Interstellar Medium 2020

Lecture 2: Physical conditions and radiative processes

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Course Contents

1. Introduction and ecology of the interstellar medium
2. Physical conditions and radiative processes
3. HI 21cm line and the 2-phase ISM
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7. Molecular energy levels and excitation
8. Interstellar dust
9. Thermal balance and the 2-phase ISM
10. Molecular clouds
11. Shocks, supernova remnants and the 3-phase ISM
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Previous Lecture

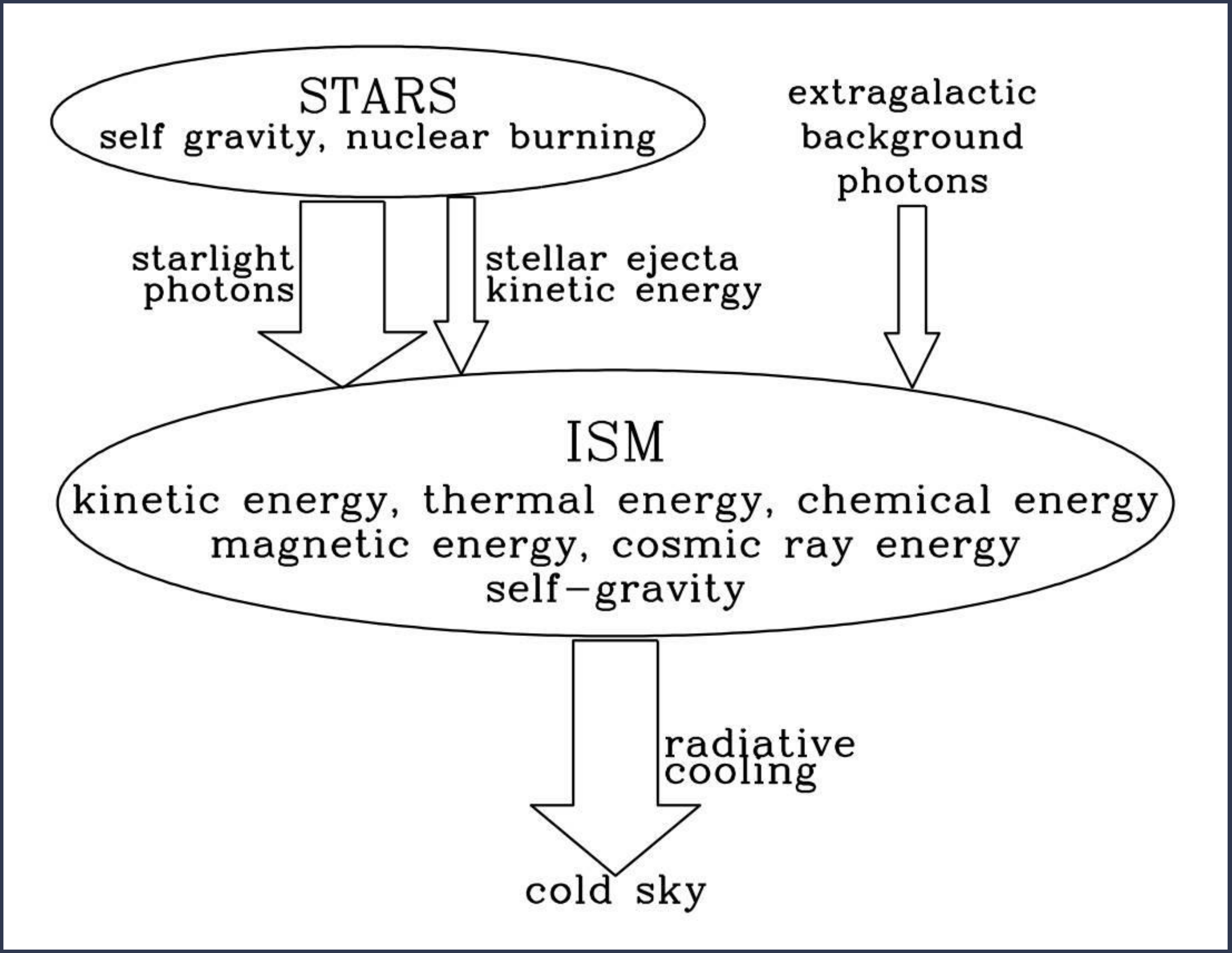
Introduction and Ecology of the Interstellar Medium

1. Discovery of the ISM and brief history
2. Constituents of the ISM
    - Objects
    - Phases
3. Energy densities

Today’s Lecture

1. Basic physical conditions
2. Radiation quantities
3. Radiative transitions
4. Radiative transfer

The ISM is not in thermodynamic equilibrium



(Draine, Fig. 1.3)

Detailed balance

Thermodynamic Equilibrium implies:

detailed balance

every process is balanced exactly by its counterprocess

This is manifestly untrue in the ISM

It is also untrue locally:
hence no Local Thermodynamic Equilibrium (LTE)
(in constrast to, e.g., stellar interiors)

Are these distributions valid in the ISM?

Maxwell distribution of particle kinetic energies?

Planck distribution of radiation energies?

Boltzmann distribution of level population?

Maxwell distribution

- Elastic collisions are sufficiently frequent to thermalize velocity distribution (see e.g., Spitzer 1978, Physical Processes in the Interstellar Medium)

- Maxwell distribution is valid in the ISM

- Usually $T_{\mathrm{kinetic}} \equiv T_{\mathrm{electrons}} = T_{\mathrm{ions}} = T_{\mathrm{neutrals}}$
  (NB: exceptions exist)

Planck distribution

- The interstellar radiation field deviates strongly from a Planck function
- Planck distribution of radiation energies is not generally valid in the ISM

Boltzmann distribution

$$n_i = \frac{g_i e^{-\frac{E_i}{kT}}}{Z(T)}$$

$$Z(T) = \sum_i g_i e^{-\frac{E_i}{kT}}$$

g_i : level degeneracies (statistical weights)

$Z(T)$: partition function

Boltzmann distribution

- Boltzmann distribution is not generally valid in the ISM
- Define *excitation temperature* T_{ex} by

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-(E_u - E_l)/kT_{\rm ex}}$$

- The excitation temperature is defined per transition
- In general $T_{ex} \neq T_{kin}$; if $T_{ex} = T_{kin}$ the level populations are called *thermalized*; if $T_{ex} < T_{kin}$ we speak of *subthermal excitation*

Statistical equilibrium

- In the absence of thermodynamic equilibrium (and hence detailed balance) in the ISM the weaker condition of statistical equilibrium is valid:

sum of rates of all processes populating level *i* =
sum of rates of all processes depopulating level *i*

$$\frac{dn_i}{dt} = \sum_j (-R_{ij} n_i + R_{ji} n_j) = 0 \qquad \forall i$$

- R_{ij} is the transition rate (in s^{-1}) for a particular process causing a transition from level *i* to level *j*

Today's Lecture

1. Basic physical conditions
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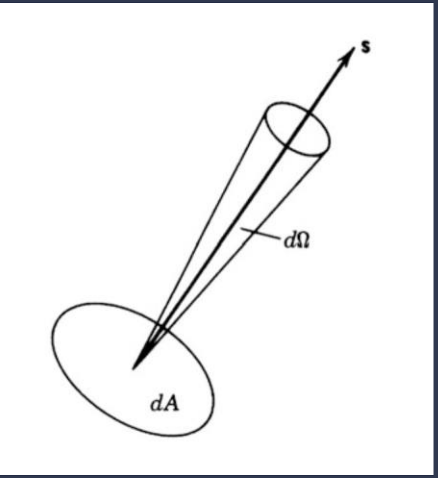
Radiation

Energy in radiation: let dE_ν be the energy in radiation at frequency ν, in frequency interval $d\nu$, from solid angle $d\Omega$, flowing through an area dA, in a time interval dt :



$$dE_\nu = I_\nu \, d\nu \, d\Omega \, dA \, dt$$

$$I_\nu(\nu, \hat{n}, \vec{r}, t)$$

is called the specific intensity (sometimes: surface brightness)
Units: erg s^{-1} cm^{-2} sr^{-1} Hz^{-1}
(or something equivalent)

NB:

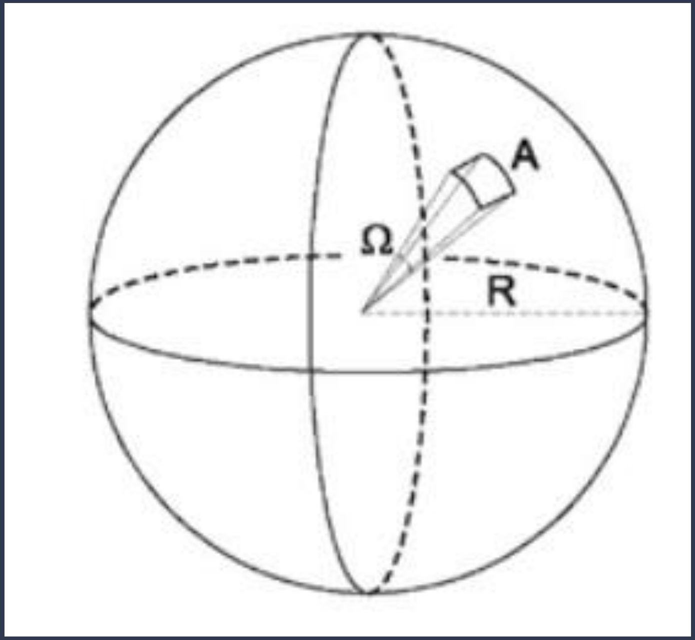
1. we can also use I_λ (with corresponding units)
2. In LTE:

$$I_\nu = B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

3. Specific intensity is distance-independent

Reminder: solid angle

$$d\Omega = \frac{dA}{R^2}$$



Entire sphere has solid angle 4π sr (steradian).

