Astro 350

Lecture 23

Oct. 17, 2011

Announcements:

- Discussion Question 7 due Wednesday
- HW7 due Friday

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. My work in Pisa has shown that all objects fall at the same rate, regardless of their mass, shape, or composition. Seems like a pretty special force to me!

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: $a \propto F/m_{\mathrm{intertial}}$. But an object also has **gravitational mass** which sets the strength of its coupling to the gravitational field–making massive objects heavier: $F_{\mathrm{grav}} = m_{\mathrm{grav}} g$. 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 goes to Newton's gravity in the limit of weak fields). 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...

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"?

Life Near a Black Hole

Experiment: lower astronaut (Jodie) near $R_{\rm Sch}$
we are at mission control, far away ($r_{\rm us} \gg R_{\rm Sch}$)
communicate w/ light signals

when viewing photons (or clock ticks)
emitted at $r_{\rm em}$, observed at $r_{\rm obs}$
general rule:

$$\frac{\Delta t_{\rm obs}}{\Delta t_{\rm em}} = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \sqrt{\frac{1 - R_{\rm Sch}/r_{\rm obs}}{1 - R_{\rm Sch}/r_{\rm em}}} \tag{2}$$

What do we see?

obs=us: $r_{\rm obs} \to \infty$; em=Jodie: $r_{\rm em} > R_{\rm Sch}$

- Jodie's watch: $\Delta t_{\rm obs}/\Delta t_{\rm em} = 1/\sqrt{1 - R_{\rm Sch}/r_{\rm em}} > 1$
  $\to \Delta t_{\rm obs} > \Delta t_{\rm em}$! appears to tick slow! time dilation!
- wavelengths: $\lambda_{\rm obs} > \lambda_{\rm em}$! redshift!

Q: and Jodie?

What do we see?

intuitively: expect inequalities to reverse...and they do

obs=Jodie: $r_{\rm obs} > R_{\rm Sch}$; em=us: $r_{\rm em}\to\infty$:

- our watches: $\Delta t_{\rm obs}/\Delta t_{\rm em} = \sqrt{1 - R_{\rm Sch}/r_{\rm em}} < 1$
  $\to \Delta t_{\rm obs} < \Delta t_{\rm em}$! appears to tick fast!
- wavelengths: $\lambda_{\rm obs} < \lambda_{\rm em}$! blueshift!

When Jodie returns:

then $r_{\rm em} = r_{\rm obs}$

- $\Delta t_{\rm obs} = \Delta t_{\rm em}$: her watch ticks at same rate as ours!
- but the *elapsed time* is shorter on her watch
  and so she is younger than her twin!

Life Inside a Black Hole

once inside R_{Sch}, no getting out
all matter $\rightarrow$ center $\rightarrow$ point (?): "singularity"
i.e., finite mass M in volume $V = 0$ $\rightarrow$ density $\rho = M/V \rightarrow \infty$!
D'oh! known laws of physics break down

A few remarks:

- we know that all observers travel to center
- don't know what happens once there
- regardless, certain that you die if you go in
- in a way, it's not a relevant question, since can't get info out even if went in (no Nobel Prize!)
- once crushed to $< 10^{-33}$ cm, quantum mechanics important
  i.e., need quantum theory of relativistic gravity!
  ... but there isn't one...yet
- if you have quantum gravity theory, please tell instructor and we'll publish it (your name may even go first!)

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 $\rightarrow$ 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 $\rightarrow$ SN $\rightarrow$ BH left behind
if supergiant companion, close orbit:
some gas falls onto BH $\rightarrow$ compressed, heated $\rightarrow$ 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)
from high-energy electrons e

radio source at center (?): $\boxed{\text{Sgr A}^*}$
size 2.4 AU(!), variable emission in radio, X-ray
`www: X-ray 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

$$r_{\mathrm{Sch}} = 1.1 \times 10^7 \text{ km} = 0.74 \text{ AU} = 3.6 \times 10^{-7} \text{ pc} \qquad (3)$$

$\rightarrow$ 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
spectral lines broad $\to v_{\rm rms} \gtrsim 10,000$ km/s!

AGN vary w/ time: fluctuations $t \sim$ weeks
$\to$ size $d \lesssim ct \sim 1000$ AU
but $M \sim v^2 d/G \sim 10^8 M_\odot$
Huge mass in tiny region: $\to$ black hole, supermassive!

Hubble Telescope: QSO (point) + resolved hosts
`www: HST SQO hosts`
some: merging galaxies
others: “undisturbed” galaxy?!

Supermassive Black Holes

MH has supermassive BH: quiet
QSO have supermassive BH: active

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
$\rightarrow$ $\boxed{M_{\rm BH}/M_{\rm sph} \sim const \sim 0.006}$
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?

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!)