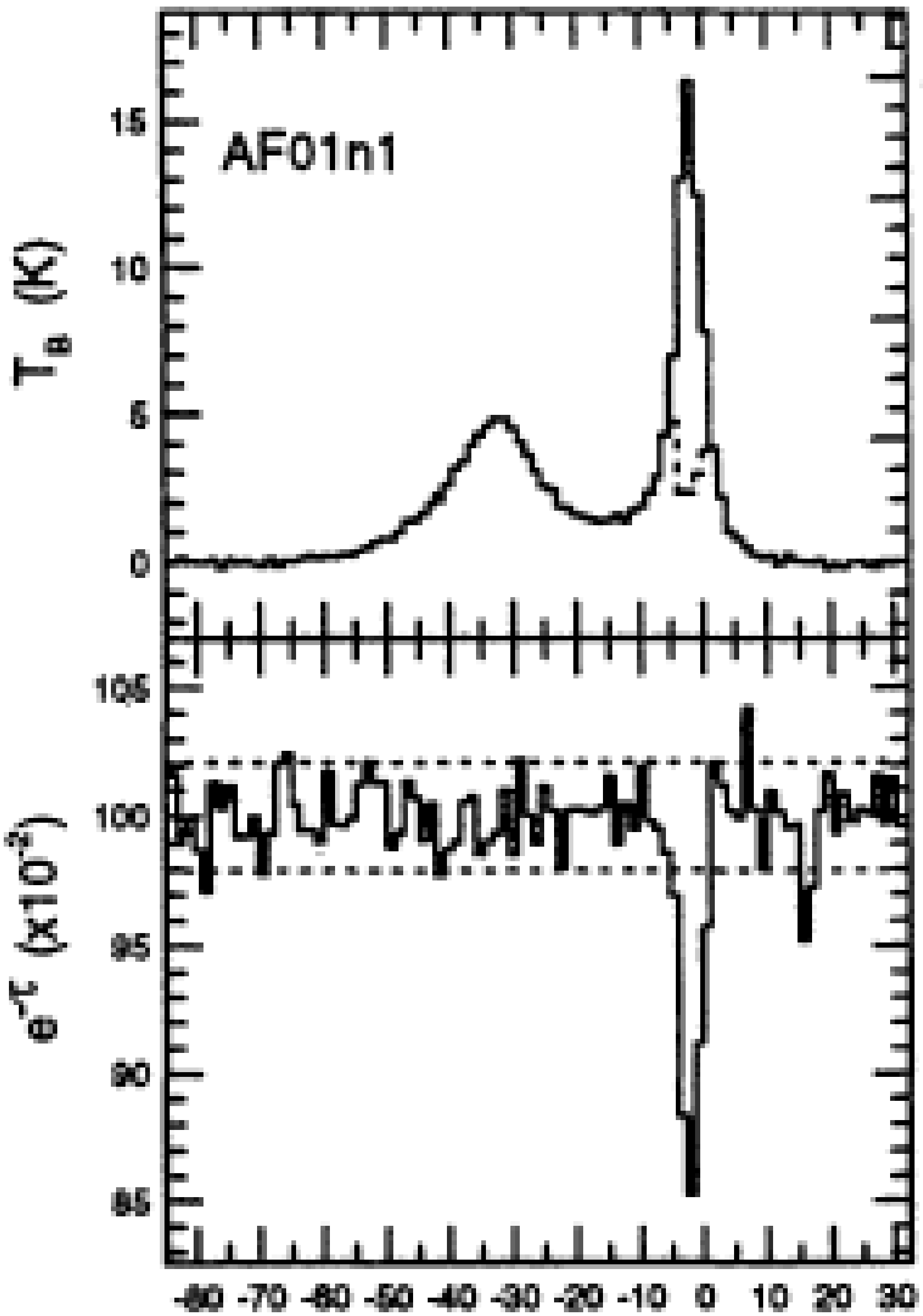
Handout 22: The Interstellar Medium (ISM)

- Calculation of 21 cm intensity
  - The density of hydrogen n is small (1/cm^3)
  - The number in the upper state is even smaller
    - Typical collision rate $\langle n\sigma v\rangle \sim 1/300$ y
      - Lifetime excited state 3 My >> 300 y
      - Upper and lower states in Thermodynamic Equil.
      - Energy gap $h\nu \ll kT$
      - $n_{upper}/n_{lower} = g_{upper}/g_{lower} = 3/1$
      - ¾ of H atoms in upper state
  - The 21 cm line never seen in the lab
    - L limited to meters
  - In space L can be very large, 100's of pc

Neutral, HI clouds in galaxy

- Dust is optically thin at 21 cm
  - Extinction ~ $1/\lambda$ or $1/\lambda^2$
- Can see whole galaxy
  - See HI **clouds**
    - n ~ 100/cm^3
      - From optically thin intensity
      - Assume cloud width = L
    - T ~ 50 K
      - From emission and absorption by the same cloud
    - Visual extinction $A_V \sim N_H$
      - $A_V = N_H / 10^{21} cm^{-2}$



Emission/Absorption from HI clouds sgive:optical depth τ and T of cloud.