Useful: 1 $\text{arcsec}^2 = 2.35 \cdot 10^{-11}$ sr

Photon occupation number

An alternative, equivalent (and often simpler) way to express specific intensity is by the photon occupation number:

$$n_\gamma(\nu, \hat{n}, \vec{r}, t) = \frac{c^2}{2h\nu^3} I_\nu(\nu, \hat{n}, \vec{r}, t)$$

Note that in LTE we have:

$$n_\gamma(\nu, \hat{n}, \vec{r}, t) = \frac{1}{e^{h\nu/kT} - 1}$$

with the limiting cases:

$$h\nu \gg kT \ \Rightarrow n_\gamma \ll 1$$
$$h\nu \ll kT \ \Rightarrow n_\gamma \gg 1$$

Brightness temperature

Another equivalent quantity is the (Rayleigh-Jeans) brightness temperature:

$$T_b(\nu) = \frac{c^2}{2k\nu^2} I_\nu$$

In the radio regime (where $h\nu << kT$) this is actually a temperature of a Planck curve:

$$I_\nu = B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

$$h\nu \ll kT \;\Rightarrow I_\nu \approx \frac{2h\nu^3}{c^2} \frac{1}{\frac{h\nu}{kT}} = \frac{2k\nu^2}{c^2} T$$

NB: Draine calls this T_a (antenna temperature)

Flux density

The quantities discussed so far are suitable for extended objects. But very often we observe an object as a point source (e.g., stars, distant galaxies). What then?

Only specific intensity integrated over solid angle is now available, so:

$$F_\nu = \int I_\nu \, d\Omega$$

This is called flux density, with units erg s^{-1} cm^{-2} Hz^{-1}. A more practical unit is a Jansky, where 1 Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}.

Note that F_ν is not an intrinsic property of the source but proportional to D^{-2} (why?).

Luminosity

We can now calculate the total energy radiated by an object, which we call specific luminosity (if per spectral interval) or luminosity (integrated over the spectrum, or over part of it):

$$L_\nu = 4\pi D_L^2 F_\nu$$

$$L = \int L_\nu d\nu$$

The units of luminosity are erg s^{-1}, or, more practical, solar luminosities, where $L_\odot = 3.8 \cdot 10^{33}$ erg s^{-1}.

Specific energy density

We can first write down the direction-averaged specific intensity

$$\bar{I}_\nu = \frac{1}{4\pi}\int I_\nu \, d\Omega = \frac{1}{4\pi} F_\nu$$

from which we can easily derive the specific energy density, with units erg cm^{-3} Hz^{-1}:

$$u_\nu = \frac{1}{c}\int I_\nu \, d\Omega = \frac{4\pi}{c}\bar{I}_\nu = \frac{1}{c} F_\nu$$

(think about why the factor 1/c appears)

What when

	continuum	integrated spectral line
point source (or extended object spatially integrated)	F_ν in Jy	e.g., $F_\nu \Delta v$ in Jy km s^{-1}
extended object	I_ν *or* I_λ with units such as erg s^{-1} cm^{-2} Hz^{-1} $arcsec^{-2}$, erg s^{-1} cm^{-2} μm^{-1} $arcsec^{-2}$, Jy sr^{-1} in radio: T_b (in K) or I_ν in e.g., mJy $beam^{-1}$	I with units such as erg s^{-1} $arcsec^{-2}$ or Jy km s^{-1} sr^{-1} in radio: $T_b \Delta v$ (in K km s^{-1}) or I in e.g., mJy km s^{-1} $beam^{-1}$

Extended object, continuum

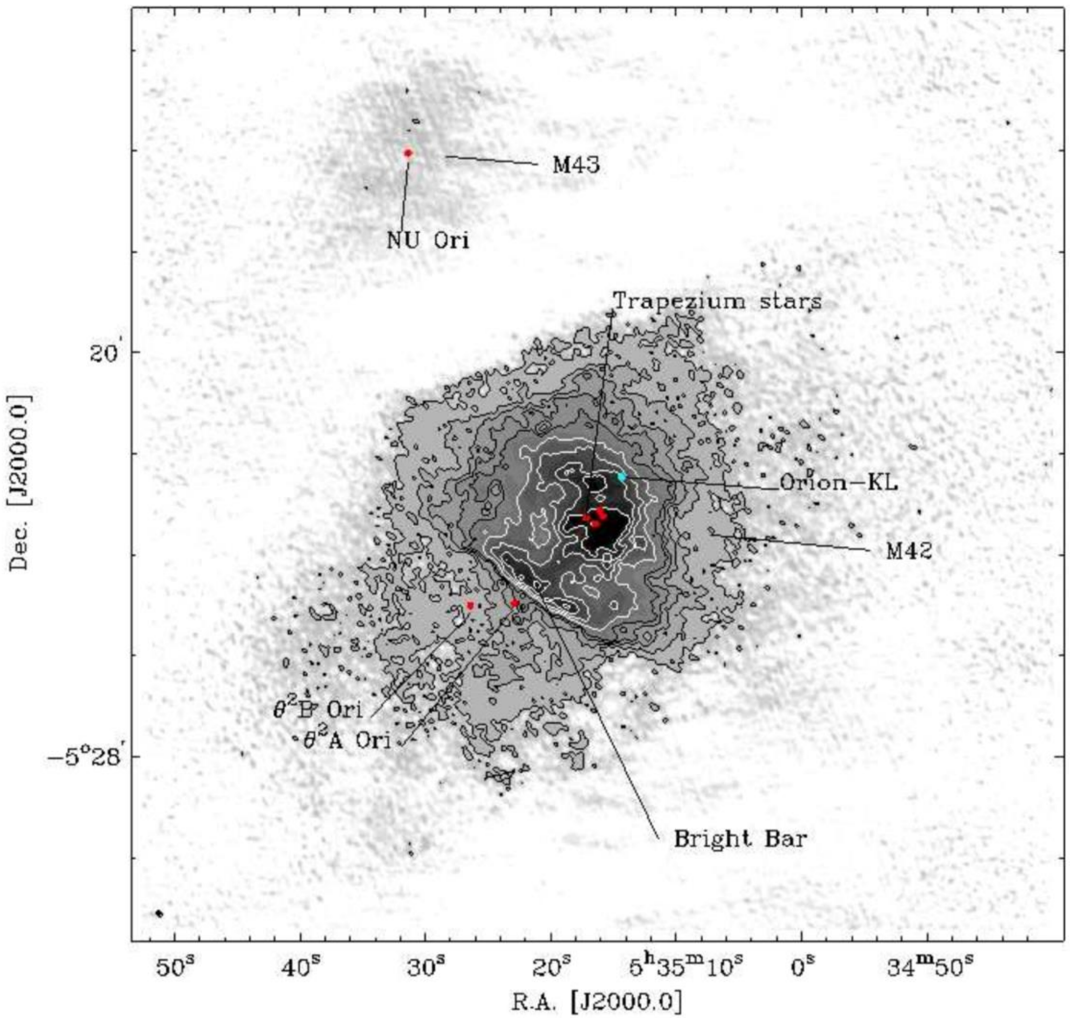
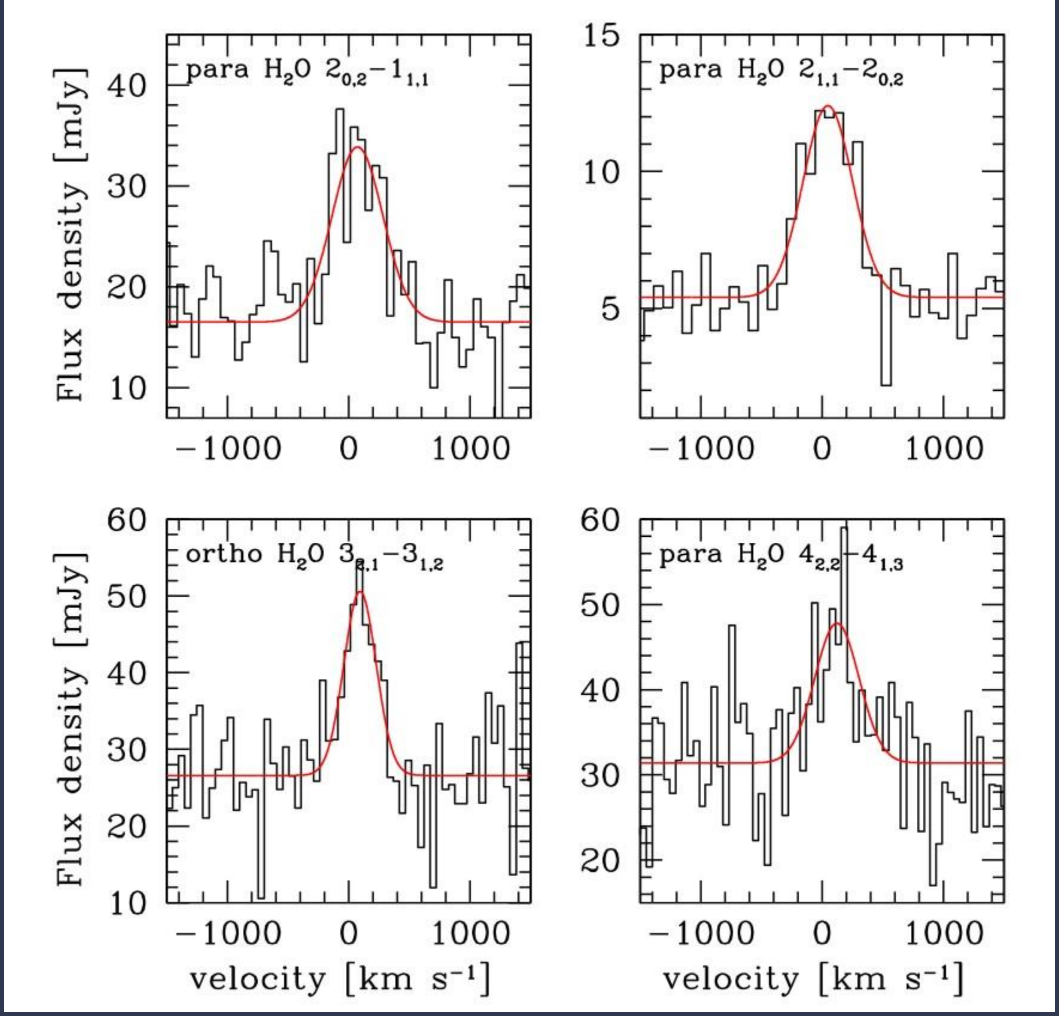


