Astro 406

Lecture 13

Sept. 25, 2013

Announcements:

- **PS 4 due Friday**

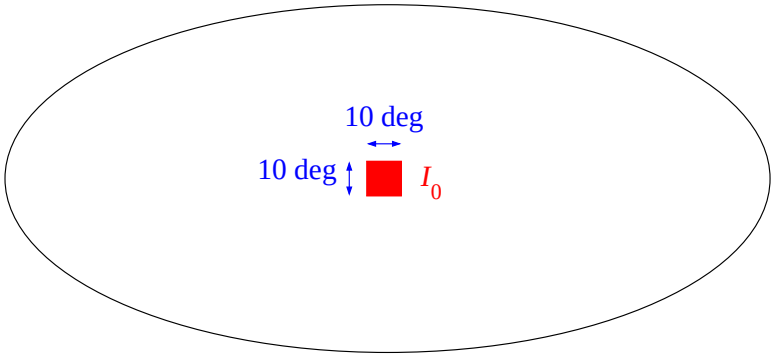
  helpful(?) hint on next slide
- iClicker scores posted on Compass; check for accuracy!
- ASTR 401: introduction draft due Monday

PS4 Hint: Intensity and Flux

recall: *flux F = power/area*
  well-defined for *pointlike (unresolved) source*
but what if light source is *resolved = spread over sky*?
intensity I = flux/(area on sky) = flux/solid angle = $dF/d\Omega$

PS4: observed intensity map for ^{26}Al decay gamma rays
note: grid line spaced every 30° in ℓ and b

your mission: find total flux $F = \int_{\rm sky} I \; d\Omega$
oversimplified example:
map with intensity $I = 0$ everywhere
except a $10^\circ \times 10^\circ$ region where
$I_0 = 10^{-3}$ [photons] cm^{-2} s^{-1} sr^{-1}
$\rightarrow \Omega = (10 \text{ deg})^2 = 100 \text{ deg}^2$
$\rightarrow F = I_0 \; \Omega$, with Ω in radian^2 = sr
Final hint: you should find $F \sim (10^{-5}$ to $10^{-3})$ cm^{-2} s^{-1}



Last time: Milky Way rotation curve

Q: what's a rotation curve?

Q: what does ours look like?

Q: where does the Sun fall on the curve?

Q: what does it mean?

Milky Way Rotation Curve: Summary

Measure circular speed $V(R)$ vs R, plot: "rotation curve"
Q: sketch Galactic rotation curve? where does Sun appear?
`www: real data`

beyond inner MW, $v(R) \rightarrow v_0 \approx 220$ km/s = const
$\rightarrow$ "flat rotation curve"

But recall: for circular orbits

$$m(r) = \frac{v^2 r}{G} \Rightarrow \quad m(50 \text{ kpc}) \gg M_\star + M_{\text{gas}} \tag{1}$$

Mass grows even when *no luminous matter present*!

Either:
(1) derivation wrong (Newton/Einstein gravity fails!), or
(2) **most of MW** ($\sim 80 - 90\%$!) is in **halo** of dark matter

Dark Matter Candidates

black holes
neutron stars
white dwarfs
Jupiters, brown dwarfs
} compact objects

hot $\sim 10^6$K gas
neutrinos
relic particles from earliest moments of big bang

Q: how do we figure out which (if any) are right?

Worked Stupid Example: Jello^{TM} Dark Matter

Imagine: Milky Way dark matter is Jello^{TM}!?!
$\Rightarrow$ 80–90% of Milky Way mass is *Jello^{TM} dark matter* (JDM)
this has consequences!

Assume: parfait-sized blobs, $m_{\rm blob} = 100$ g
but local dark matter density roughly $\rho_{\rm dm} \sim 10^{-24}$ g/cm^3
[you'll improve this estimate in PS4]

but $\rho_{\rm Jello} \approx \rho_{\rm water} = 1$ g/cm^3
Q: how can we have $\rho_{\rm dm} \neq \rho_{\rm Jello}$?
Q: so what is number density of jello blobs?

dark matter density $\rho_{\rm dm} \ll \rho_{\rm Jello}$:
$\rightarrow$ Milky Way volume is not solidly filled with Jello
$\rightarrow$ mostly empty space between blobs

JDM *number* density is $n_{\rm jdm} = \rho_{\rm dm}/m_{\rm blob} \sim 10^{-26}$ particles/cm^3

typical interparticle spacing:
$\ell = n_{\rm jdm}^{-1/3} \simeq 5000$ km $\lesssim$ R$_{\rm Earth}$

But if they are the DM, they are everywhere!
including the solar neighborhood!
$\Rightarrow$ as the Solar System orbits the MW
we move through a $v = v_{\rm circ,\odot} \sim 200$ km/s DM "blizzard"!