Look at bright extragalactic source behind cloud

Intensity = $I_0 \exp(-\tau)$, solve for τ

Look at emission from the cloud

Intensity = $[1- \exp(-\tau)]$BI(T), solve for T

Cloud near 0 km/s: optical depth about 0.14, brightness T 16 K ➔ T about 112 K

Cloud near -35 km/s: optical depth < 0.05, brightness T ~ 5 K, ➔ T > 200 K

Molecular clouds

- In clouds with visual extinction > 1 mag
  - H disappears, H_2 forms (and other molecules)
  - Dust important
    - Shield $h\nu$ > 4 eV dissociating photons
    - Greatly enhance H_2 formation rate
      - 2 H atoms come together
      - H_2 molecule forms
      - No place to put the extra 4 eV of energy
        - They fly apart again
      - 3rd body needed
        - Conserve energy and momentum
        - Energy used to eject H_2 molecule from dust grain

CO tracer of molecular clouds

- Unfortunately, H_2 very hard to detect
  - Zero dipole moment ➔ weak (forbidden) rad'n
  - Minimum $h\nu$ rot'l energy ➔ 28 μm
    - Energy ~ 1/28 eV ➔ T > 300 K to excite
      - Versus 15 K typical molecular cloud T
  - Prodigious dust emission totally swamps feeble H_2 radiation
- Use abundant CO molecule to trace
  - ~ 10^{-4} of H_2, but
    - Has electric dipole moment (non-symmetric)
    - Radiation at 2.6 mm ➔ T > 3 K can excite
      - Dust emission weak at 2.6 mm

Molecular clouds – Where stars form

- Example: Orion Molecular cloud
  - Density ~ 1,000 cm^-3
  - T ~ 20 K
  - Size ~ 10 pc
    - M ~ 10^5 – 10^6 solar, a Giant Molecular Cloud
- Within cloud, see “dense cores”
  - Size ~ 0.01 pc, density 10^7 cm^-3
    - Calculate extinction and M
      - ~ 100 mag, ~ 10 solar masses
  - We believe stars form in these “dense cores”

Cloud collapse – Jeans criterion

- Recall: lack of collapse ➔ H'static equil.
  - dP/dr = -gρ everywhere
- If P not high enough – collapse @ free-fall timescale
  - t = (1/2)Period ~ 1/sqroot(Gρ)
- Stability ➔ virial equilibrium
  - K.E. = -(1/2)P.E.
    - If K.E. is below this, the P = nkT is insufficient
    - Collapse occurs (the Jeans' criterion)

Jeans collapse

Jeans Collapse criterion

use $PE = \frac{-3}{5}\cdot\frac{G\cdot M^2}{R}$ i.e. const. density

and $KE := \frac{3}{2}\cdot N\cdot k\cdot T$ $N = \frac{M}{\mu\cdot m_H}$

gives $M_{Jeans}(T,\rho) := \left(\frac{5\cdot k\cdot T}{G\cdot\mu\cdot m_H}\right)^{\frac{3}{2}}\cdot\left(\frac{3}{4\cdot\pi\cdot\rho}\right)^{\frac{1}{2}}$

dense core $T := 70\cdot K$ $n := 10^7\cdot cm^{-3}$

$\mu \equiv 2$ $\rho := n\cdot\mu\cdot m_H$ $\rho = 0.33210^{-16}\cdot\left(gm\cdot cm^{-3}\right)$

$M_{Jeans}(T,\rho) = 4.316M_{sun}$ $\frac{1}{\sqrt{G\cdot\rho}} = 2.129\times 10^4 yr$

$R_{Jeans} := \left(\frac{5\cdot k\cdot T}{G\cdot\mu\cdot m_H}\right)^{\frac{1}{2}}\cdot\left(\frac{3}{4\cdot\pi\cdot\rho}\right)^{\frac{1}{2}}$ $R_{Jeans} = 0.013pc$

Star Formation

- Cloud core masses (i.e. radii) often exceed the Jeans limit
  - Collapse is happening
  - Free-fall timescale ~ 10,000 y
    - Very quick, c.f. Kelvin-Helmholtz 10 My
  - Extinction very large
    - At visible, > 400 mag
    - Regions hidden from view
    - Must study at IR and radio wavelengths