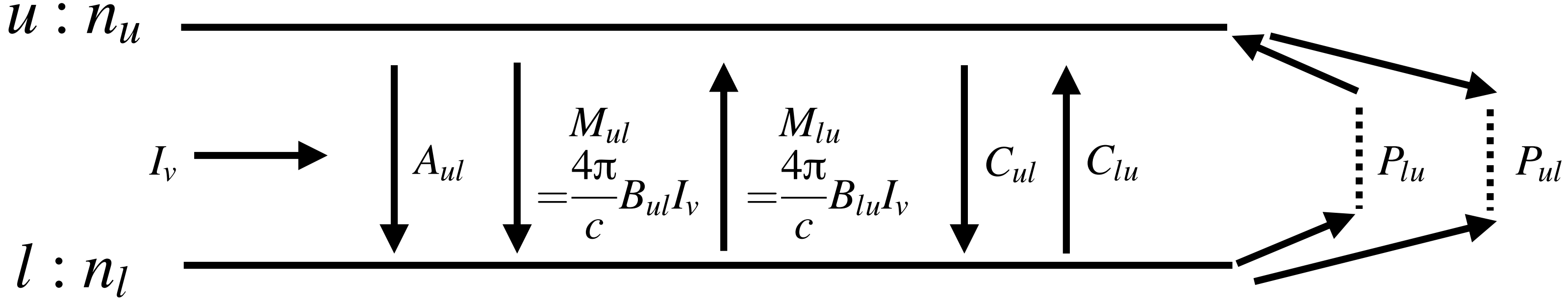

Non-LTE $n_u(A_{ul} + C_{ul} + M_{ul} + P_{ul}) = n_l(C_{lu} + M_{lu} + P_{lu})$

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- Steady State [Statistical Equillibrium]

$$n_u(A_{ul}+C_{ul}+M_{ul}+P_{ul}) = n_l(C_{lu}+M_{lu}+P_{lu})$$

For simplification, assume

$$\begin{aligned} C_{ul} \approx C_{lu} \approx C \\ M_{ul} \approx M_{lu} \approx M \\ A \ll C\ ,\ A \ll M \end{aligned}$$

$$\frac{n_u}{n_l} = \frac{P_{lu}+M+C}{P_{ul}+M+C}$$

For more simplification, assume $g_u = g_l$

in a special case

$$\begin{aligned} (n_u-n_l)|_{M=C=0} &= (n_u+n_l)\frac{P_{lu}-P_{ul}}{P_{lu}+P_{ul}} \\ &= n\,\frac{P_{lu}-P_{ul}}{P_{lu}+P_{ul}} \\ &\equiv \Delta n_0 \end{aligned}$$

in a more general case

$$\Delta n = \frac{\Delta n_0}{1+\frac{2(C+M)}{P}}$$

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- Population Inversion

$$\Delta n = \frac{\Delta n_0}{1+\frac{2(C+M)}{P}}$$

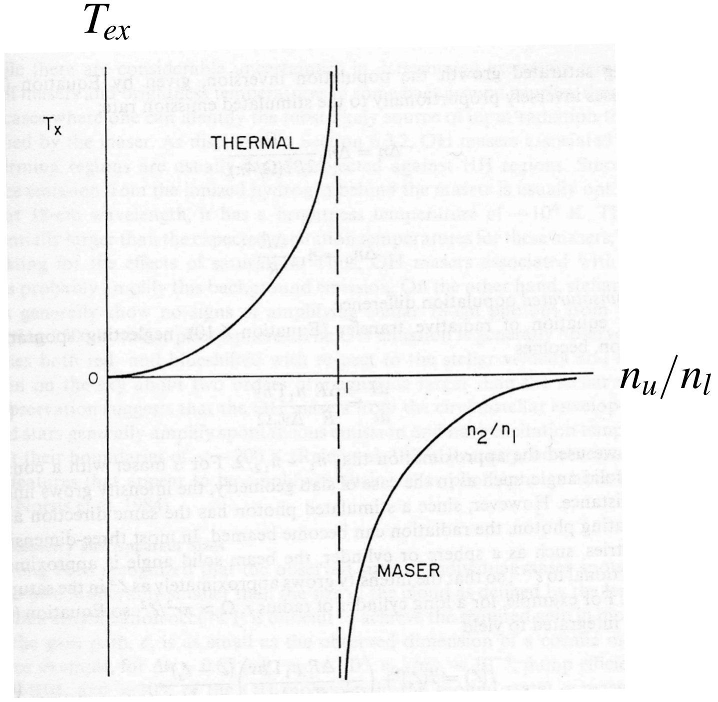
If $\Delta n_0 > 0 \;\Rightarrow\; \Delta n > 0$

