Astro 501: Radiative Processes
Lecture 31
November 16, 2018

Announcements:
- Welcome back!
- **Problem Set 10** due Friday

- **Final Exam**

Scheduled time: Friday Dec 14, 7pm to 10pm
open book, open notes, not internet or other help

Vote! Exam Format
(a) in class as scheduled
(b) take-home, no collaboration, submit scanned answers
2pm (after Solstice Party) to 10pm

Before Break: 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

Last Time: Vacancies in the Sky

Barnard: starless "vacancies" on the sky

Trumpler: open cluster distance comparison
angular diameter distance vs luminosity distance
Q: what are these?
Q: what did he find?
Q: what does it imply?

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

$$\frac{F_\lambda}{F_\lambda^0} = 10^{-(2/5)A_\lambda} \tag{1}$$

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

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

extinction measures optical depth
also: in magnitudes $m_{\text{obs}} = m_{\text{no dust}} + A$

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

$$E(B-V) \equiv A_B - A_V \tag{3}$$

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 → 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 λ → some very small dust grains exist

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

$$R_V \equiv \frac{A_V}{A_B - A_V} = \frac{A_V}{E(B-V)} \approx \frac{\sigma_V}{\sigma_B - \sigma_V} \tag{4}$$

- 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., $(\mathrm{C/H})_{\mathrm{ism,obs}}$ vs $(\mathrm{C/H})_{\odot}$

Results:

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

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!

Dust Temperature

We have seen: interstellar dust absorbs starlight
but what happens next?

long story short:

- energy from photons is *thermalized* in dust grains
- which then *radiate* as black bodies
- dust temperature set by absorption/emission equilibrium at $T_{\mathrm{dust}} \sim 10 - 100$ K, depending on environment
- observable in the *infrared*

`www: the sky in mid-far infrared`

Lesson: *dust reprocesses starlight into thermal IR!*

Implication:

starlight dominated by luminous massive stars

→ dust IR emission traces extincted UV/optical from these stars

→ probes star formation rate!

Special Relativity for the Impatient

Spacetime

see S. Carroll, *Spacetime and Geometry*; R. Geroch, *General Relativity from A to B*

evolving view of space, time, and motion:
Aristotle → Galileo → Einstein

Key basic concept: **event**
occurrence localized in space and time
e.g., firecracker, finger snap
idealized → no spatial extent, no duration in time

a goal (*the* goal?) of physics:
describe relationships among events

Q: consider collection of all possible events–what's included?

Spacetime Coordinates

Each event specifies a unique point in space and time
collection of all possible events = **spacetime**

lay down coordinate system: 3 space coords, one time
4-dimensional, but as yet time & space unrelated

e.g., time t, Cartesian x, y, z: event $\rightarrow (t, x, y, z)$
physics asks (and answers) what is the relationship
between two events, e.g., (t_1, x_1, y_1, z_1) and (t_2, x_2, y_2, z_2)

Note: more on spacetime in Director's Cut Extras to today's notes

Galilean Relativity

consider *two laboratories*
(same apparatus, funding, required courses, vending machines)
move at constant velocity with respect to each other

Galileo:
no experiment done in either lab (without looking outside)
can answer the question "which lab is moving"
→ *no absolute motion*, only relative velocity

Newton: laws of mechanics invariant
for observers moving at const $\vec{v}$
"*inertial observers*"

Implications for spacetime
no absolute motion → *no absolute space*
(but still no reason to abandon absolute time)

Galilean Frames

each inertial obs has own personal frame:
obs (“Angelina”) at rest in own frame: (x, y, z) same for all t
but to another obs (“Brad”) in relative motion $\vec{v} = v\hat{x}$
B sees A’s frame as time-dependent:

$$x_{\text{A as seen by B}} = x' \quad = \quad x - vt \tag{5}$$

but still absolute time: $t' = t$
Newton’s laws (and Newtonian Gravity) hold in both frames
can show: $d^2\vec{x}/dt^2 = \vec{F}(\vec{x}) \Rightarrow d^2\vec{x}'/dt'^2 = \vec{F}(\vec{x}')$
“Galilean invariance”

Geometrically:
different inertial frames → transformation of spacetime
slide the “space slices” at each time
(picture “shear,” or beveling a deck of cards)

Trouble for Galileo

Maxwell: equations govern light
very successful, but:

- predicts unique (constant) light speed c–relative to whom?
- Maxwell eqs **not** Galilean invariant

Lorentz: Maxwell eqs invariant when

$$\begin{aligned} t' &= \gamma(t - vx/c^2) && (6) \\ x' &= \gamma(x - vt) && (7) \\ y' &= y && (8) \\ z' &= z && (9) \end{aligned}$$

with Lorentz factor $\gamma = 1/\sqrt{1 - v^2/c^2}$

Einstein:
Lorentz transformation not just a trick
but correct relationship between inertial frames!
$\Rightarrow$ this is the way the world is

Einstein: Special Relativity

consider two *nearby events*
(t, x, y, z) and $(t + \Delta t, x + \Delta x, y + \Delta y, z + \Delta z)$

different inertial obs *disagree* about Δt *and* $\Delta \vec{x}$
but all *agree* on the value of the **interval**

$$\Delta s^2 \equiv (c\Delta t)^2 - (\Delta x)^2 - (\Delta y)^2 - (\Delta z)^2 \quad (10)$$

$$= (c\Delta t)^2 - (\Delta \ell)^2 \quad (11)$$

Note: interval can have $\Delta s^2 > 0, < 0, = 0$

quantities agreed upon by all observers: *Lorentz invariants*

Light pulse: $\Delta \ell = c\Delta t$
$\rightarrow \Delta s_{\text{light}} = 0$
$\rightarrow$ light moves at c in all frames!

Motion and time:

Consider two events, at rest in one frame:

$\Delta\vec{x}_{\text{rest}} = 0$ in rest frame, so

$\Delta s = c\Delta t_{\text{rest}}$: $c\times$ elapsed time in rest frame

In another inertial frame, relative speed v:

events separated in space by $\Delta x' = v\Delta t'$

$$\Delta s = \sqrt{c^2 \Delta t'^2 - \Delta x'^2} = \sqrt{c^2 - v^2}\Delta t' = \frac{1}{\gamma} c\Delta t' \tag{12}$$

since Δs same: infer $\Delta t' = \gamma \Delta t_{\text{rest}} > \Delta t_{\text{rest}}$

$\Rightarrow$ moving clocks appear to run slow

(special) relativistic **time dilation**

$\Rightarrow$ no absolute time (and no absolute space)

H. Minkowski:

> “Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.”