Astro 350

Lecture 21

Oct. 17, 2012

Announcements:

- **HW 6** due next time

  Office Hours: TA Thurs. 9:30-10:30am

  Instructor: today 1:30-2:30am
- **Discussion 6** due today
- **Discussion 7** posted today, due next Wednesday

Last time: General Relativity and Black Holes

Anachronistic News Network
Point⇔Counterpoint: Gravity

Moderator–G. Galilei: The discussion today–what is gravity? Ike, what say you?

I. Newton: Gal, gravity is but one example of a **force**–a particularly beautiful one, to be sure (did I mention I invented it?) but a force like any other (e.g., the electrostatic force of that Frenchman, Coulomb).

Galilei: Let me stop you right there, Ike. My work in Pisa has shown that all objects fall at the same rate, regardless of their mass, shape, or composition. If you understood my work, you'd realize that that gravity is a uniquely special force!

Newton: There you go again, Gal. If you'd let me finish, I was going to explain. Any object has an **inertial mass**, which determines its response to acceleration–making massive objects harder to speed up: $a \propto F/m_{\text{intertial}}$. But an object also has **gravitational mass** which sets the strength of its coupling to the gravitational field–making massive objects heavier: $F_{\text{grav}} = m_{\text{grav}}\ g$. Now it so happens that an object's inertial mass is the *same* as ist gravitational mass. This particular accident leads to the result you observed and I explained.

A. Einstein: I have to jump in here. We know that objects fall the same way, regardless of any of their properties. This is the **equivalence principle**. Gravity is a unique interaction in being so democratic in its influence. Ike would have us believe that this is just a curious coincidence. But since falling is so universal, its origin is obviously best found in the very structure of space and time, not in some miraculous force. This is the heart of General Relativity (which by the way behaves the same as Newton's theory when gravity is weak). GR says that spacetime is "curved" and that motion in a gravity field ("falling") is a response to this curvature, much as a ball rolling on a dimpled, rubber sheet.

A. Einstein: I might add that this curvature has many consequences, one of which is that even light rays should be bent by gravity. Which by the way I predicted and was confirmed in observations during the 1919 solar eclipse. In your face, Ike!

Galileo: Oooh–snap! More when we come back after these important messages from our sponsors...

Demo: Newtonian gravity vs spandex GR spacetime

Black Holes: Summary Thus Far

black hole of mass M has size (radius)

$$R_{\text{Sch}} = \frac{2GM}{c^2} \tag{1}$$

the **Schwarzchild** radius

Note

- $R_{\text{Sch}} \propto M$: more massive $\rightarrow$ bigger black hole

- recipe: to turn *any* mass M into a black hole
  crush to size smaller than R_{Sch}

Q: in what way is a black hole "black"?

Q: in what way is a black hole a "hole"?

iClicker Poll: Life Far Away From a Black Hole

Future industrial accident ("mistakes were made")
causes Sun to be crushed to black hole
without gain or loss of mass

What happens to Earth's orbit?

A nothing: same orbit!

B spirals in: aaargh!

C stronger gravity, orbit closer, more elliptical
but does not fall in

D weaker gravity, orbit closer, more elliptical
but does not fall in

No change in orbit!

when **outside** of Sun, gravity acceleration is
$a = GM_{\odot}/r^2$: only M matters
gravity same as if Sun were $1M_{\odot}$ BH

gravity outside star **not** increased by becoming BH
no more pull than before!
$\rightarrow$ "black hole threat" not any more dangerous than
"nearby star gravity" threat

So sleep well tonight!

Note:
so far, BH discussed as theoretical objects
Q: how to "see" one to test theory? No light escapes!!

Evidence for Black Holes

recall: in death of $M > 30 M_\odot$: gravity wins, collapse unstoppable
black hole formed $\to$ should be inevitable part of star formation

how detect? no light emitted from BH, but:
can observe matter interacting with BH

X-ray binaries: stellar-mass black holes (few $M_\odot$)
massive star born in bound system with less massive star
larger star $\to$ SN $\to$ BH left behind
if supergiant companion, close orbit:
some gas falls onto BH $\to$ compressed, heated $\to$ X-rays

what you see: giant star orbiting unseen massive companion,
and emitting X-rays
`www: Cygnus X-1`

Our Own Galactic Center

central ~ 30 pc of Galaxy:
can't see optically (*Q: why?*), but can in other wavelengths:
extended (non-point) radio emission (Sagittarius A)
radio source at center (?): Sgr A*

in infrared wavelengths: can see stars near Sgr A*
and they move! `www: Sgr A* movie`
elliptical paths! closest: period $P = 15.2$ yr
semi-major axis: $a = 4.64 \times 10^{-3}$ pc
$\rightarrow$ enclosed mass $(3.7 \pm 1.5) \times 10^6 M_\odot$
Q: and so?

the center of our Galaxy contains a black hole!

Sgr A* Schwarzchild radius

$$r_{\mathrm{Sch}} = 1.1 \times 10^{7}\ \mathrm{km} = 0.74\ \mathrm{AU} = 3.6 \times 10^{-7}\ \mathrm{pc} \qquad (2)$$

→ not resolved (yet) but upcoming missions should see horizon!

Many questions for cosmology:

- how did it get there?
- Sgr A* low luminosity, "quiet"
  compared to more "active" galactic nuclei `www: AGN: M87`
  why? open question....

