Astro 210

Lecture 12

Feb 14, 2011

Announcements

- Hour Exam 1 in class Friday
  info online
- Planetarium shows: today, tomorrow, Thursday, next Mon
  registration, report forms, info online
- Night Observing this week Mon–Thurs. *Dress warmly!*
  report forms, info online

Last time: light=electromagnetic radiation as astronomer's tool

- *Q: why "electromagnetic"? why "radiation"?*

iClicker Poll: Orange & Blue at the Races

Which travels faster in a vacuum?

A **orange** light (note: $\lambda_{\text{orange}} > \lambda_{\text{blue}}$)

B **blue** light (note: $f_{\text{blue}} > f_{\text{orange}}$)

C speeds are exactly the same

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also from last time:

flux $F = (dE/dt)/A =$ incident power/collecting area

Q: how does your eye interpret flux?

Radiation from a Spherical Source

consider a **spherical** source of light
emitting equal amounts of radiation in all directions

at emitter surface, radius R, flux is F_{surf}

Q: what is total light power L *emitted from source?*

now consider a sphere of radius $r > R$, concentric with source
(between R and r is vacuum)

Q: what is total light power incident on sphere at r*?*

Q: what is flux $F(r)$ *at* r*?*

Inverse Square Law for Flux

recall flux definition: $F = \frac{dE/dt}{A} = \frac{\text{incident power}}{\text{collecting area}}$

Spherical source emitting flux F_{surf} from surface at R:
radiated power (light energy outflow per unit time) = **luminosity**

$$L = L_{\text{emit}} = \text{surface area} \times \text{flux at surface} = 4\pi R^2 F_{\text{surf}} \qquad (1)$$

for concentric sphere at $r > R$:
total incident power (energy *inflow*) must equal source *outflow* due to energy conservation:

$$L_{\text{incident}} = L_{\text{emit}} = L \qquad (2)$$

and flux is just

$$F(r) = \frac{L}{4\pi r^2}$$

observed flux =apparent brightness depends on

- source via $F \propto L$
- observer distance via $F \propto 1/r^2$: **inverse square law** for flux

Kirchoff's Rules

can classify three basic kinds of spectra:

diagram: hot solid, cooler gas, lines of sight

1. A hot and opaque solid, liquid or dense gas emits a continuous spectrum (A)
diagram: continuous spectrum: F vs λ

2. A hot low-density (transparent) gas produces emission line spectrum
note: pattern of lines specific to element
diagram: emission line spectrum: F vs λ

3. Continuous radiation viewed though cooler gas produces an absorption line spectrum

label C on diagram

diagram: absorptions line spectrum

note: the lines absorbed have same color/wavelength as the lines in emission line spectrum: F vs λ

these effects are godsends for astrophysics!

Q: why?

Observer's Scorecard

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You can see an awful lot, just by looking.
  -- Asrophysicist Yogi Berra
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can use emission/absorption lines to inventory kinds of elements in an astronomical source

light spectrum gives atom "fingerprint" or "barcode"

spectrum $\rightarrow$ composition

Example: The Sun

Sun, stars hotter, denser in center cooler, less dense at surface
so: sunlight/starlight shows *Q: what kind of spectrum?*
`www: Sun spectrum`
amount absorbed in each line → amount of atoms
→ **composition** of Sun; works for other stars too!

Note: as yet, don't know where lines comes from
who assigns cosmic barcodes?

for this, need to understand how light interacts with matter

Matter

Recall:

matter
$\downarrow$
molecules
$\downarrow$
atoms
$\swarrow$ $\searrow$
nucleus electrons
$\swarrow$ $\searrow$
protons neutrons

atoms come in **elements**

92 natural, 23+ artificial

`www: periodic table`

determined by nuclear charge $Z = \#$ protons

e.g., hydrogen H: $Z = 1$

uranium U: $Z = 92$

same element (same # p) can have different # neutrons

$\rightarrow$ "isotopes"

examples: most hydrogen is ^{1}H $= \boxed{1p,\ 0n}$

but $\sim 10^{-4}$ of hydrogen is deuterium ^{2}H $= \boxed{1p,\ 1n}$

most U is ^{238}U $= \boxed{92p,\ 146n}$; about $\sim 1\%$ is ^{235}U $= \boxed{92p,\ 143n}$

atom net charge fixed by # electrons

$\#\ e = \#\ p \rightarrow$ neutral

$\#\ e = \#\ p - 1 \rightarrow$ singly ionized

Note: all p, n, e are absolutely *identical* and *indistinguishable*

this turns out to be crucial for the understanding of matter

in a quantum mechanical way

Atoms & Spectra

how are spectral lines ("barcode") related to atom structure?