FIG. 1.— Continuum emission of the Orion Nebula at 1420.4 MHz, constructed using a multi-scale deconvolution (see Sect. 2.2). Contours indicate surface brightness levels of 20, 40, 60, 80 and 100 mJy beam^{-1} (black contours) and 150, 200, 250, 300 and 350 mJy beam^{-1} (white contours). The small ellipse in the lower lefthand corner indicates the FWHM size and the orientation of the synthesized beam (7.″2 × 5.″7 at a position angle of 29.°7). The image has been corrected for primary beam attenuation. The principal massive young stars are indicated by red dots. A cyan dot indicates the position of the Orion-KL region.

Van der Werf *et al.*, 2013 (VLA data)

Spectral line



Van der Werf *et al.*, 2011

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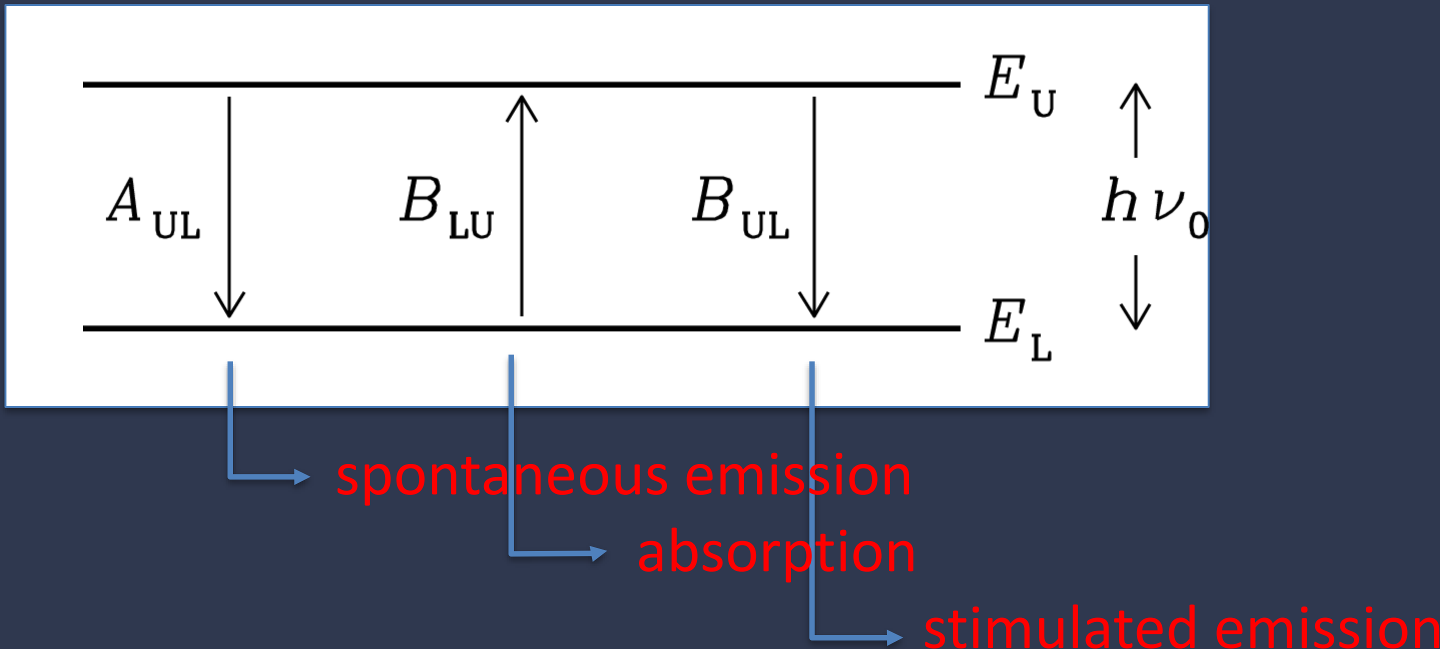
Einstein coefficients

Caution: note different definitions of Einstein *B* coefficients between Draine (which we follow) and Rybicki & Lightman.

The definitions are related by $\boxed{B_D = \frac{4\pi}{c} B_{R\&L}}$.

There is no difference for the *A* coefficients.

Radiative transitions and Einstein coefficients



In all cases, a photon of frequency $\nu_{ul} = \dfrac{E_u - E_l}{h}$ is emitted or absorbed.

In reality this is not monochromatic but has a line profile function φ_ν centred on ν_{ul} and normalized such that $\int \varphi_\nu d\nu = 1$.

1) Spontaneous emission

$X_u \rightarrow X_l + h\nu_{ul}$

The number of spontaneous transitions per unit of time and volume is $-\frac{dn_u}{dt}$ (units: $cm^{-3}\ s^{-1}$).

This rate must be proportional to the density of particles in the upper state. Hence for spontaneous emission:

$$\boxed{-\frac{dn_u}{dt} = \frac{dn_l}{dt} = A_{ul} n_u}$$

where A_{ul} (in s^{-1}) is the Einstein coefficient for spontaneous emission.

NB: $1/A_{ul}$ is then the radiative lifetime of the upper level.

2) Absorption

$X_l + h\nu_{ul} \rightarrow X_u$

The rate for this process must be proportional to both the density of particles in the lower state and the radiation energy density at frequency ν_{ul} (taking into account the line profile). Hence for absorption:

$$\boxed{\frac{dn_u}{dt} = -\frac{dn_l}{dt} = B_{lu} n_l \int u_\nu \varphi_\nu d\nu}$$

where B_{lu} is the Einstein coefficient for absorption.

3) Stimulated emission

$X_u + h\nu_{ul} \rightarrow X_l + 2h\nu_{ul}$

The rate for this process must be proportional to both the density of particles in the upper state and the radiation energy density at frequency ν_{ul} (taking into account the line profile). Hence for stimulated emission:

$$\frac{dn_l}{dt} = -\frac{dn_u}{dt} = B_{ul} n_u \int u_\nu \varphi_\nu d\nu$$

where B_{ul} is the Einstein coefficient for stimulated emission.

