Astro 350

Lecture 6

Sept. 10, 2012

Announcements:

- *Homework 2* due at start of class Friday
  Note: problem 5(a) wording clarified today
  take another look if you downloaded already
- *Discussion 2* on Compass, due by start of class Wednesday

Last time: Newtonian Universal Gravity

Q: why universal?

Q: what things gravitate? what doesn't *gravitate?*

Q: properties of gravity force?

Q: what doesn't *gravity depend on?*

Q: what's so good about Newtonian gravity?

Cosmology: Progress Report after Newton

Recall: Cosmology is a mystery story

Based on evidence we can observe, want to understand:

- structure of Universe: how big? map of contents across space?
- contents of Universe: what ingredients is it made of?
- origin & evolution of U.: birth? past? future?
- rules of the game: what makes the Universe this way?

Cosmological progress so far:

Kepler precisely described planet motion

Newton explained planet motion, agrees with observation!

Lessons from Newtonian Triumph

Lesson from Newtonian success: insight into rules of the game

- powerful laws exist explaining *all* motion due to forces
- planet motion is due to force of gravity

  $\Rightarrow$ gravity determines behavior of the cosmos!

Also important implications for structure of Universe

Q: What?

Hint: what does Copernican picture say about size of U?
and what does this in turn imply?

recall: to naked eye, stellar parallax is undetectable
stars don't seem to "wiggle" annually on sky

so if parallax exists, wiggle must be small
$\Rightarrow$ stars must be very far away!

But if stars hugely far away, and can still be seen
they must emit a lot of light
$\rightarrow$ perhaps stars are like the Sun!

Q: what do we need to know to answer this?

Light

Light deeply connected to
electric charge and force, magnetic force

Experiments show:
changing E force generates M force
hanging M force generates E force

1. E&M linked: "electromagnetic force"

2. EM disturbances can travel through space:
   each regenerates the other: E $\rightarrow$ M $\rightarrow$ E $\rightarrow$ M $\rightarrow$ ...
   electromagnetic waves = "EM radiation"

Light as Electromagnetic Waves

light is an electromagnetic phenomenon:

- created by motions (in fact: acceleration) of electric charges
- that is: light must be created by charged particles
  e.g., in light bulb, hot filament drives electron motion

but light itself is *made of* electromagnetic fields

- which exert forces on charged particles
- that is: light interacts with charged paricles
  e.g., in antenna, electrons driven back and forth

note: if an elementary particle has *zero* electric charge (neutral):

- it cannot emit light
- it cannot absorb or scatter light

Light as Electromagnetic **Waves**

light is a type of **wave**:

a wave is oscillating disturbance in a medium
wave can travel, medium does not
Demo: the wave!

snapshot in space, taken at one instant of time:
diagram
wavelength $\boxed{\lambda}$ size of one cycle
$\longrightarrow$ wave "ID number"

intensity $\boxed{I}$
"strength" of wave = "height of peaks"
Demo: slinky: same wavelength, diff't intensities

Q: Sound waves: how do we experience λ? I?
Q: Light waves: how do we experience λ? I?

Sound:

$\lambda \leftrightarrow$ pitch

high pitch (treble): small λ

low pitch (bass): large λ

intensity = loudness

Light:

$\lambda \leftrightarrow$ color

visible light: larger λ: more red

smaller λ: more blue

intensity = apparent brightness

Note for experts: in more detail, we distinguish

- *flux* = apparent brightness of unresolved (point-like) source e.g., stars, distant quasars
- *intensity* = surface brightness of resolved (extended) source e.g., Moon, planets, nearby galaxies

The Speed of Light

Light is very fast!
So fast that it was a feat to measure the speed in lab
now known quite well

$$c = \text{constant} = 299,792,458 \text{ m/s}$$
$$= 3.0 \times 10^8 \text{ m/s} = 186,000 \text{ miles/s} = 6.7 \times 10^8 \text{ miles/hr}$$

enormous–but not infinite!
→ finite speed of light hugely important for astronomy
→ telescopes are time machines *Q: how?*

note: light speed c is *same* for all λ
Q: what would happen if this were not true?

The Electromagnetic Spectrum

EM waves can have λ outside of visible range

`www: EM spectrum` **most** wavelengths are invisible to human eyes!

Generally, light is combination of pure waves
with different λ

distribution of intensities:
different brightness at diff. λ: **spectrum**

diagram: sketch spectrum axes
Q: spectrum of laser pointer?
Q: spectrum of white light?

Technology Tim's Terminology Tip: "Radiation"

Warning!
meaning of "radiation" in Physics, Astronomy, Cosmology
$\neq$ "radiation" in everyday parlance!

In Physics, Astronomy, Cosmology...and more importantly...
In this course and on the exams:
radiation = movement of energy through space
carried by particles or waves

Examples:
ordinary visible light! e.g., flashlight, sunlight, starlight, ...
completely benign and indeed necessary for life!
but also invisible EM waves: radio, UV, X-ray...
and even non-EM particles: neutrinos...

Beware Confusion: "radiation" so defined $\neq$ radioactivity!
more on radioactivity later...

