Astro 210

Lecture 37

April 23, 2018

Announcements:

- **HW 11: The Final Frontier posted, due 5:00pm Friday**

- Grades: we are catching up! keep checking Moodle

Last Time: Searching for Black Holes

Black holes themselves are invisible*
can can detect them via their strong gravitational effects
on their close surroundings

example: binary stars
X-rays emitted from unseen massive companion

*this ignores Hawking radiation–see below

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: $\boxed{\text{Sgr A}^*}$
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* Schwarzschild radius

$$r_{\mathrm{Sch}} = 1.1 \times 10^7 \text{ km} = 0.74 \text{ AU} = 3.6 \times 10^{-7} \text{ pc} \tag{1}$$

$\rightarrow$ not resolved (yet) but: *Event Horizon Telescope*
has data and right now is processing possible first images!

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`
  $\rightarrow$ 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 $\rightarrow v_{\text{rms}} \gtrsim 10,000$ 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`
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
$\longrightarrow$ maybe active galaxies are phase in evolution?

BH mass **correlated** with host gal stellar (spheroid) mass
$\longrightarrow$ $\boxed{M_{\mathrm{BH}}/M_{\mathrm{sph}} \sim const \sim 0.006}$
constant "BH fraction"
$\longrightarrow$ 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?

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 accelerating charges cause ripples in electromagnetic field
= EM radiation!
⇒ moving masses emit **gravitational radiation**
propagating distortion in spacetime
also carries away energy (and angular momentum)

for experts:

- EM radiation sources are time-varying dipoles
  but no negative mass → no gravitational dipoles
- gravity wave sources are time-changing quadrupoles

Gravitational Wave Sources

expected signal is amazingly tiny
only hope to see strongest sources:
most violent disturbances, hightest gravity, fastest motions

- **binary pair of neutron stars**

neutron stars in pairs (binaries)
orbit $\longrightarrow$ emit gravity waves $\longrightarrow$ lose energy
$\longrightarrow$ fall in $\longrightarrow$ decrease period P

strategy: search for a pulsar in a binary system
with a neutron star as the partner

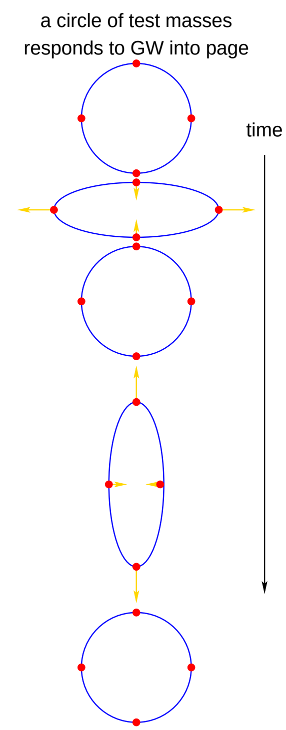
observed! "binary pulsar" shows exactly the expected orbit decay
indirect evidence of GW! $\rightarrow$ Nobel Prize!

Gravitational Wave Effects

EM waves: oscillating EM fields

effect: test charges accelerated

measure by: currents in antenna $\rightarrow$ power!



gravity waves: oscillating spacetime ripple

expansion $\leftrightarrow$ contraction

effect: test masses accelerated

measure with: compare lengths of perpendicular arms

tiny effect $\rightarrow$ mind-boggling precision needed

arm length change: *strain* $h \equiv \Delta L/L \sim 10^{-21}$!

to detect directly: measure time-changing strain due to wave

- very long arms $L \sim 2$ km
- compare lengths via gigantic interferometer
- build multiple observatories to confirm (and localize) signal

`www: LIGO, Virgo`

Gravitational Wave Observatories

online now: ground-based detectors sensitive to binary mergers with stellar masses

Advanced LIGO: operational since 2015 `www: LIGO` interferometers (detectors) in Washington state and Louisiana

VIRGO: operational since 2017
one detectors near Pisa, Italy; less

when possible signal reported:
- confirm with multiple detectors
- localize on the sky
- scan that region with telescopes!