Q: what would this mean? How could we test it?

As we move through JDM, some hits Earth!

Calculate: mean free time against JDM-Earth collisions
recall: $\tau = 1/(n\sigma v)$
here: $n = n_{\text{jdm}}$, $v = v_{\text{circ},\odot}$, and
$\sigma \approx \pi R^2_{\text{Earth}} = 1.3 \times 10^{18}$ cm^2 *Q: why this?*

So if Jello$^{\text{TM}}$ is the Dark Matter,
then we have one JDM fall from the sky every

$$\tau_{\text{jdm}} = \frac{1}{n_{\text{jdm}} \sigma_{\oplus} v_{\text{circ},\odot}} = 4 \text{ sec} \tag{2}$$

Q: how does this rule out JDM as the Dark Matter?
Q: loopholes for JDM?
∞ *Q: Larger lessons for ruling Dark Matter candidates in or out?*

The Search for Dark Matter

Does dark matter really exist in the Milky Way?
If so, what form does it take?

$\Rightarrow$ difficult problem! ("highly non-trivial")
have to work hard and be clever

This week: we will cross off half our list!

Ideal tool: a method which
- detects any kind of mass
- is accessible to telescopes, ideally optical ones
- is independent of rotation curves and can be a consistency check on their results

In fact–nature has been kind, and Einstein showed the way...

Gravitation Revisited

Newton gravity force law

$$\vec{F}_{\text{grav}} = -\frac{GMm}{r^2}\,\hat{r} \tag{3}$$

implies that if M moves $\rightarrow$ r changes

$\rightarrow$ *gravity force changes instantaneously over all space!*

"signal" of motion instantaneously transmitted throughout the universe

Einstein sez: this is *totally illegal! an unmitigated disaster!*

no signal–including gravity–can move faster than c!

Special relativity built to address this problem

Maxwell's Equations already have signal speed $= c$

$\rightarrow$ no need to revise E&M

The Equivalence Principle Revisited

How to go about revising gravity? Where to start?

Recall Galileo atop the Tower of Pisa:
gravity $\rightarrow$ all objects move (accelerate) the same way in free fall
  regardless of object mass, shape, composition not new result,
but different explanations...

Newton sez:
it just so happens that gravitational mass
  the way objects "feel" or "couple to" gravity $F_{\text{grav}} = m_{\text{grav}} g$
is always exactly the same as inertial mass
  the way objects resist acceleration $a = F/m_{\text{inert}}$

Einstein sez:
too amazing to be a coincidence, must be deeper...

Einstein's Equivalence Principle

Einstein notes:
Gravity causes acceleration, but in "democratic" way:
all objects accelerate the same

Einstein's Equivalence Principle:
in a closed room, no experiment can distinguish
(non-gravitational) acceleration from gravity

But note: acceleration is aspect of motion
relates to objects' travel through space and time
$\rightarrow$ gravity=acceleration equivalence will have impact
(i.e., bizarreness) on space and time

Rocket Thought Experiment

`www: illuminating animation`

Consider flashlight aimed horizontally:

- ⋆ light ray deflected
- ⋆ entire light path bent (in fact, a parabola!)
  "gravity's rainbow"

iClicker Poll: Rocket Lasers

Install lasers and detectors in rocket basement and attic measure λ_{obs} during acceleration

Resulting effect on photons?