NB: the newly generated photon has same frequency, direction, phase and polarization as the original photon. The laser is based on this.

Relations between Einstein coefficients

It is easy to derive the following relations between the Einstein coefficients:

$$B_{lu} = \frac{g_u}{g_l} B_{ul}$$

$$B_{ul} = \frac{c^3}{8\pi h \nu^3} A_{ul}$$

Footnote: oscillator strength

In stead of A_{ul}, a quantity that is often used (and tabulated) in the literature is the oscillator strength f_{lu} .

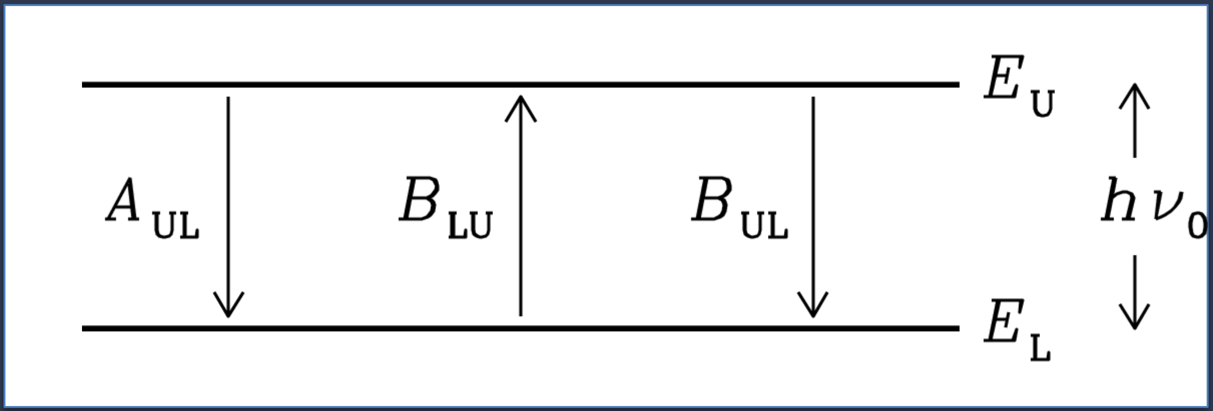
This is related to A_{ul} by

$$\boxed{A_{ul} = \frac{8\pi^2 e^2 \nu_{lu}^2}{m_e c^3} \frac{g_l}{g_u} f_{lu}}$$

where m_e is the mass of the electron.

See Draine Sect 6.3 for further information.

Radiative transition rate equations with n_γ



Recall $\boxed{n_\gamma = \dfrac{c^2}{8h\nu^3} I_\nu}$ so $\boxed{\bar{n}_\gamma = \dfrac{c^2}{2h\nu^3}\bar{I}_\nu = \dfrac{c^3}{8\pi h\nu^3} u_\nu}$.

Now the rate equations can be written (assume φ_ν narrow)

spontaneous emission

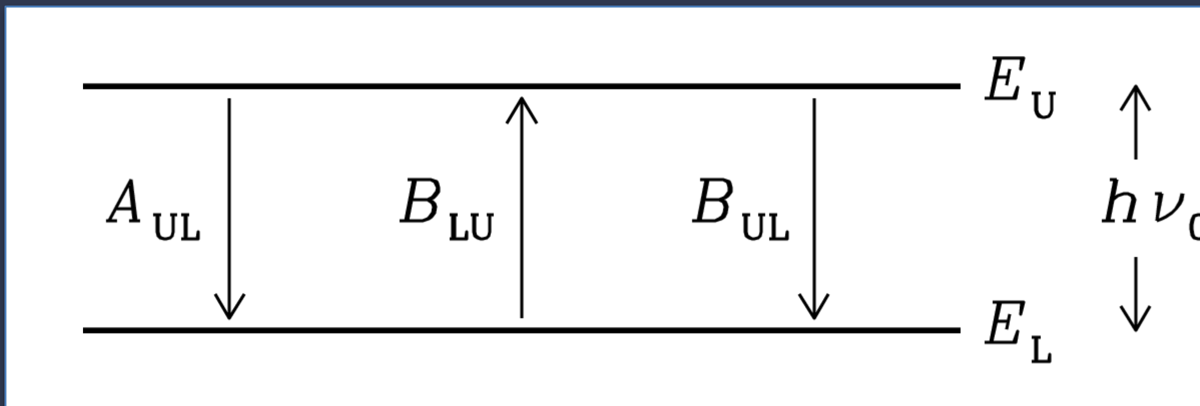
$$\left(\frac{dn_l}{dt}\right)_{u\to l} = n_u A_{ul}(1 + \bar{n}_\gamma)$$

stimulated emission

$$\left(\frac{dn_u}{dt}\right)_{l\to u} = n_l \frac{g_u}{g_l} A_{ul} \bar{n}_\gamma$$

absorption

When is stimulated emission important?



spontaneous emission

$$\left(\frac{dn_l}{dt}\right)_{u\to l} = n_u A_{ul}(1+\bar{n}_\gamma)$$

stimulated emission

$$LTE: n_\gamma = \frac{1}{e^{h\nu/kT}-1}$$

Importance of stimulated emission depends on n_γ

$h\nu \gg kT \Rightarrow n_\gamma \ll 1$ optical, UV, X-ray,...

$h\nu \ll kT \Rightarrow n_\gamma \gg 1$ radio

Line profile

The line profile is a combination of

1. natural linewidth (quantum uncertainty)
   This gives a Lorentz profile with wings falling off as ν^{-2}

2. Doppler motions (thermal + bulk motion)
   Thermal motions give a Gaussian profile with wings falling off as $\exp(-\nu^2)$

Their convolution is a Voigt profile.

The natural linewidth is always much smaller than the thermal linewidth, so in practice the line profile is Gaussian (with one exception – see later).

Gaussian line profile

Maxwell distribution:

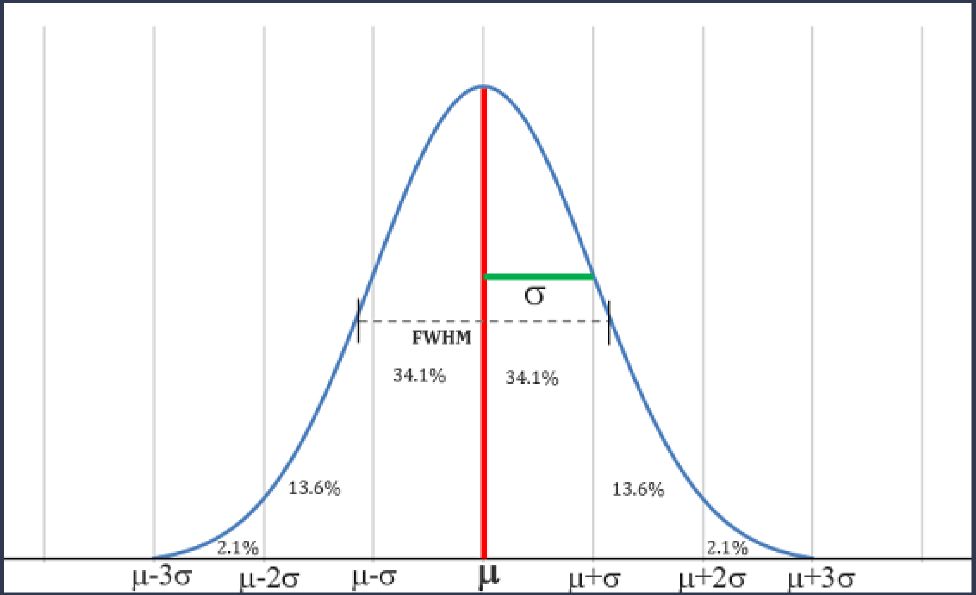
fraction $f_v\, dv$ of particles with velocity between v and $v+dv$ is

$$f_v dv = \frac{1}{\sqrt{2\pi}\sigma_v} e^{-\frac{(v-v_0)^2}{2\sigma_v^2}} dv$$

$$\sigma_v = \sqrt{\frac{kT_k}{m}}$$

$$\Delta v_{\mathrm{FWHM}} = \sqrt{8\ln 2}\,\sigma_v = 2.35\,\sigma_v$$

1-dimensional velocity dispersion



In frequency:

$$\varphi_\nu = \frac{1}{\sqrt{2\pi}\sigma_\nu} e^{-\frac{(\nu-\nu_0)^2}{2\sigma_\nu^2}}$$

$$\sigma_\nu = \sigma_v \frac{\nu_0}{c}$$

For hydrogen:

phase	T_k [K]	σ_v [km s^{-1}]
CNM	100	1
WNM, WIM	10^4	10
HIM	10^6	100

Core *vs.* wings

Sufficiently far from the line centre, the Lorentz wings ("damping wings") will dominate (see *v*-dependence given earlier).

