

Astro 210
Lecture 37
April 25, 2011

Announcements

- HW 11—last one! 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 replaces/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
Schwarzschild radius

$$R_{\text{Sch}} = \frac{2GM}{c^2} \quad (1)$$

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_{Sch} appear to distant observers?

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

So far: discussed *predicted* black hole properties
that is: General Relativity says

black holes *can* exist in nature

≈ but question remains: is there *evidence*
that black holes *do* exist in nature?

Evidence for Black Holes

recall: in death of $M > 30M_{\odot}$: 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

ω 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

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

→ 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

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

→ 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 & below Galactic center [www](#): gamma-ray images
→ 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 $\rightarrow v_{\text{rms}} \gtrsim 10,000$ 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

o

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

→ maybe active galaxies are phase in evolution?

BH mass **correlated** with host gal stellar (spheroid) mass

→ $M_{\text{BH}}/M_{\text{sph}} \sim \text{const} \sim 0.006$

constant “BH fraction”

→ supermassive BH formation is part of gal formation!

Open Questions:

- how does a $10^{7-8}M_{\odot}$ BH ($R_{\text{Sch}} \sim \text{AU}$)
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 electromagnetic 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

Galaxies: Sweet Home Milky Way

The Milky Way

www: MW mosaic

www: MW dust lane closeup

Milky Way to eye:
irregular band of light

MW is band on 2-D sky – a *great circle*

Q: what about 3-D space?

iClicker Poll: The Milky Way that Meets the Eye

Vote your conscience!

What's the main source of light in the naked-eye MW?

- A** predominantly gas
- B** predominantly stars
- C** roughly equal mix