Astro 210

Lecture 36

April 22, 2011

Announcements

- HW 10 due
- HW 11 available–last one! due next Friday

Last time:

- neutron stars – hypderdense objects
  resulting from massive star death
- gravity revisited: Einstein equivalence principle
  Q: what's that?
  Q: consequences?
  Q: how to test?

Light Bending: The Sun

In principle: *all* gravitating objects bend light
including you, me, the earth...
In practice: need strong gravity source to create
effect large enough to observe

Einstein (1915) devised first test: the Sun

- Sun's gravity deflects starlight rays *diagram: paths*
- the stronger the gravity along the path
  the bigger the deflection
  ...in fact, bending angle $\alpha = 4GM_\odot/R_{\text{closest}}c^2$

$\Rightarrow$ biggest effect for starlight just "grazing" edge of Sun

Q: why is this technically challenging to see?

Q: how to get around the problem?

1919 Eclipse: Give it up for Big Al!

Problem: Sun's glare obscures surrounding starlight
Solution: block glare with eclipse!

1919: total solar eclipse in Southern hemisphere
expedition led by Sir Arthur Eddington

⋆ starlight bent! Woo hoo!

⋆ relativistic gravity confirmed!

⋆ Einstein an instant celebrity

`www: NYTimes headlines`

Now tested many times, and very accurately
seen in clusters of Galaxies

`www: HST gravitational lens Abell 2218`

• all starlight bending experiments confirm Einstein!

General Relativity

Einstein's gravity: General Relativity

Newton: matter causes force (gravity)
$\rightarrow$ particles follow curved lines in
"flat" (Euclidean geometry) space

Einstein: bold leap, rejected Newton
matter causes spacetime to be "curved"
$\rightarrow$ particles follow straight lines ("geodesics")
in curved space

space and time dynamic
not fixed once and for all

Black Holes

Laplace (1790's)
recall: escape velocity $v_{\rm esc} = \sqrt{2GM/R}$
HW 3: What if star has M, R with $2GM/c^2R > 1$?
then $v_{\rm esc} > c$!
light cannot escape! $\rightarrow$ black hole

Wrong argument (Newtonian gravitation)
...but right answer!

in death of $M > 30 M_\odot$*: gravity wins
collapse unstoppable
black hole formed $\Rightarrow$ inevitable part of star formation

*Exact "threshold mass" for SN $\rightarrow$ BH uncertain

Black Hole Properties

any object of *any* mass M can (in principle) become a black hole!

size: Schwarzschild radius

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

radius also provides BH "recipe":

- *crush* object M *smaller than* $R_{\rm Sch}$ $\rightarrow$ *get BH!*
- example: for mass of Sun $R_{\rm Sch} = 2GM_\odot/c^2 = 3.0$ km
  but actual $R_\odot = 7 \times 10^6$ km
  $\rightarrow$ the Sun is not a black hole! (whew!)
- for mass of Earth: $R_{\rm Sch} = 1$ cm!

The Black Hole Horizon

Why call $R_{\rm Sch}$ the BH radius? nothing is there!

True, but: $R_{\rm Sch}$ marks "point of no return"
horizon: surface enclosing the BH
i.e., horizon is surface of sphere w/ radius $R_{\rm Sch}$

horizon is one-way "membrane"
once inside $r \leq R_{\rm Sch}$ nothing can escape...even light!
cosmic roach motel!

Hence:
no light escapes $\rightarrow$ black
but nothing else moves as fast $\rightarrow$ nothing else escapes $\rightarrow$ 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:

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

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 does Jodie 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!

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 $M > 30M_\odot$: 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

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

`www: Cygnus X-1`