$$\frac{n_u}{n_l} = e^{-h\nu_0/kT_{eX}} > 1$$

$$\Downarrow$$

$$T_{ex} < 0$$

excitation temperature



Galactic Radio Astronomy - Masers

- Amplification [in transfer equation]

$$\frac{dI_v}{ds} = \frac{\alpha I_v}{1 + I_v/I_s} + \varepsilon$$

$$\alpha = \frac{h v_0}{c} B \frac{\Delta n_0}{1 + \frac{2C}{P}} \phi(v)$$

$$I_s = \frac{cP}{2B\Omega_m}(1 + \frac{2C}{P})$$

$$\varepsilon = \frac{h v_0}{4\pi} n_u A \phi(v)$$

Unsaturated
exponential amplification

$$I_{v_0} = I_0 e^{\alpha L} + \frac{\varepsilon}{\alpha_0}(e^{\alpha_0 L} - 1)$$

$$T_b = T_c e^{\alpha L} + |T_{ex}|(e^{\alpha_0 L} - 1)$$

Saturated
linear amplification

$$I_{v_0} = I_0 + (\alpha_0 I_s + \varepsilon) L$$

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- Line width [in transfer equation] : unsaturated case

$$I_{\nu_0} = I_0 e^{\alpha L} + \frac{\varepsilon}{\alpha_0}(e^{\alpha_0 L} - 1)$$

$$T_b = T_c e^{\alpha L} + |T_{ex}|(e^{\alpha_0 L} - 1)$$

consider background amplification

$$T_b(\nu)=T_c e^{\alpha(\nu)L}$$

$$\alpha(\nu) = \alpha_0 exp\left(-\frac{(\nu-\nu_0)^2}{2\sigma_0^2}\right)$$

$$T_b(\nu)=T_c e^{\alpha_0 exp\left(-\frac{(\nu-\nu_0)^2}{2\sigma_0^2}\right)L}$$

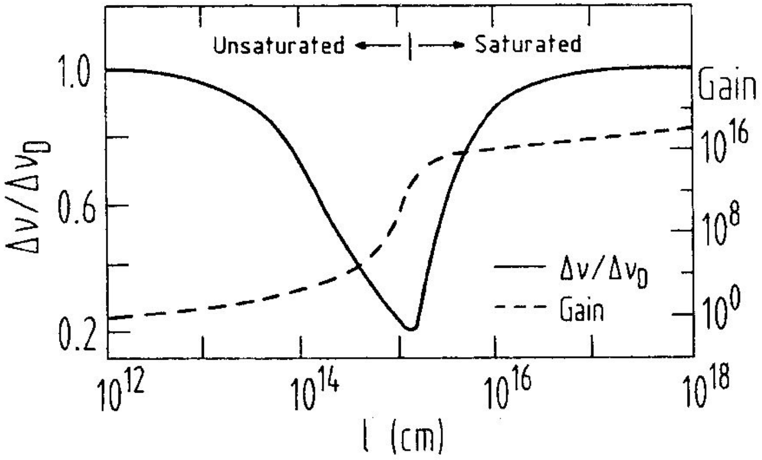
$$\alpha(\nu) \approx \alpha_0\left(1 - -\frac{(\nu-\nu_0)^2}{2\sigma_0^2}\right)$$