GW 150914

Sept. 14, 2015:
gravitational wave signal appears in both LIGO detectors!
`www: GW 150914 signal`

strain pattern $h(t)$ matches textbook predictions
for **merging black holes**!!
- early signal: increasing frequency and amplitude – **inspiral**
- peak signal: maximum amplitude, very rapid variability – **merger**
- late signal: decreasing amplitude – **ringdown**

binary masses: $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$
final mass: $62^{+4}_{-4} M_\odot$
converted to gravity wave energy: $3.0^{+5}-5 M_\odot c^2$
distance: $\sim$ 400 Mpc $\approx$ 1 billion light years

AMAZING! *Q: because?*

First LIGO Event: Revolution

this single detection of binary black hole merger
which lasted ~ 0.1 sec in total
has profound implications

LIGO for the first time:
- directly detected gravitational radiation
- revealed nature produces black holes $> 10 M_\odot$
- showed that BH binary systems exist
- ...and can collide within the age of the Universe
- observed the birth of the final black hole
- verified and quantified the gravity wave energy release

And: **LIGO inaugurated the age of gravity wave astronomy**

GW 170817: Neutron Star Merger

Aug. 17, 2017: just before solar eclipse
first LIGO detection of gravity waves from *merging neutron stars*

at same time as gravity wave signal
burst of gamma rays also seen by NASA's *Fermi* telescope

all available telescoped searched sky region
that was source of gravity waves plus gamma rays
signal found across the EM spectrum!

Birth of a Kilonova and the Heaviest Elements

results fit expectations for *kilonova/macronova*
models of **merging neutron stars**

- merged object very massive, but still not clear if it immediately became a black hole or high-spin NS

- dimming optical/infrared signals point to neutron star matter ejected at $v \sim 0.1 - 0.3c$!!

- reactions in decompressing neutron-rich likely made heavy elements: all the way to uranium! (the "r-process")

Are Black Holes Forever?

star's lives are a struggle against gravity

black holes represent ultimate triumph of gravity

General Relativity (without quantum mechanics) shows that:
adding matter to black hole increases its mass
and thus the size of the event horizon
can prove: *area of BH horizon never decreases*
note similarity to 2nd law of thermo...

Stephen Hawking, 1970's: combined quantum mechanics and BH theory
quantum mechanics: uncertainty principles
$\Delta x \; \Delta p \geq \hbar/2$, but also $\Delta E \; \Delta t \geq \hbar/2$
$\longrightarrow$ can create pairs of "virtual particles" with energy E
if they go away in time $\sim \hbar/E$
Hawking: what happens near BH horizon?

Hawking Radiation

Near horizon of black hole
virtual particle pairs created

- one can fall in, allowing the other to escape
- net effects: black holes radiate particles!

more amazing: Hawking showed particle energy spectrum is *thermal* with temperature

$$T_{\rm bh} = \frac{\hbar c^3}{8\pi k G M} = 6.2 \times 10^{-8} \frac{M_\odot}{M} \tag{2}$$

so: very low for stellar mass BHs!!

but this means black holes lose energy!
$\longrightarrow$ have to become *smaller, less massive* over time
eventually: *black holes should evaporate!*

Black Hole Evaporation and Lifetimes

black holes emit thermal *Hawking radiation* with $T \propto 1/M$

thus they have a surface (horizon) flux $F_{\rm horizon} = \sigma T^4 \propto 1/M^4$
and a luminosity $L = F_{\rm horizon} A_{\rm horizon} \propto 1/M^2$

and so the time to radiate the black hole rest energy $E = Mc^2$
is the evaporation time, i.e., the black hole lifetime:

$$\tau_{\rm evap} \sim \frac{Mc^2}{L} \sim 2 \times 10^{67} \text{ years} \left(\frac{M}{M_\odot}\right)^3 \tag{3}$$

lessons:

- for solar/stellar mass black holes ($M \gtrsim 1 M_\odot$)
  lifetime $\gg$ age of Universe: evaporation unimportant
- BH masses $M \lesssim 10^{12}$ kg evaporate rapidly!