Astro 501: Radiative Processes
Lecture 31
November 16, 2018

Announcements:

- **Problem Set 9** due now
- **Problem Set 10** due Friday after break

Last time: two-level systems with collisions and radiation
critical density *Q: what's that? physical significance?*

Nebular Diagnostics

consider a *diffuse nebula*: low-density gas generally irradiated by stars

Q: expected optical spectrum?

`www: example spectra`

Q: how to use spectra to measure T*? density?*

Nebular Diagnostics

diffuse nebulae: usually optically thin in visible band

continuum radiation is not blackbody

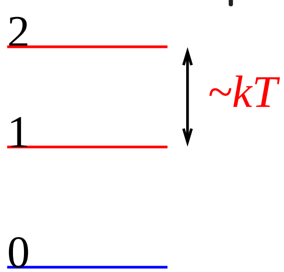
and reprocesses stellar radiation with $T \sim 3000 - 30,000$ K

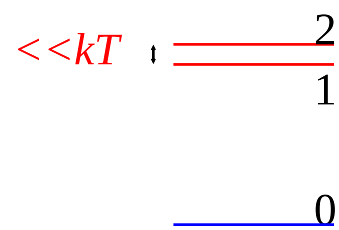
spectra dominated by *emission lines*

$\longrightarrow$ need to use these to determine T, density

Identify ions with the following excited state structures

levels separated by $\Delta E \sim kT$ levels separated by $\Delta E \ll kT$





ω for collisional excitations in ground state:

Q: what controls emission line ratios in each case?

For $\Delta E \sim kT$:
emission ratio $j(2 \rightarrow 0)/j(1 \rightarrow 0)$ exponentially sensitive to T
temperature diagnostic

For $\Delta E \ll kT$:
emission ratio $j(2 \rightarrow 0)/j(1 \rightarrow 0)$ *insensitive* to T

- low density: line ratios set by collision rates: Ω_{20}/Ω_{10}
- high density: excited states come in equilibrium, by spontaneous emission rates: A_{20}/A_{10}
- measured ratio probes density regime

density diagnostic

More in Director's Cut Extras

Starless Vacancies

Strange Things are Afoot at the Circle K

E. E. Barnard (1907, 1910)

noted "vacancy" on the sky – starless regions

now called "*dark clouds*"

`www: Barnard's images`

"It almost seems to me that we are here brought face to face with a phenomenon that may not be explained with our present ideas of the general make-up of the heavens." –Barnard 1907

R. J. Trumpler (1930)

compared distance measures to open star clusters

luminosity distance vs *angular diameter distance*

Q: what's an open cluster?

Q: what are these distances?

Trumpler 1930: Open Cluster Key Project

luminosity distance: identify *standard candle*
with known luminosity L, and measured flux F
infer distance

$$d_L = \sqrt{\frac{L}{4\pi F}}$$

angular diameter distance identify *standard ruler*
with known linear size R, and measured angular diameter θ
infer distance

$$d_A = \frac{R}{\theta}$$

Q: but how did he know luminosity L? physical size R?
`www: Trumpler data` *Q: trends?*

also found stellar *colors* increasingly *red* with larger distance
Q: possible explanations? implications?

Cosmic Dust: Evidence

Trumpler 1930: ratio $d_L/d_A \geq 1$, increases with distance

$$\frac{d_L}{d_A} \propto \frac{1}{R}\sqrt{\frac{L}{F}} \tag{1}$$

observed d_L/d_A increase requires distant clusters are either:

- progressively more luminous – but why?
- progressively smaller – but why?
- anomalously dimmer, i.e., flux F increasingly *attenuated*

increased reddening with distance $\rightarrow$ not due to source geometry

$\longrightarrow$ space filled with medium that *absorbs* and *reddens* light

$\Rightarrow$ **interstellar dust** `www: modern images of dark clouds`

∞

Interstellar Dust

Interstellar Extinction

consider an object of *known flux density* F_λ^0
Q: candidates?

due to dust absorption, *observed flux* density is $F_\lambda < F_\lambda^0$
quantify this via **extinction** A_λ

$$\frac{F_\lambda}{F_\lambda^0} = 10^{-(2/5)A_\lambda} \tag{2}$$

compare optical depth against dust absorption:
$F_\lambda / F_\lambda^0 = e^{-\tau_\lambda}$, so

$$A_\lambda = \frac{5}{2} \log_{10} e^{\tau_\lambda} = 2.5 \ \log_{10}(e) \ \tau_\lambda = 1.086 \ \tau_\lambda \ \mathrm{mag} \tag{3}$$

extinction measures optical depth

Q: what does reddening imply about A_λ?