$$T_b(\nu)=[T_c e^{\alpha_0 L}]e^{-\frac{\alpha_0 L}{2\sigma_0^2}(\nu-\nu_0)^2}$$

$$=T_{\nu_0} e^{-\frac{\alpha_0 L}{2\sigma_0^2}(\nu-\nu_0)^2}$$

line-width and path length

$$\sigma = \frac{\sigma_0}{\alpha_0 L}$$



Galactic Radio Astronomy - Masers

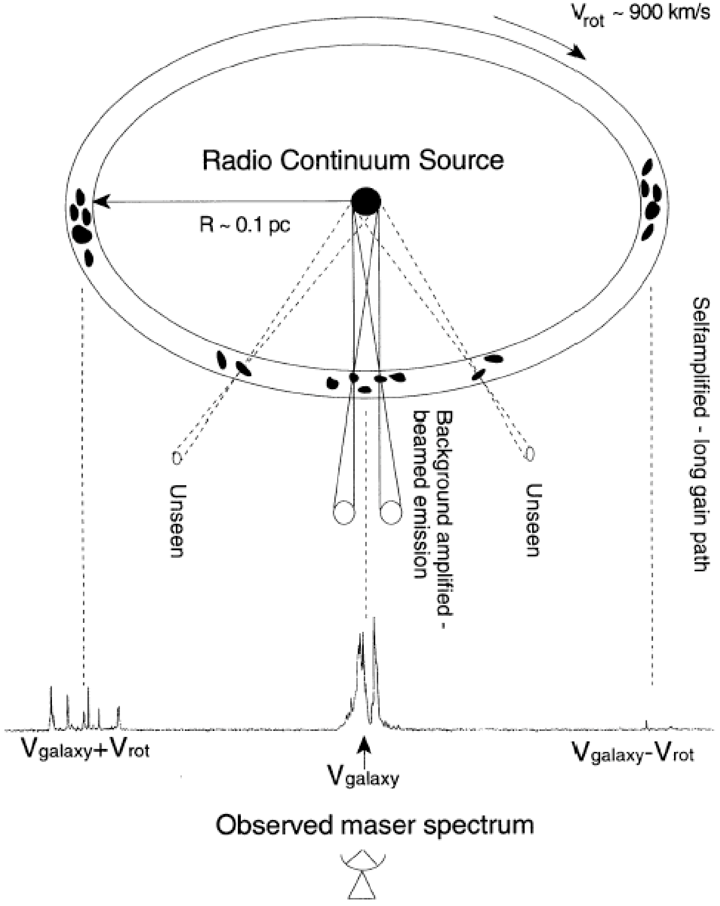
- Masers
  - physical condition required
    - population inversion : still mostly poor understood
      - collisional pumping
      - radiative pumping
  - physical information provided
    - density/temperature (required for pumping)
    - accurate velocity (required for pumping)
      - kinematic information on “small” parcel of gas
    - accurate (relative) positional information
      - proper motion measurements - distance

Galactic Radio Astronomy - Masers

- Masers
  - species
    - OH, H_2O, SiO, H_2CO, CH_3OH, HCN, NH_3,H-recomb
  - locations
    - Galactic
      - ISM : star forming regions, HII regions
        - OH, H_2O, SiO, H_2CO, CH_3OH, NH_3, H-recomb
      - stellar : circumstellar envelopes around evolved stars
        - SiO, OH, H_2O, HCN
      - solar : comets
    - Extragalactic
    - “megamaser” (~1e6 times brighter than galactic counterparts), or even “gigamaser” for OH
      - H_2O in NGC 4945 (Santos and Lepine 1979)
      - OH in Arp 220 (Baan et al. 1982)
      - circumnuclear disk
        - amplification of radio continuum
        - OH (FIR?),H_2CO (FIR/Radio?), H_2O (collisional?)
        - star formation?

Galactic Radio Astronomy - Masers

- Megamasers : SMBH in NGC 4258 (Syfert-2 AGN)



Galactic Radio Astronomy - Masers

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