Balmer hydrogen gas $\to$ emission line spect. (visible λ)
found empirical pattern to lines

$$\lambda = 3.65 \times 10^{-7} \frac{n^2}{n^2 - 4} \text{ m} \quad n \text{ integer } \geq 3 \tag{3}$$

(1) only these lines seen and no others
(2) simple mathematical structure cries out for explanation!

try it! for $n = 3$:
$\lambda_{n=3} = 3.65 \times 10^{-7} \frac{9}{9-4} \text{m} = 656\text{nm}$
Q: what color is this? `www: Balmer spectrum`
`www: Sun spectrum;` Hα $\to$ the Sun contains hydrogen!

Prince Louis-Victor de Broglie

not only light behaves like particle & wave
but also matter:
$\rightarrow$ matter waves exist!?!

what is λ?
for photons, λ and $p = E/c$ related:

$$\lambda = \frac{c}{f} = \frac{c}{E/h} = \frac{hc}{E} = \frac{h}{p} \tag{4}$$

de Broglie hypothesis/guess: same holds for matter

$$\lambda = \frac{h}{p} = \frac{h}{mv} \tag{5}$$

i.e., matter has wave properties
expect to show up on lengthscales $\sim \lambda$

Q: so why doesn't a baseball diffract out of your hand?

A Quantum Baseball?

regulation mass $m = 5$ oz $= 0.14$ kg
easy toss: $v \sim 1$ m/s
$\rightarrow$ momentum $p = mv \sim 0.14$ kg m/s
$\rightarrow$ de Broglie wavelength

$$\lambda_{\rm deB,baseball} = \frac{h}{p} = 5 \times 10^{-33} \text{ m} \lesssim 10^{-14} \times \text{size of proton} \quad (6)$$

wave properties and hence quantum effects unobservably small!
$\rightarrow$ expect baseballs to exhibit classical (Newtonian) behavior
$\rightarrow$ can't blame fielding errors on quantum mechanics!

Q: in what circumstances would quantum effects not be small?
i.e., for what objects is $\lambda_{\rm deB}$ *larger?*

Bohr model of the atom

quantum structure of atom: e orbits are matter waves

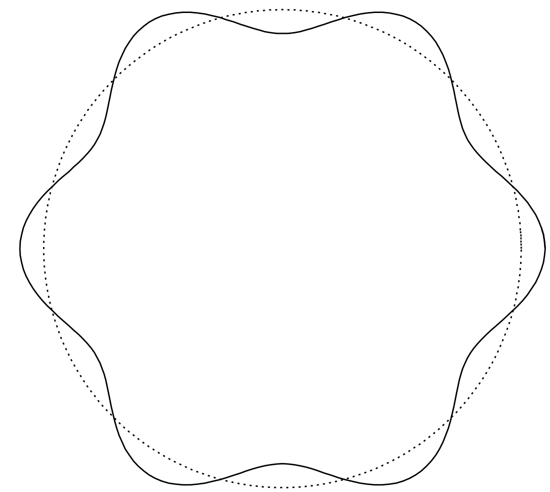
- de Broglie waves $\rightarrow$ standing waves in atom
- e orbits circular
- only certain radii, speeds allowed ("quantized states") $\rightarrow$ only certain allowed energies
- during e transitions between states, photon emitted $\rightarrow$ photon energies quantized $\rightarrow$ spectral lines

Together, these assumptions → atom structure

standing waves:
Demo: slinky
e orbit path length an integer multiple of λ:

$$2\pi r = n\lambda = n\frac{h}{m_e v} \tag{7}$$

→ for each n, radii and speeds related



Coulomb force provides centripetal accel:
Q: remind me–what is Coulomb force?

Coulomb force: electrical attraction between opposite charges
an inverse square law! same structure as gravity!

$$F = \frac{q_1 q_2}{r^2} = \frac{e^2}{r^2} \tag{8}$$

(cgs charge units: $e^2_{\mathrm{cgs}} = k e^2_{\mathrm{SI}} = e^2_{\mathrm{SI}}/4\pi\varepsilon_0$)

Coulomb provides centripetal acceleration:

$$\frac{e^2}{r^2} = m_e \frac{v^2}{r} \tag{9}$$

another relation between r and v
$\rightarrow$ two equations, two unknowns $\rightarrow$ solution exists