Astronomy 501: Radiative Processes

Lecture 32

Nov 7, 2022

Announcements:

- **Problem Set 10–penultimate!–on Friday**
- **Radiative Meme Submission on Canvas**
  brilliant submissions already

Last time: Nebular Diagnostics
more in Director's Cut Extras

Build Your Toolbox–Line Radiation

emission physics: matter-radiation interactions

Q: physical conditions for line emission? absorption?

Q: physical nature of sources?

Q: spectrum characteristics?

Q: frequency range?

real/expected astrophysical sources of line radiation

Q: what do we expect to emit lines? absorb lines?

Q: relevant temperatures? EM bands?

Toolbox: Line Radiation

emission physics

- physical conditions: excitation or de-excitation of bound states
- physical sources: atoms and molecules
  wavelengths act as "barcode" for composition!
  also nuclear lines at MeV energies
- spectrum: line position ↔ transition energy
  possibly with Doppler and gravitational red/blueshifts
  linewidth: intrinsic+thermal+pressure broadening+turbulent

astrophysical sources of lines

- emitters: radiative and/or collisional excitations
  probes density, temperature, and radiation field
- temperatures: up to $\sim 10^5$K for H, higher for metal lines
- EM bands: UV/optical/IR for permitted atomic lines
  IR/mm/radio for molecular and spin-flip lines

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 → not due to source geometry

→ space filled with medium that *absorbs* and *reddens* light

⇒ **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 $\lambda \ll a_{\text{dust}}$ dust size
- scattering/absorption for $\lambda \sim a_{\text{dust}}$
- small effects for $\lambda \gg a_{\text{dust}}$

implications of extinction curve:

- peak wavelength → characteristic *dust size* $r_{\text{dust}} \sim 0.2\mu\text{m}$
- expect reddening at $\lambda \sim r_{\text{dust}}$
  but complete extinction for $\lambda \ll r_{\text{dust}}$
- reddening at small λ → 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

A Clue to Dust : Interstellar Depletion

Experiment:

- measure local interstellar *atomic absorption lines* that appear in the spectra of nearby bright stars, e.g., ρOph
- infer *interstellar abundances*, and express as ratio: element/H
- compare with *solar system abundances* for element/H e.g., $(C/H)_{\rm ism,obs}$ vs $(C/H)_\odot$

Results:

- for some elements, abundances similar e.g., $(Ar/H)_{\rm ism,obs} \approx (Ar/H)_\odot$, and $(O/H)_{\rm ism,obs} \approx 0.5\ (O/H)_\odot$
- but other elements show strong **depletion** e.g., $(Fe/H)_{\rm ism,obs} \lesssim 10^{-2}\ (Fe/H)_\odot$, and $(Ca/H)_{\rm ism,obs} \approx 2 \times 10^{-4}\ (Ca/H)_\odot$

Q: why this difference?

Dust: Composition

interstellar *atomic absorption lines* trace
element in *atomic* form
→ measure interstellar *gas-phase abundances* only!

but *dust* particles are in *solid phase*! “*grains*”
do not give atomic lines!

nearby ISM likely nearly has *nearly solar composition*
but some elements mostly in gas phase, others mostly in grains

Depletion pattern correlated with **condensation temperature**
i.e., temperature at which a dilute vapor → 50% solid

`www: observed depletion pattern`

- *low* T_{cond} *elements*: *volatile* (Kr, Ar, C, O, ...)
  small/no depletion
- *high* T_{cond} *elements*: *refractory* (Fe, Ni, Ti, Ca, ...)
  large depletion

Q: what is this trying to tell us?

depletion correlated with condensation temperature

suggests physical picture:

- dust formed out of high-temperature material
  e.g., ejecta from dying stars
  note: AGB stars have dusty shells
- as this vapor cools, refractory elements form dust first
- small depletion for $T_{\mathrm{cond}} \lesssim 700 - 800$ K
  either gas never gets this cool,
  or more likely, density becomes too low to form dust
  by collisional processes

Warning!

when using interstellar abundances, never forget that
these only include elements in the gas phase!

Director’s Cut Extras

Awesome Example: C^+ 158μm

singly ionized carbon: C^+ or C ii

ground state hyperfine splitting $J = 3/2, 1/2$

$$\begin{aligned} \Delta E/k &= 91.21\ \text{K} && (6) \\ \lambda &= 158\ \mu\text{m} && (7) \\ A_{10} &= 2.4 \times 10^{-6}\ \text{s}^{-1} = (4.8\ \text{days})^{-1} && (8) \end{aligned}$$

Q: waveband? appropriate telescopes?

critical densities

$$\begin{aligned} n_{\text{crit}}(\text{H}) &\sim 3000\ \text{cm}^{-3} && (9) \\ n_{\text{crit}}(e^-) &\sim 50\ \sqrt{T/10^4\,\text{K}}\ \text{cm}^{-3} && (10) \end{aligned}$$

consider a low density, optically thin region with C^+

Q: what are the level populations?

Q: if upper level collisionally excited, what happens?

Q: where is this likely to occur?

C^+ Hyperfine Emission as a Star-Formation Coolant

low density parts of star-forming regions
- contain C ii,
- but are below critical densities
- and optically thin: not radiatively excited

so: *upper level "subthermal"* → *collisions can excite*

and if collisional excitation occurs
- radiative de-excitation is the most likely
- [C ii] 158 μm photon emitted
- usually optically thin, lost from system: *observable!*
- removes energy: *coolant*

This line is a major tracer of diffuse star-forming regions!

Q: what should an all-sky map of 158 μm look like?

`www: all-sky`, `www: external galaxies`

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 Temperature Diagnostic

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*
→ need to use these to determine T, density

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 $dn_{13}/dt = \langle \sigma_{e1\to 3} v \rangle \; n_1 \; n_e \propto \Omega_{13} e^{-E_{13}/kT} n_1 n_e$
- probability for 3 → 1 transition: $A_{31}/(A_{31} + A_{32})$ *Q: why?*

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

$$j_{31} = E_{31}\dot{n}_{13}\frac{A_{31}}{A_{31}+A_{32}} = E_{31}\left\langle\sigma_{31}v\right\rangle\frac{A_{31}}{A_{31}+A_{32}}n_1 n_e \tag{11}$$

and from the 3 → 1 transition is

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

thus the emissivity ratio and hence line ratio is

$$\begin{aligned} \frac{j_{31}}{j_{21}} &= \frac{A_{31}E_{31}}{A_{32}E_{32}}\,\frac{(A_{31}+A_{32})\left\langle\sigma_{31}v\right\rangle}{(A_{31}+A_{32})\left\langle\sigma_{21}v\right\rangle + A_{31}\left\langle\sigma_{31}v\right\rangle} && (13)\\ &= \frac{A_{31}E_{31}}{A_{32}E_{32}}\,\frac{(A_{31}+A_{32})\Omega_{31}e^{-E_{32}/kT}}{(A_{31}+A_{32})\Omega_{21} + A_{31}\Omega_{31}e^{-E_{32}/kT}} && (14) \end{aligned}$$

excellent! *Q: Why?*

3-level atom line ratio

$$\frac{j_{31}}{j_{21}} = \frac{A_{31}E_{31}}{A_{32}E_{32}} \frac{(A_{31}+A_{32})\Omega_{31}e^{-E_{32}/kT}}{(A_{31}+A_{32})\Omega_{21}+A_{31}\Omega_{31}e^{-E_{32}/kT}} \tag{15}$$

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!