This happens for $\boxed{|v - v_0| \gg 4.5\,\sigma_v}$.

This will always be irrelevant except for extremely strong lines (in practice only in specific HI Lyman α absorption lines, so-called damped Lyman α absorbers).

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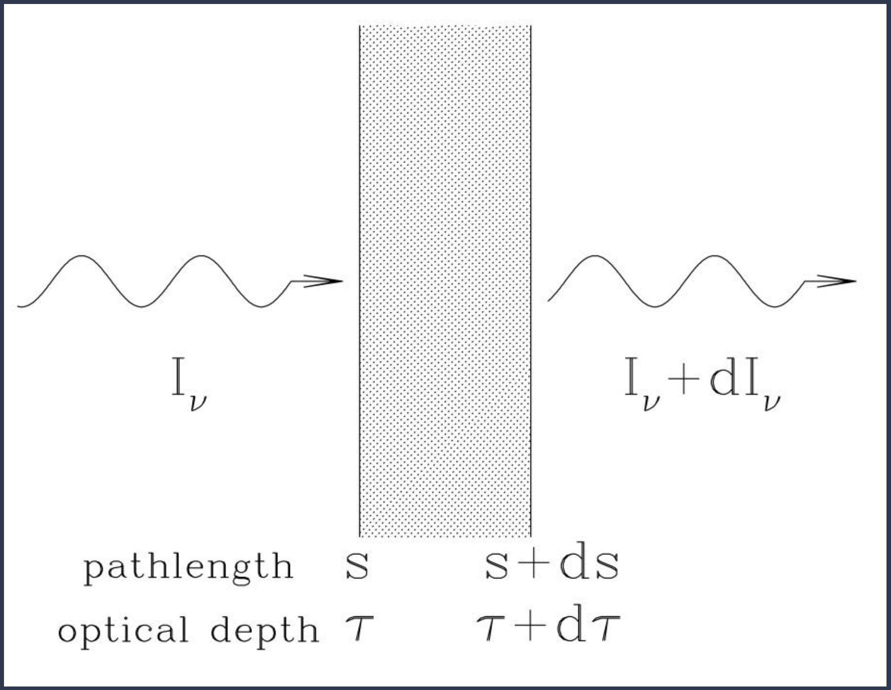
Radiative transfer

Incident radiation: I_ν
At the far side: $I_\nu + dI_\nu$

What is dI_ν?

NB: scattering ignored
(only radiative transitions)



$$\boxed{dI_\nu = -I_\nu \kappa_\nu ds + j_\nu ds}$$

spontaneous emission

net absorption (=absorption corrected for stimulated emission)

j_ν : emissivity [erg s^{-1} cm^{-3} Hz^{-1} sr^{-1}]

κ_ν : absorption coefficient [cm^{-1}]
normally positive but not always (when not?)

Emissivity

- Spontaneous emission: number of radiative decays *u*→*l* per unit of time and volume: $n_u A_{ul}$
- → power radiated in this transition per unit volume: $h\nu_{ul}\, n_u\, A_{ul}$
- and per steradian: $(h\nu_{ul} / 4\pi)\, n_u\, A_{ul}$
- and with a line profile φ_ν:

$$\boxed{j_\nu = \frac{h\nu_{ul}}{4\pi} A_{ul} n_u \varphi_\nu}$$

all information on line shape and central frequency are encoded in φ_ν

Absorption coefficient

Easiest approach is by considering cross sections:

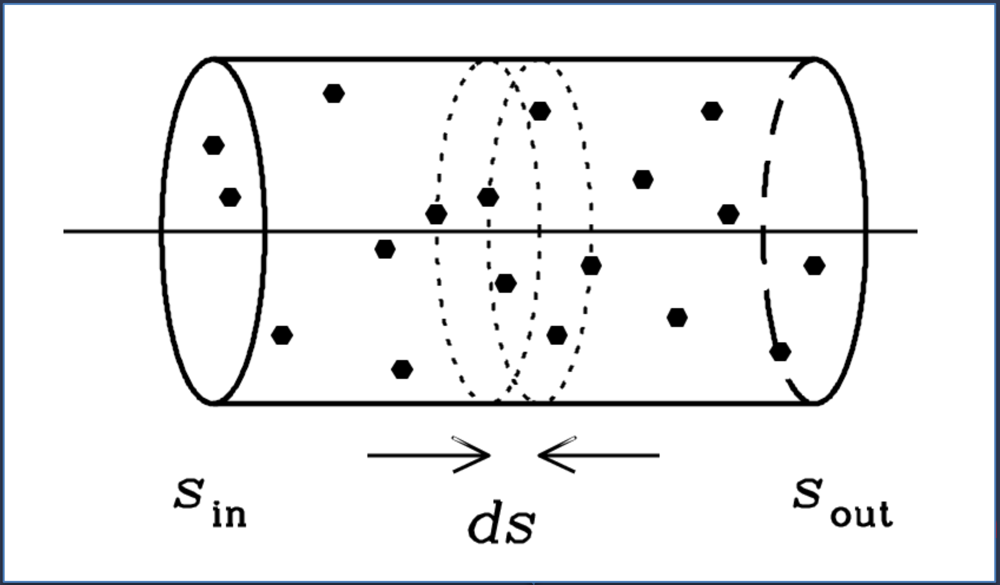
$$\kappa_\nu = n_l \sigma_{lu}(\nu) - n_u \sigma_{ul}(\nu)$$

absorption

stimulated emission

So: how do we connect the cross sections to the Einstein coefficients?

Cross section and Einstein coefficients



Cylinder length: *c dt*

Absorption cross section for a particle: $\sigma_{lu}(\nu)$

$$dn_u = n_l\, c\, \frac{u_\nu}{h\nu} \sigma_{lu}(\nu)\, d\nu\, dt$$

$$\left(\frac{dn_u}{dt}\right)_{l\to u} = n_l \int \sigma_{lu}(\nu) c\, \frac{u_\nu}{h\nu} d\nu \approx n_l c \frac{u_\nu}{h\nu} \int \sigma_{lu}(\nu) d\nu$$

Absorption cross section and line profile

$$dn_u = n_l\, c\, \frac{u_\nu}{h\nu} \sigma_{lu}(\nu)\, d\nu\, dt$$

$$\left(\frac{dn_u}{dt}\right)_{l\to u} = n_l c \frac{u_\nu}{h\nu} \int \sigma_{lu}(\nu)\, d\nu = B_{lu} n_l \int u_\nu \varphi_\nu d\nu$$

Combining with the relations between the Einstein coefficients, we find

$$\sigma_{lu}(\nu) = \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \varphi_\nu$$

with

$$\int \varphi_\nu d\nu = 1$$

Absorption coefficient

$$\kappa_\nu = n_l \sigma_{lu}(\nu) - n_u \sigma_{ul}(\nu)$$

Use relation $\sigma_{ul} \leftrightarrow B_{ul}$ & relation $B_{ul} \leftrightarrow B_{lu}$
$\rightarrow$ relation $\sigma_{ul} \leftrightarrow \sigma_{lu}$:

$$\kappa_\nu = n_l \sigma_{lu}(\nu) \left(1 - \frac{n_u/n_l}{g_u/g_l} \right) = n_l \sigma_{lu}(\nu) \left(1 - e^{-\frac{h\nu_{ul}}{kT_{ex}}} \right)$$

Use definition of T_{ex}

Now use relation $\sigma_{lu} \leftrightarrow B_{lu}$ & relation $A_{ul} \leftrightarrow B_{lu}$:

Absorption coefficient

$$\kappa_\nu = n_l \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \left(1 - e^{-\frac{h\nu_{ul}}{kT_{ex}}}\right) \varphi_\nu$$

frequency dependence is in φ_ν

absorption

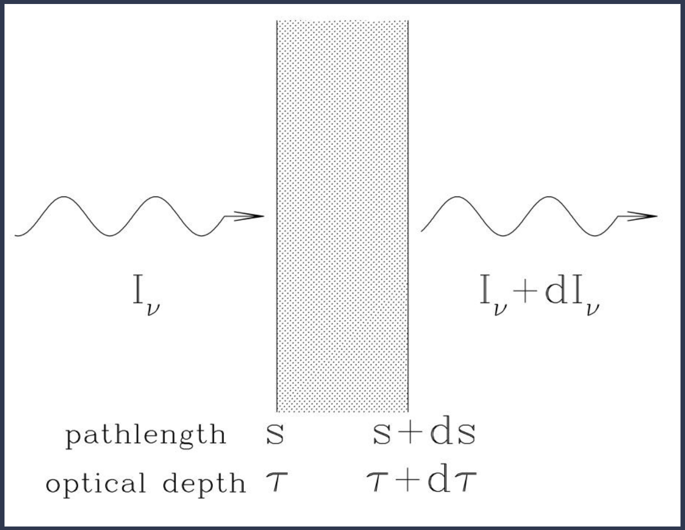
stimulated emission

Equation of transfer

Define optical depth τ_ν:

$$\boxed{d\tau_\nu = \kappa_\nu ds}$$

so $$dI_\nu = -I_\nu \kappa_s ds + j_\nu ds = -I_\nu d\tau_\nu + \frac{j_\nu}{\kappa_\nu} d\tau_\nu$$