Moving Light Sources: Doppler Effect

moving wave source $\rightarrow$ shift in λ
observed color $\lambda_{\text{obs}} \neq$ emitted color λ_{em}

`www: doppler animation`

- ▷ source approaching $\Rightarrow$ λ shorter: **blueshift**
- ▷ source receding $\Rightarrow$ λ longer: **redshift**

Q: why is this fantastically useful for astronomers (and cops)?

Dopper $\rightarrow$ detect motions and even measure speed
just by looking!

shift depends only on
relative motion in **radial** direction ("line of sight")
towards observer

Approximate expression

$$\frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \frac{\Delta\lambda}{\lambda_{\text{em}}} = \frac{v}{c} \tag{1}$$

where v is radial speed
formula usually good enough (i.e., as long as $v/c \ll 1$)
Q: what's going on if $\Delta\lambda < 0$?

Stars and the Sun

a few heliocentric Greeks guessed that the stars are like the Sun, only far away

Newton pushed this further and showed that this is true

Q: what data is needed for comparison?

Stellar Physical (Turn Head, Cough)

Star Masses

can measure in binary systems: 2 stars in bound orbits

`www: binary star`

recall Kepler/Newton: $GMP^2 = 4\pi a^3$ so

$$M = \frac{4\pi a^3}{GP^2} = \frac{a_{\rm AU}^3}{P_{\rm yr}^2} M_{\rm Sun} \tag{2}$$

result: star masses range $0.1 M_{\rm Sun} \lesssim M_\star \lesssim 100 M_{\rm Sun}$

$\rightarrow$ Sun is in heart of range: a typical star mass-wise

Star Power

power = rate of energy flow or consumption
= energy output/time

$$P = \frac{E}{t} \quad (= dE/dt) \tag{3}$$

light power = light energy outflow: **luminosity**
$\longrightarrow$ "star wattage"

Star Light, Star Bright

to naked eye, in clear sky:
about 6000 (!) stars visible over celestial sphere
$\Rightarrow$ about 3000 at any one night
...but this is just the "tip of the iceberg"

many many more stars exist
but unseen by naked eye
Galileo, using telescope, was first to realize this
philosophical problem at the time:
What is the point of having stars we can't see?

stars appear to have different brightnesses
brightest (other than Sun): Sirius – "dog star"

iClicker Poll: Star Brightness

Vote your conscience!

Stars observable *by the naked eye* appear to have a wide range of brightnesses

Why?

A they emit similar amounts of light (similar luminosities L), but are at different distances

B they emit very different amounts of light (different L) but are at similar distances

C they emit very different amounts of light (different L) and are also at very different distances

Apparent Brightness vs Luminosity

apparent brightness: what we/scopes actually perceive
energy flow (light power) per area
apparent brightness or **flux** $F = P/A$

consider spherical star: light power output is luminosity L
when observing at distance (radius) R
  light spread over area $A = 4\pi R^2$
so observable flux is

$$F = \frac{L}{4\pi R^2} \tag{4}$$

crucial fact: observed F depends on L but also on R
$\rightarrow$ headlights blinding nearby, tolerable far away

Want to know L, but measure F
to solve $L = 4\pi R^2 F$ need distance R
Q: how measure?

Stellar Distances: Parallax

Recall: Earth orbit $\rightarrow$ shifting viewpoint on stars
$\rightarrow$ nearby stars appear to shift relative to distant stars
diagram: parallax geometry
parallax angle p = shift from midpoint

from parallax angle p can find
distance $d = 1\ \text{AU}/\tan p$ (exact formula)

but shift very small: p tiny (< 1 arc second $= 1/3600$ degree)
$\rightarrow$ "skinny triangle" law works just fine:
$\tan p \approx p_{\text{radians}}$

$$d = \frac{1\ \text{AU}}{p_{\text{radians}}} = \frac{200,000\ \text{AU}}{p_{\text{arcsec}}} = \frac{1\ \text{parsec}}{p_{\text{arcsec}}} \tag{5}$$

Star Distances and Parsecs

from parallax p find distance

$$d = \frac{1 \text{ parsec}}{p_{\text{arcsec}}} \tag{6}$$

- new distance unit: $1\text{parsec} = 1 \text{ pc} = 200,000 \text{ AU}$
- nearest star: $d(\alpha \text{ Cen}) = 1.3 \text{ pc}$
  $\rightarrow$ 1 pc is typical star-star distance in a galaxy
- light travels 1 pc in 3 yrs: $1 \text{ pc} = 3$ light years (lyr)

Star Luminosity

armed with distances to stars,
can find their luminosities

Compare Sun vs star luminosities:

- Sun ($\odot$): $L_\odot = 4\pi(1\ \text{AU})^2 F_\odot = 4 \times 10^{33}$ Watts
  the Sun is a 4×10^{33} Watt lightbulb!
- other stars: luminosity range $10^{-3} L_\odot < L_\star < 10^6 L_\odot$
  huge range, Sun in middle $\rightarrow$ Sun is typical luminosity-wise

$\Rightarrow$ the Sun is a typical star!
note how this fits well into the "Copernican worldview"