A no effect: λ unchanged if emitter and detector both accelerate with rocket

B attic detectors see *blueshift*
basement detectors see *redshift*

C attic detectors see *redshift*
basement detectors see *blueshift*

D both detectors see *redshift*

E both detectors see *blueshift*

Rocket experiment:

- light bending
- as photon travels, acceleration changes detector v relative to emitter
  upgoing (downgoing) photon seen to redshift (blueshift)

But by equivalence principle:
must find *same result due to gravity*, so:

⋆ gravity bends light rays

gravitational lensing

⋆ observers in basement see blueshift of attic photons!
and observers in attic see redshift of basement photons!

gravitational redshift/blueshift

Note: gravitational red/blueshift confirmed in lab!
Q: how would you do the experiment? what are you looking for?
`www: Pound-Rebka expt`

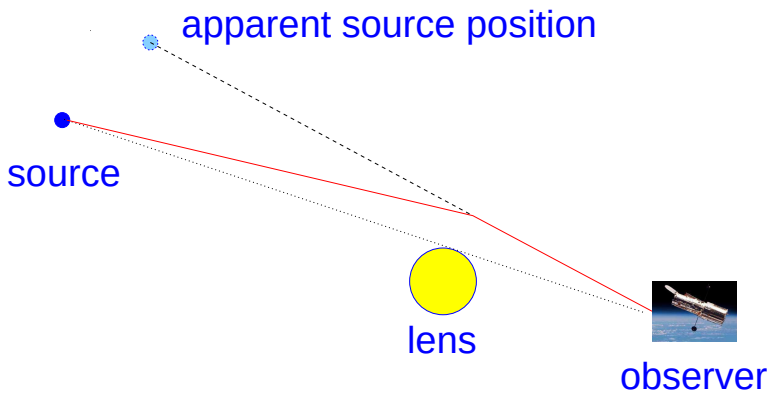
Q: how to test lensing effects in real world?

Light Bending: The Sun

In principle: *all* gravitating objects bend light
including you, me, the earth...
In practice: need strong gravity source to create
effect large enough to observe

Einstein (1915) devised first test: the Sun

- Sun's gravity deflects starlight rays
- the stronger the gravity along the path
the bigger the deflection



$\Rightarrow$ biggest effect for starlight just "grazing" edge of Sun

Q: why is this technically challenging to see?

Q: how to get around the problem?

1919 Eclipse: Give it up for Big Al!

Problem: Sun's glare obscures surrounding starlight
Solution: block glare with eclipse!

1919: total solar eclipse in Southern hemisphere
expedition led by Sir Arthur Eddington

⋆ starlight bent! Woo hoo!

⋆ relativistic gravity confirmed!

⋆ Einstein an instant celebrity

`www: NYTimes headlines`

• all starlight bending experiments confirm Einstein!

Gravity 2.0: General Relativity

Einstein's gravity: General Relativity

Newton: matter causes force (gravity)
$\rightarrow$ particles follow curved lines in
"flat" (Euclidean geometry) space

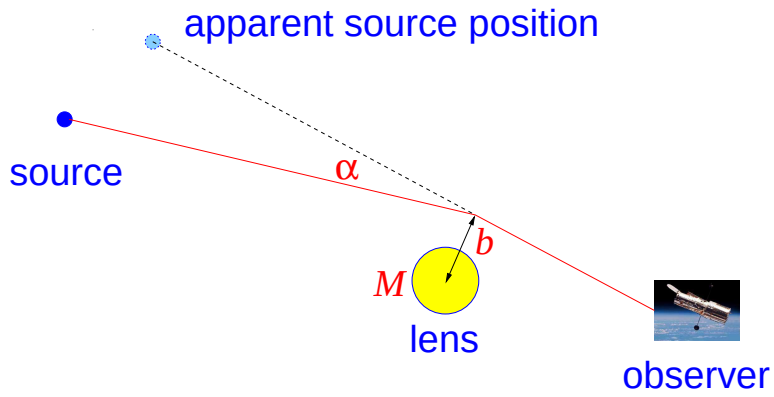
Einstein: bold leap, rejected Newton
matter causes spacetime to be "curved"
$\rightarrow$ particles follow straight lines ("geodesics")
in curved space

space and time dynamic
not fixed once and for all

Light Bending Quantified: Point Mass

the setup:

- light ray incident on
- a point mass M
- with distance of closest approach b



Einstein result: light deflected by angle

$$\alpha = \frac{4GM}{c^2 b} \tag{4}$$

Q: how could this be useful for detecting MW dark matter?