Also define the source function S_ν: $S_\nu = \frac{j_\nu}{\kappa_\nu}$

so $$\boxed{dI_\nu = (S_\nu - I_\nu) d\tau_\nu}$$

with the formal solution (see Draine Sect. 7.4 for derivation):

$$I_\nu(\tau_\nu) = I_\nu(0) e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)} S_\nu d\tau'_\nu$$

radiation emitted by the slab but also attenuated by it

incoming radiation attenuated by the slab

Kirchhoff's Law for spectral line radiation

Evaluate S_ν using the derived expressions for j_ν & κ_ν:

$$S_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT_{ex}}}-1} = B_\nu(T_{ex})$$

This is the spectral line version of Kirchhoff's Law (which can be shown to be valid for all thermal radiation).

So $$I_\nu = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)}\, B_\nu(T_{ex}(\tau'_\nu))d\tau'_\nu$$

Simplify by taking T_{ex} constant:

$$I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(T_{ex})(1 - e^{-\tau_\nu})$$

radiation thermalizes more and more as it passes through the slab

incoming radiation attenuated by the slab

Equation of transfer

$$\boxed{I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(T_{ex})(1 - e^{-\tau_\nu})}$$

or

$$\boxed{T_b = T_c e^{-\tau_\nu} + T_{ex}(1 - e^{-\tau_\nu})}$$

background continuum

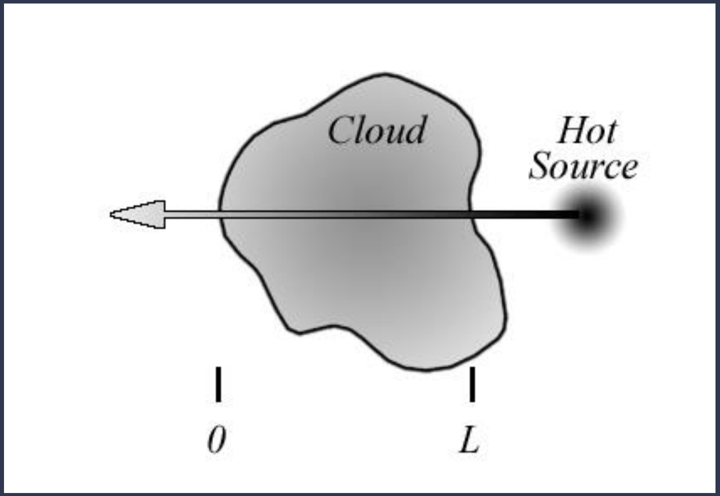
Limiting cases:

1. Optically thick: τ_ν >>1: $$\boxed{I_\nu = B_\nu(T_{ex})}$$

   (where has the spectral line gone?)

Limiting cases

$$I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(T_{ex})(1 - e^{-\tau_\nu})$$

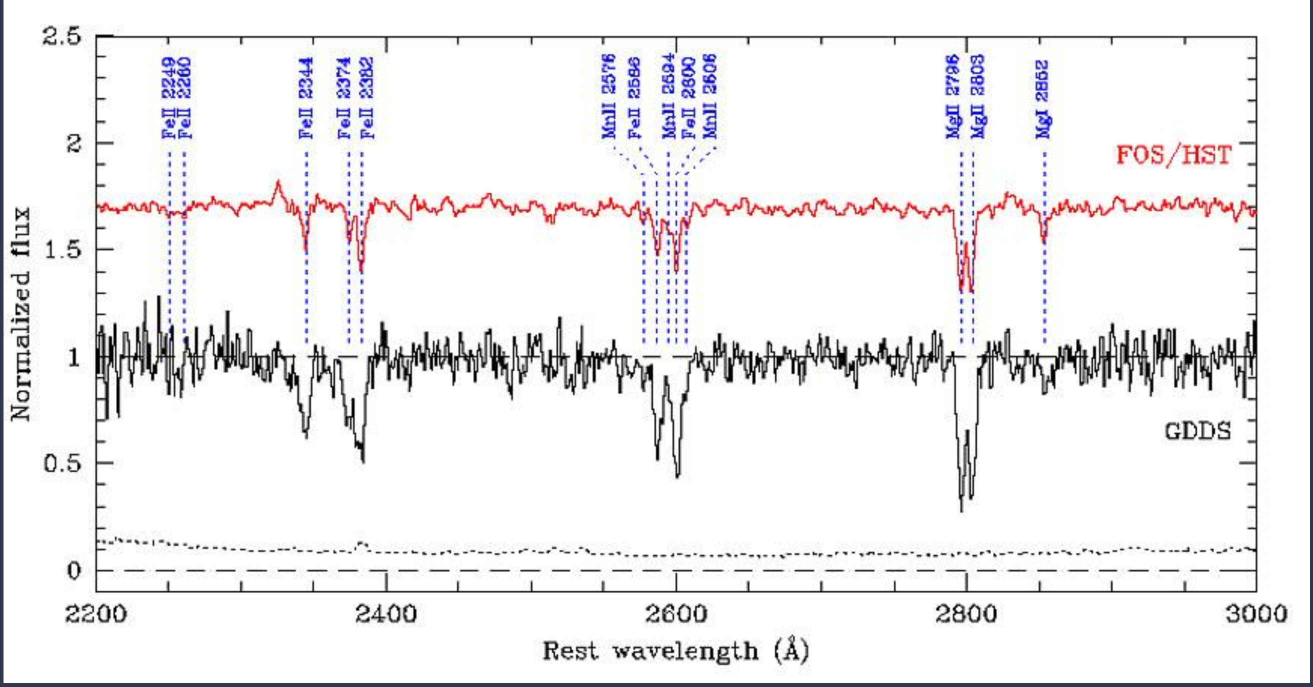


2. Bright background object

optical/UV regime: upper level almost unpopulated

→ T_{ex} very low, so

$$I_\nu = I_\nu(0)e^{-\tau_\nu}$$



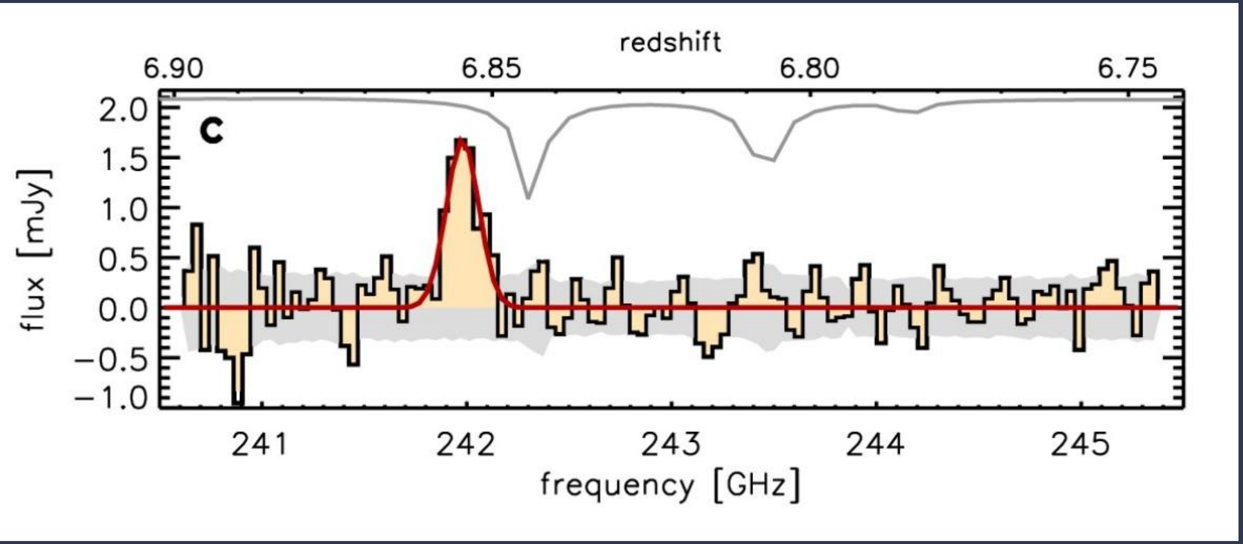
Limiting cases

$$\boxed{I_\nu = I_\nu(0)e^{-\tau_\nu} + B_\nu(T_{ex})(1 - e^{-\tau_\nu})}$$

3. Optically thin: τ_ν << 1 (for simplicity also assume no background source):

$$I_\nu = B_\nu(T_{ex})(1 - e^{-\tau_\nu}) \approx B_\nu(T_{ex})(1 - 1 + \tau_\nu) = \tau_\nu B_\nu(T_{ex})$$