∞

Galaxies and Black Holes

The Milky Way is not the only galaxy with a central black hole

active galaxies: most L from non-star sources
emission is from galactic nucleus:
active galactic nuclei = AGN

orbits near center $\rightarrow$ rotation curves
allow us to find mass: typically $M \sim v^2 d/G \sim 10^8 M_\odot$
Huge mass in tiny region: $\rightarrow$ black hole, supermassive!

Supermassive Black Holes

our Milky Way galaxy has supermassive BH: "quiet" = low L
active galaxies have supermassive BH: huge L

recent result:
all galaxies have supermassive BH! ...but most quiet
$\rightarrow$ maybe active galaxies are phase in evolution?

BH mass **correlated** with host gal stellar (spheroid) mass
$\rightarrow$ $\boxed{M_{\mathrm{BH}}/M_{\mathrm{sph}} \sim const \sim 0.006}$
constant "BH fraction"
$\rightarrow$ supermassive BH formation is part of gal formation!

Open Questions:

- how does a $10^{7-8} M_\odot$ BH ($R_{\mathrm{Sch}} \sim$ AU) know about the $10^{11-12} M_\odot$ galaxy it lives in (and vice versa)?
- how does a SMBH "grow" – what are the "seeds," and how are they "fed"?
- Are there any galaxies without SMBH? Are there any SMBH without galaxies? Either way, what does this mean?

Modern Cosmology

Cosmology: The Big Picture

Take science to the largest arena possible:
study the Universe as a physical system

- structure
- dynamics
- composition
- origin
- evolution

Mapping the Universe: The Real Data

recall: galaxies are the "building blocks" of the universe today

so to find the structure of the Universe today
need to map galaxies across all of the observable universe
→ a big and ongoing job!

space is 3-dimensional, so cosmic maps should be 3-D too
but to get started, let's look at 2-D "slices" `www: 2dF galaxy survey--scan strategy`
`www: 2dF galaxy survey--results`
`www: SDSS galaxy survey--results`

Q: what do you notice when looking closely?
Q: what do you notice when "stepping back and squinting"?
Q: how does on slice compare to another?
Q: why the dropoff at large distances?
Q: so what do we learn about how do galaxies fill the universe?

The Large-Scale Structure of the Universe: I

Observations teach us that, to a "first approximation":
the Universe *today* is

1. homogeneous: average properties same at all points
e.g., mass density anywhere is same as mass density everywhere!

and

2 isotropic: looks same in all directions

universe is homogeneous & isotropic:
the **"cosmological principle"**
first guessed(!) by A. Einstein (1917)

Q: as exact (not approximate) statement,
cosmo principle obviously false! Why?
In what sense could it be true?

Example: Cosmo principle and galaxy properties

Q: if cosmo principle true, how reflected in observations of galaxies at any given time?

Q: how could you test this?

Q: what does cosmo principle say about how galaxy properties evolve with time?

Cosmo principle and galaxy properties:

at any given time:

- **average** density of galaxies same everywhere
- distribution of galaxy properties same everywhere

e.g., types, colors, L, M, ...

- time evolution: must maintain large-scale homogeneity and isotropy

but otherwise, **by itself** principle allows any changes!

Real Galaxies in the Real Universe

Beyond the First Approximation

cosmo principle a very good approximation
on large scales ($\gtrsim$ 50 Mpc)
`www: 2dF`

but do observe fluctuations around average galaxy density
`www: 2dF maps`
on small to medium scales ($\lesssim$ 50 Mpc),
galaxies **clustered** in space:

- loners: “field” galaxy
- few ($\lesssim$ 50) galaxies: group
- 100’s-1000’s of galaxies: cluster
- assemblies of groups and clusters: supercluster

Director's Cut Extras

Time Dilation and Falling Light

consider light wave:
emitted with wavelength λ_{em}, frequency f_{em}
$\rightarrow$ wave crest emitted every $(\Delta t)_{\text{em}} = 1/f_{\text{em}}$ seconds

But observer in region with stronger gravity
will see downgoing wave crests every $(\Delta t)_{\text{obs}} < (\Delta t)_{\text{em}}$ sec
while observer in region with weaker gravity
will see upcoming wave crests every $(\Delta t)_{\text{obs}} > (\Delta t)_{\text{em}}$ sec

Q: what does this mean for observed light properties: f_{obs}*?* λ_{obs}*?*

Gravitational Redshifting of Light

When distant emitted in *strong* gravity region
seen by observer in *weak* gravity region
upcoming light crests at intervals $(\Delta t)_{\rm obs} > (\Delta t)_{\rm em}$
and so frequency is *lower*: $f_{\rm obs} = 1/(\Delta t)_{\rm obs} < f_{\rm em}$
while wavelength is *longer*: $\lambda_{\rm obs} = c/f_{\rm obs} = c(\Delta t)_{\rm obs} > \lambda_{\rm em}$
$\Rightarrow$ longer $\lambda \rightarrow$ redshift: **gravitational redshift**

Similarly, when downgoing light observed, grav blueshift

1960s: gravity redshifts observed in lab
Harvard experiment: laser from basement to attic!
(big technical challenge due to small shift in weak Earth gravity)
$\rightarrow$ Big Al confirmed again (but of course!)