Astro 350

Lecture 21

Oct. 12, 2011

Announcements:

- HW6 due next time
  Office hours: instructor–after class today
  TA–tomorrow 2-3pm
- Discussion Question 6 due today

Last time: towards a relativistic theory of gravity

Q: Why does Einstein frown on Newtonian gravity?

Q: What is the equivalence principle?

Q: What does the rocket experiment imply about gravitational effects on light, clocks?

Newton gravity force law

$$F_{\text{grav}} = \frac{GMm}{R^2} \tag{1}$$

implies that if M moves $\rightarrow$ R changes

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

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

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

Einstein's Equivalence Principle:

in a closed room, no experiment can distinguish

(non-gravitational) acceleration vs gravity

Rocket Experiment: `www: illuminating animation`

⋆ light ray deflected

⋆ entire light path bent (in fact, a parabola!)

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

⋆ gravity bends light rays

gravitational lensing

Also: in accelerating spaceship:

⋆ clocks in basement run slower than clocks in attic!
in fact, attic clocks faster by $\Delta t = t_{\text{attic}} - t_{\text{basement}} = g\Delta h^2/c^3$

⋆ time "warping" but now due to gravity:
"**gravitational time dilation**"

⋆ gravity influences "flow" of time!

Q: how to test these 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 *diagram: paths*
- the stronger the gravity along the path
  the bigger the deflection
  ...in fact, bending angle $\alpha = \dfrac{4GM_\odot}{c^2 R_{\text{closest}}}$

$\Rightarrow$ 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`

Now tested many times, and very accurately
• all starlight bending experiments confirm Einstein!

Moreover, once established, grav lensing is a very powerful tool
Q: why would it be useful?

Gravitational Lensing and Dark Matter

gravitational lensing reveals presence, strength of gravity whether or not the gravitating objects emit light!
$\rightarrow$ just what the doctor ordered to test for dark matter!
and/or black holes

General strategy:

- find "background" light source behind unseen gravity source
- observe image of background objects
- from image distortion $\rightarrow$ infer presence, amount, distribution of unseen mass!

Q: how might we test for DM in our own Galaxy?

Searching for Milky Way Dark Matter: MACHOs

Recall: "conventional" dark matter candidates include
"compact" star-like objects:
brown dwarfs, white dwarfs, neutron stars, black holes

if dark matter = MAssive Compact Halo Objects (MACHOs)
then find via lensing

setup *diagram: sketch*

- use nearby galaxy (Large Magellanic Cloud) as background light source
- monitor lotsa LMC stars (i.e., millions)

recall: DM (here, MACHOs) in motion: $v \approx 200$ km/c
sometimes: MACHO will wanders close to line of sight
towards a LMC star

Q: what will happen–if MACHO exactly in sightline?
if near sightline?

Gravitational Microlensing

if MACHO exactly aligned

- all incoming rays bent equally $\rightarrow$ see a ring
  the "Einstein ring"
- more light deflected towards observer $\rightarrow$ total flux higher
  $\rightarrow$ brightness amplification

if MACHO comes close to sightline but never aligned

- ring splits to 2 images (arcs of circles)
- brightness amplification still observed

In practice:

- rings, arcs from MACHOs too small to see, but
- *can* detect amplification of brightness
  experiments performed to look for this

iClicker Poll: Microlensing and Dark Matter

Vote your conscience!

It's 1993. First microlensing results are in.
Will they find MACHOs as Milky Way dark matter?

A Yes: MACHOs found in halo, masses point to black holes

B Yes: MACHOs found in halo, masses point to neutron stars

C Yes: MACHOs found in halo, masses point to white dwarfs

D No: no/few MACHOs found in halo, dark matter is something else

Microlensing Experiments and Results

MACHO project: monitored $> 10^6$ LMC stars for 5.7 years

`www: MACHO lightcurve`

$\sim$ 12 events seen! gravitational lensing reconfirmed!

but – where are lenses: halo or LMC?

if halo lenses: $m \sim 0.5 M_{\odot}$ white dwarf?

total mass $\sim$ 20% of dark halo, definitely not 100%!

however: substantial evidence lenses are

- in LMC itself, or
- in MW thick disk

$\Rightarrow$ **no/very few compact objects in halo**

Q: does this say that the Milky Way has no DM?

Microlensing results do say:

- Milky Way halo *not* made of compact objects = MACHOs
  a very important negative result!

Microlensing results do not say:

- anything about DM that is not compact, more diffusely spread
  e.g., gas (but this has other problems) or elementary particles!
  cannot rule out (or in!), need to test in other ways
  e.g., underground experiments for particle DM

But wait! There's more...

Recall: Dark matter also seen in external galaxies

Q: how might we use gravitational lensing to detect it?

Lensing by Dark Matter in Other Galaxies

If background galaxy (or quasar) light passes thru
foreground galaxy or galaxy cluster
can resolve lensed arcs of background object `www: arcs`
use to reconstruct total mass distribution of foreground gal
$\Rightarrow$ direct probe of dark matter distribution!

Status: already done for tens of objects
conclude: total gravitating mass $\gg$ visible mass
$\rightarrow$ independent evidence for dark matter!
not only that, but can infer DM distribution!
`www: map of DM in cluster`