line shape and central frequency are encoded in τ_ν



Smit *et al.*, 2018

Optical depth and column density

$$\kappa_\nu = n_l \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \left(1 - e^{-\frac{h\nu_{ul}}{kT_{ex}}}\right) \varphi_\nu$$

so

$$\tau_\nu = n_l ds \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \left(1 - e^{-\frac{h\nu_{ul}}{kT_{ex}}}\right) \varphi_\nu = N_l \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \left(1 - e^{-\frac{h\nu_{ul}}{kT_{ex}}}\right) \varphi_\nu$$

so

$$\int \tau_\nu d\nu = N_l \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \left(1 - e^{-\frac{h\nu_{ul}}{kT_{ex}}}\right) = N_u \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \left(e^{\frac{h\nu_{ul}}{kT_{ex}}} - 1\right)$$

Now if optically thin:

$$\boxed{\int I_\nu d\nu \approx \int \tau_\nu B_\nu(T_{ex}) d\nu \approx B_\nu(T_{ex}) \int \tau_\nu d\nu = \frac{h\nu}{4\pi} A_{ul} N_u}$$

Here N_i is the column density [cm^{-2}] in level i.

Maser emission

The excitation process may give rise to inversion: $\frac{n_u}{g_u} > \frac{n_l}{g_l}$

Using $\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\frac{h\nu_{ul}}{kT_{ex}}}$ this gives $T_{ex} < 0$

Now with $\tau_\nu = N_l \frac{g_u}{g_l} \frac{c^2}{8\pi\nu_{ul}^2} A_{ul} \left(1 - e^{-\frac{h\nu_{ul}}{kT_{ex}}}\right) \varphi_\nu$ also $\tau_\nu < 0$

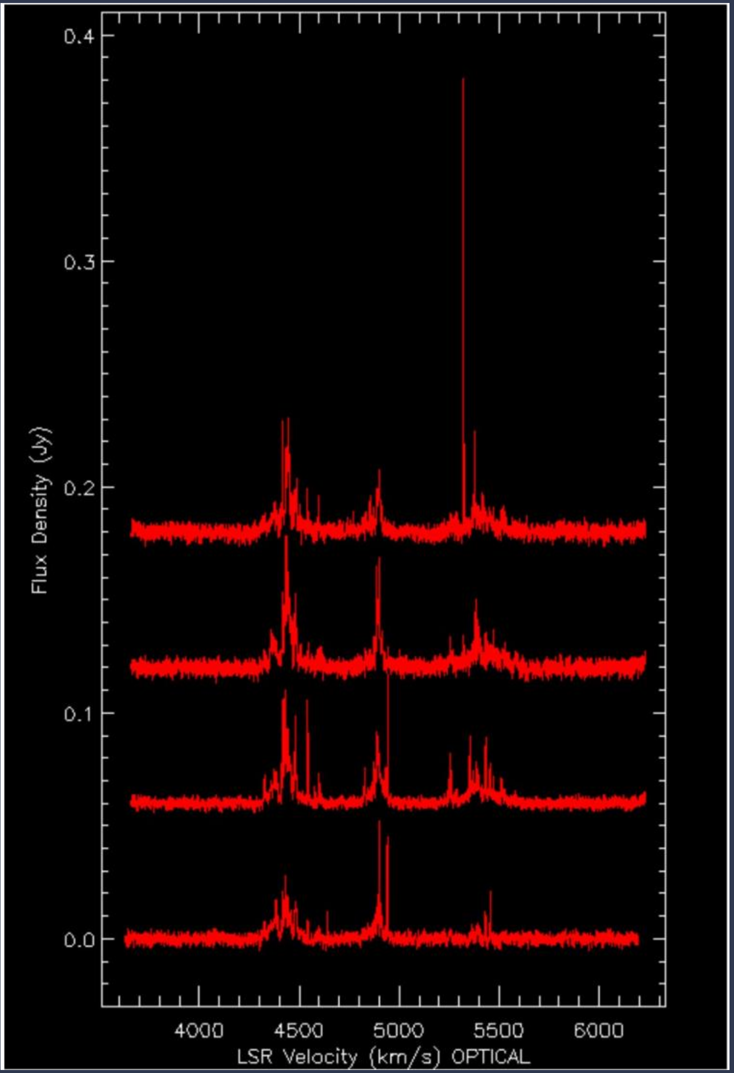
and since $I_\nu = I_\nu(0) e^{-\tau_\nu} + \ ...$ incoming radiation is now amplified:

maser emission

Interstellar masers

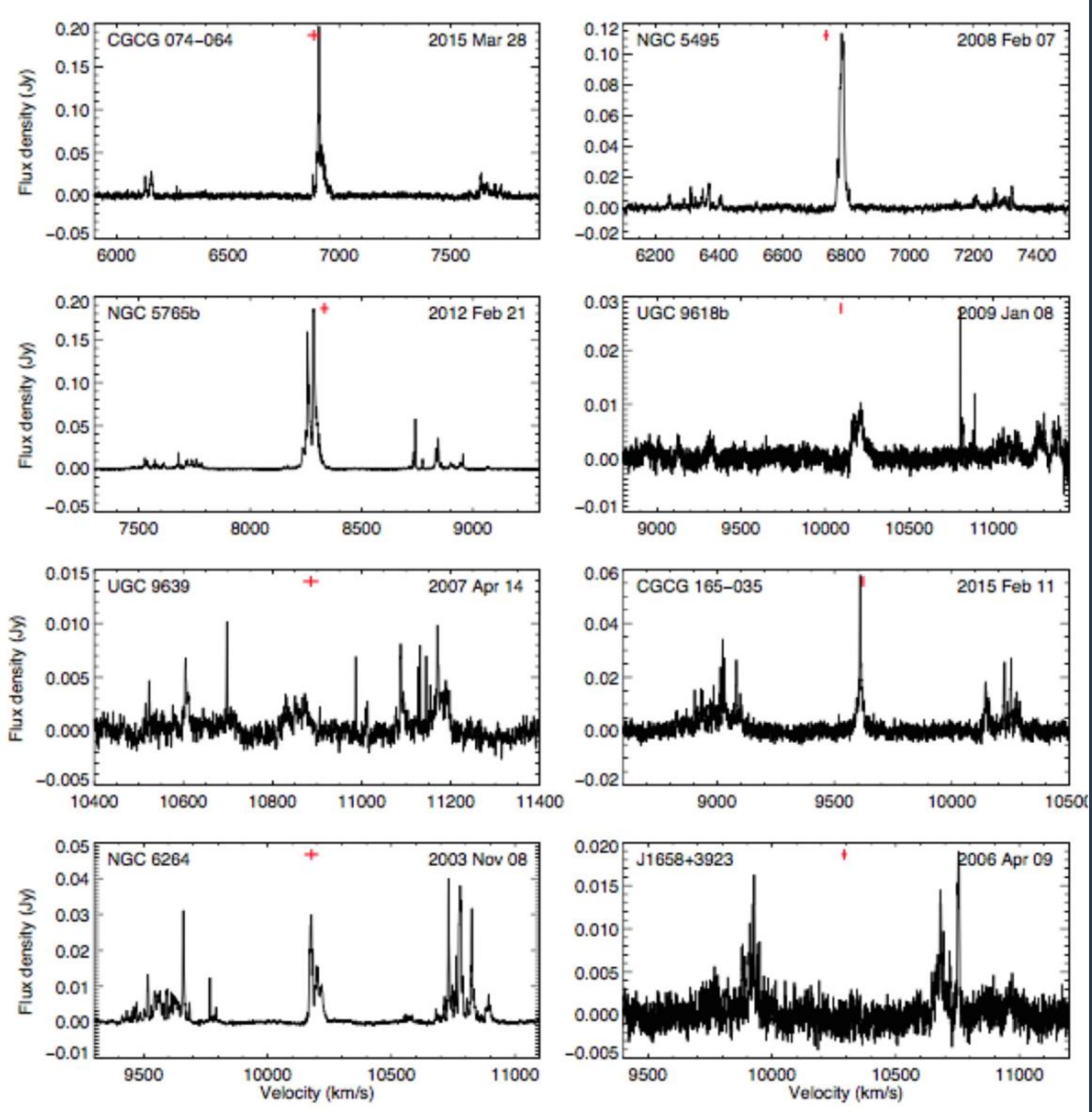
1. Maser lines are very bright
2. Lines are narrow and peaked
3. Pronounced variability
4. Maser emission comes from small "maser spots"
5. Molecules with observed maser transitions: OH, H_2O, NH_3, H_2CO, CH_3OH, SiO, HCN, etc.
6. Needs strong (IR) radiation field (and very high densities)
7. In IR-luminous galactic nuclei: OH, H_2O megamasers