Reddening

observed reddening implies A_λ stronger for shorter λ
$\rightarrow$ increases with $1/\lambda$

for source of known F_λ^0, can measure this
`www: extinction curve as a function of wavelength`
observed trend: "*reddening law*"

- general rise in A_λ vs $1/\lambda$
- broad peak near $\lambda \sim 2200$ AA $= 0.2\mu$ m

Q: implications of peak? of reddening at very short λ?

in photometric bands, define *redding* or *selective extinction*:
for passbands B and V

$$E(B-V) \equiv A_B - A_V \tag{4}$$

Q: what is selective extinction for "grey" dust $\sigma_\lambda = const$?

interstellar dust: *microscopic irregular solid bodies*
effect on radiation:

- completely absorb wavelengths $\lambda \ll a_{\rm dust}$ dust size
- scattering/absorption for $\lambda \sim a_{\rm dust}$
- small effects for $\lambda \gg a_{\rm dust}$

implications of extinction curve:

- peak wavelength $\rightarrow$ characteristic *dust size* $r_{\rm dust} \sim 0.2\mu{\rm m}$
- expect reddening at $\lambda \sim r_{\rm dust}$
  but complete extinction for $\lambda \ll r_{\rm dust}$
- reddening at small $\lambda \rightarrow$ some very small dust grains exist

note that extinction depends on sightline distance
but not *ratios* of extinction at different λ

$$R_V \equiv \frac{A_V}{A_B - A_V} = \frac{A_V}{E(B-V)} \approx \frac{\sigma_V}{\sigma_B - \sigma_V} \tag{5}$$

- Milky Way ISM typically has $R_V = 3.1$
- but within the MW, R_V varies across sightlines
  from $R_V \sim 2.1$ to ~ 5.7

Director’s Cut Extras

Temperature Diagnostics

temperature diagnostics: *pairs of lines* that are

- energetically accessible: $E_{u\ell} \lesssim kT$
- widely spaced: $\Delta E \sim kT$

consider an idealized *3-level atom*

- ground state $n = 1$, excited states $n = 2, 3$
- excited states populated by *electron collisions* at volume rate $\dot{n}_{13} = \langle \sigma_{e1\rightarrow 3} v \rangle \; n_1 \; n_e \propto \Omega_{13} e^{-E_{13}/kT} n_1 n_e$
- probability for $3 \rightarrow 1$ transition: $A_{31}/(A_{31} + A_{32})$ *Q: why?*

if electron density $n_e \ll n_{e,\text{crit}}$
then de-excitation occurs via spontaneous emission
and integrated emissivity from the $3 \rightarrow 1$ transition is

$$j_{31} = E_{31} \dot{n}_{13} \frac{A_{31}}{A_{31} + A_{32}} = E_{31} \langle \sigma_{31} v \rangle \frac{A_{31}}{A_{31} + A_{32}} n_1 n_e \tag{6}$$

and from the $3 \rightarrow 1$ transition is

$$j_{21} = E_{21} \left(\langle \sigma_{12} v \rangle + \langle \sigma_{13} v \rangle \frac{A_{32}}{A_{31} + A_{32}} \right) n_1 n_e \tag{7}$$

thus the emissivity ratio and hence line ratio is

$$\frac{j_{31}}{j_{21}} = \frac{A_{31} E_{31}}{A_{32} E_{32}} \frac{(A_{31} + A_{32}) \langle \sigma_{31} v \rangle}{(A_{31} + A_{32}) \langle \sigma_{21} v \rangle + A_{31} \langle \sigma_{31} v \rangle} \tag{8}$$

$$= \frac{A_{31} E_{31}}{A_{32} E_{32}} \frac{(A_{31} + A_{32}) \Omega_{31} e^{-E_{32}/kT}}{(A_{31} + A_{32}) \Omega_{21} + A_{31} \Omega_{31} e^{-E_{32}/kT}} \tag{9}$$

excellent! *Q: Why?*

3-level atom line ratio

$$\frac{j_{31}}{j_{21}} = \frac{A_{31}E_{31}}{A_{32}E_{32}} \, \frac{(A_{31}+A_{32})\Omega_{31}e^{-E_{32}/kT}}{(A_{31}+A_{32})\Omega_{21}+A_{31}\Omega_{31}e^{-E_{32}/kT}} \tag{10}$$

depends only on T and atomic properties

so: for appropriate systems

- measure line ratio
- look up the atomic properties
- use observed ratio to solve for T!