Astro 210
Lecture 37
November 29, 2010

Announcements
- HW 10–the final homework!–available, due Friday
- **ICES** course evaluation available online
  *please* fill it out–I *do* read & use results

Last time: General Relativity – Einstein's theory of gravity
relpaces/corrects Newton's universal gravity

example: masses released (1) from rest, or (2) with $\vec{L} \neq 0$
both theories agree on the kinds of motion that result
but Newton sez: gravity force results in acceleration
while Einstein sez:
- gravity intimately connected with space & time ( "spacetime" )
- massive objects distort spacetime "like a rubber sheet"

*Demo: spandex black hole*

Also last time: black holes – theory

Schwartzchild radius

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

*Q: What is this? Why is it important?*

*Q: How is this a recipe for making a black hole?*

*Q: How do things near $R_{\mathrm{Sch}}$ appear to distant observers?*

*Q: How do distant people & events appear observers near $R_{\mathrm{Sch}}$?*

# iClicker Poll: Black Holes

From a safe distance, you drop an object (nuclear waste? Voldemort?) on an isolated black hole.

Will you see it fall in?

A yes, no matter your distance from the hole

B maybe, depends on how far you are from the hole

C no, because it never actually falls in

D no, although it does actually fall in

# Life Inside a Black Hole

once inside $R_{\rm Sch}$, no getting out
all matter $\rightarrow$ center $\rightarrow$ point (?): "singularity"
i.e., finite mass $M$ in volume $V = 0 \rightarrow$ density $\rho \rightarrow \infty$!
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: You Thought the BP Spill Was Bad

Experiment:
Industrial accident causes Sun to be crushed to black hole
Spokesdroid from Interplanetary BP: "Mistakes were made."

Vote your conscience!

What happens to Earth's orbit?

A nothing: same orbit!

B spirals in: aaargh!

C stronger gravity, but does not fall in

# Life Far From a Black Hole

No change in orbit!

Newtonian explanation: wrong in detail, but correct spirit:
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 $\sim 30$ 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

radio source at center: 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* Schwarzschild radius

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

$\rightarrow$ not resolved (yet) but upcoming missions should see horizon!

Galactic black hole raises many questions:

- how did it get there?
- Sgr A* low luminosity, "quiet"
  compared to more "active" galactic nuclei `www: AGN: M87`
  why? open question....
- in last few months: discovery of high-energy "bubbles"
  above & belowe Galactic center `www: gamma-ray images`
  $\rightarrow$ remains of the most recent Sgr A* belch?

# 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 $\rightarrow v_{\rm rms} \gtrsim 10,000$ km/s!

AGN vary w/ time: large luminosity fluctuations over $t \sim$ weeks
$\rightarrow$ size $d \lesssim ct \sim 1000$ AU
but $M \sim v^2 d/G \sim 10^8 M_\odot$
Huge mass in tiny region: $\rightarrow$ 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
$\rightarrow$ $M_{\mathsf{BH}}/M_{\mathsf{sph}} \sim const \sim 0.006$
constant "BH fraction"
$\rightarrow$ supermassive BH formation is part of gal formation!

Open Questions:

- how does a $10^{7-8} M_\odot$ BH ($R_{\rm Sch} \sim$ 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?

# Gravitational Radiation

Black hole weirdness illustrates key aspects of General Relativity:

★ gravity and spacetime linked

★ spacetime is *dynamic*, affected by gravitating objects
like weights on a rubber sheet

Consequence: moving masses cause "ripples in spacetime"
like moving charges cause ripples in electromagnetc field
= EM radiation!

⇒ moving masses emit **gravitational radiation**

example: binary pair of neutron stars
neutron stars in pairs (binaries)
orbit $\rightarrow$ emit gravity waves $\rightarrow$ lose energy
$\rightarrow$ fall in $\rightarrow$ decrease period $P$
observed!
indirect evidence of GW! $\rightarrow$ Nobel Prize!

soon will directly measure gravity waves
`www: LIGO, LISA`
gravity waves make test masses wiggle
measure with these sensitive lasers