Maser variability

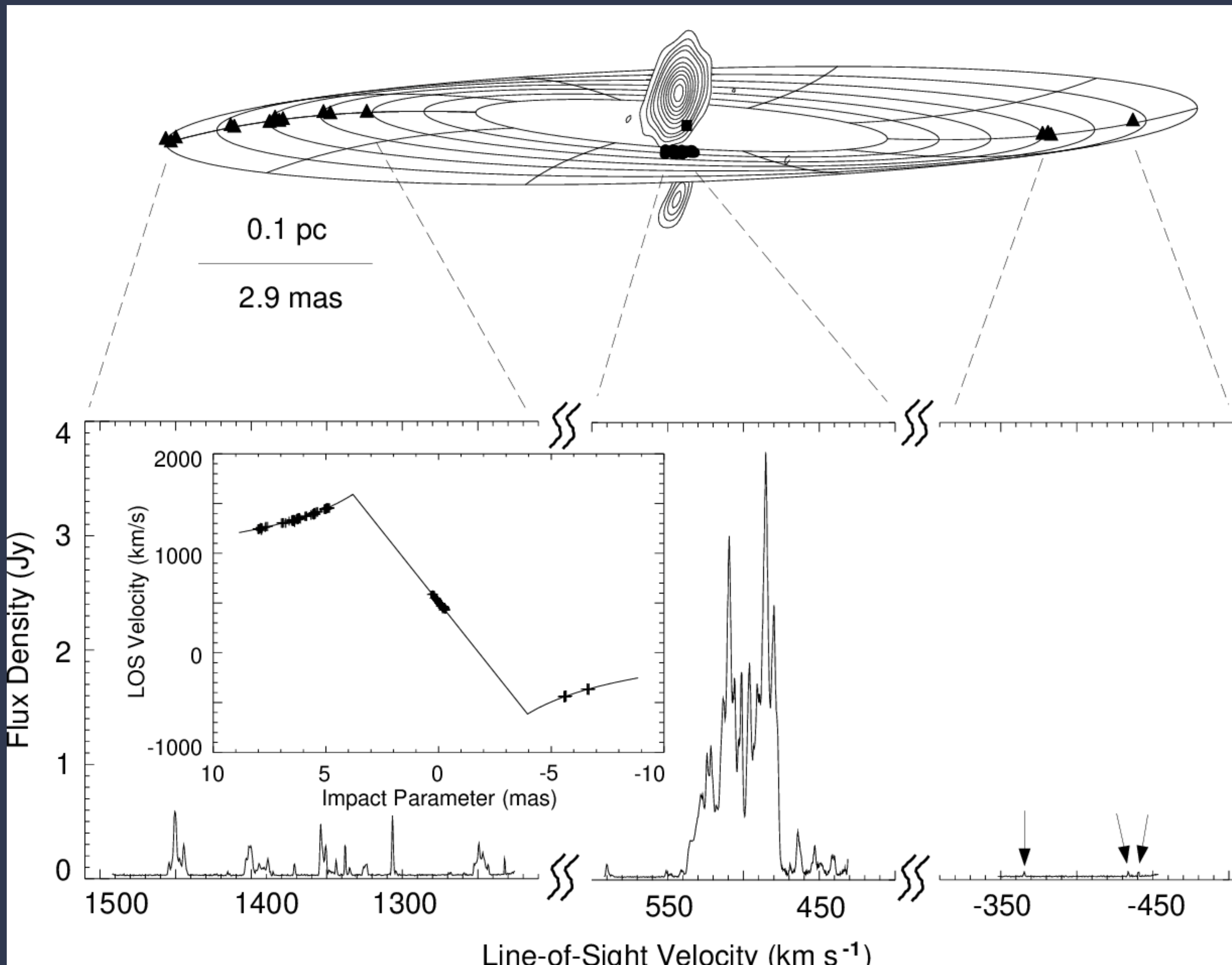


variable H_2O maser emission in IR-luminous galaxy Mrk1419

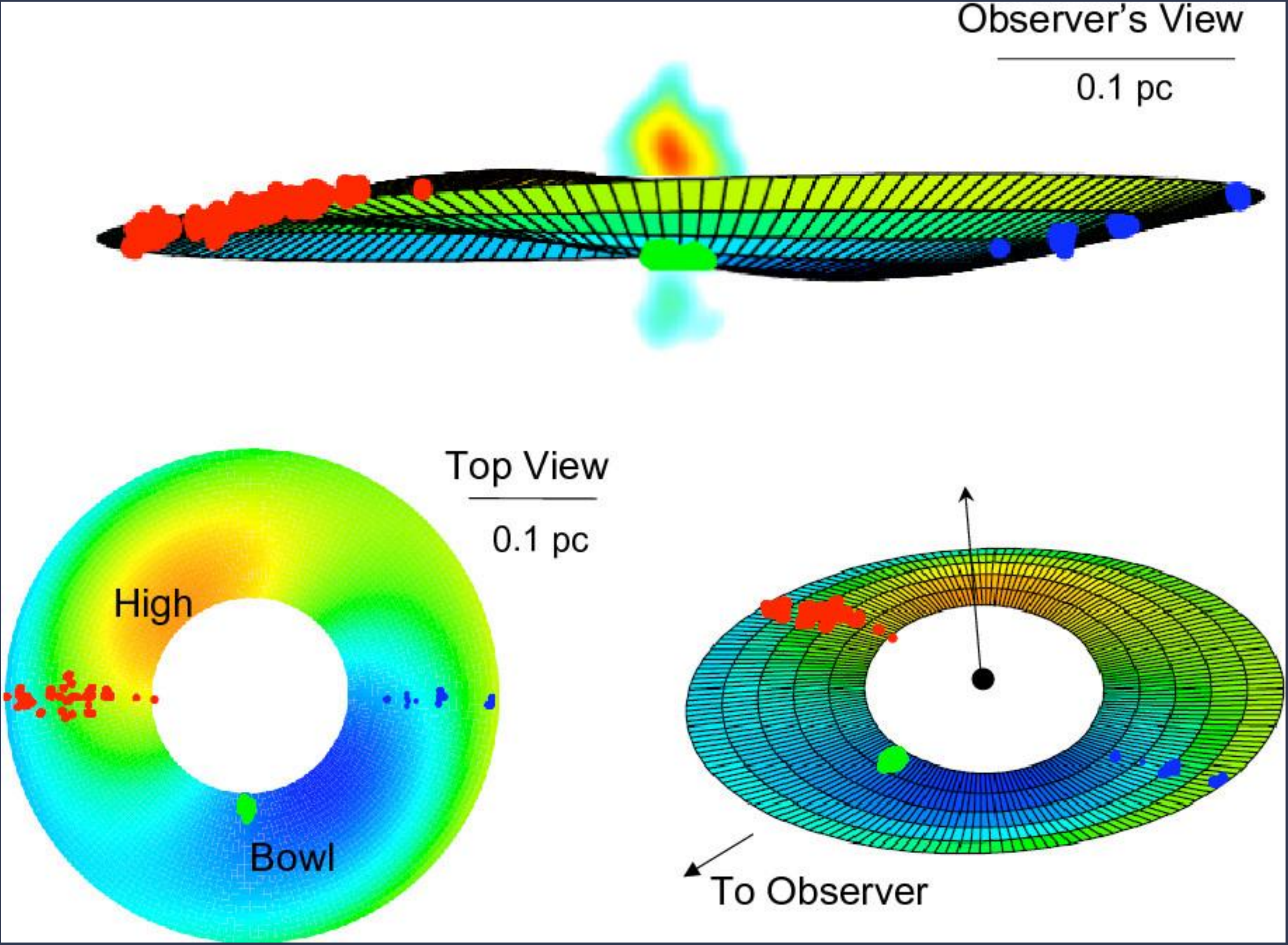
Extragalactic H_2O maser spectra



Circumnuclear H_2O masers in NGC4258



Circumnuclear H_2O masers in NGC4258



Next lecture

The HI 21cm line and the 2-phase ISM

1. Application of radiative process to the HI 21cm line
2. Line emission and absorption
3. Discovery and nature of the 2-phase ISM