Astro 210
Lecture 36
November 19, 2010

Announcements
- Computational Project due now
- HW 10–the final homework!–available, due Friday after break
- Hour Exam 2 back today; solutions posted

Last time:
supernova outcomes
- superheated, element-rich gas
- compact remnant

neutron stars and pulsars
- *Q: what's a neutron star?*
- *Q: what's a pulsar?*

Neutron star escape speed: $v_{\rm esc} \approx c/3$!
$\rightarrow$ strong gravity $\rightarrow$ Newton fails! $\rightarrow$ Big Al to the rescue

iClicker Poll: Computer Project

Which project did you do?

A I am the Master of White Dwarfs!

B I am the Surveyor of the Cosmos!

C Bad week! I bailed out this time around!

Gravitation Revisited

Newton gravity force law

$$F_{\text{grav}} = \frac{GMm}{r^2} \tag{1}$$

implies that if M moves and so r changes:

$\rightarrow$ gravity force changes instantaneously over all space!

"signal" of motion instantaneously transmitted throughout the universe

Einstein sez: this is totally illegal! an unmitigated disaster!

no signal–including gravity–can move faster than c!

Einstein's Equivalence Principle:

in a closed room, no experiment can distinguish (non-gravitational) acceleration vs gravity

Q: explain ball drop–Earth's surface vs accelerating rocket?

Rocket Experiment: `www: illuminating animation`

⋆ light ray deflected

⋆ entire light path bent (in fact, a parabola!)

But by equivalence principle:
must find same result due to gravity, so:

⋆ gravity bends light rays

gravitational lensing

Q: what if shine light from basement to attic?

Gravitational Redshifting

Also: in accelerating spaceship:

⋆ shine light from basement to attic

spacecraft & attic speed increases during light travel

$\rightarrow$ attic observer seed light *redshifted*

similarly, basement observer sees attic light *blueshifted*

Gravitatinal Redshift

And there's more:

redshift $=$ decrease in light frequency f

but $f = 1/P$, light wave oscillation period

so redshift $\rightarrow P$ increases

but light oscillations are like clock ticking, so...

Gravitational Time Dilation

⋆ clocks in basement appear to run slow
when viewed from attic!
and attic clocks appear fast when viewed from basement!

in fact, attic clocks faster by $\Delta t = t_{\text{attic}} - t_{\text{basement}} = g\Delta h/c^2$

⋆ time "warping" due to gravity:
"**gravitational time dilation**"
⋆ gravity influences "flow" of time!

Q: how to test these effects in real world?

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 $v_{\text{esc}} = \sqrt{2GM/R}$
HW 3: What if star has M, R with $2GM/c^2R > 1$?
then $v_{\text{esc}} > c$!
light cannot escape! $\rightarrow$ black hole

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

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

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

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_{Sch} the BH radius? nothing is there!

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

horizon is one-way "membrane"
once inside $r \leq R_{\text{Sch}}$ 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:

$$\frac{\Delta t_{\rm obs}}{\Delta t_{\rm em}} = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \sqrt{\frac{1 - R_{\rm Sch}/r_{\rm obs}}{1 - R_{\rm Sch}/r_{\rm em}}} \qquad (3)$$

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!

Special Pre-Break iClicker Poll

How far from this room will you be on Thanksgiving?

A $r_{\text{thanks}} < 10$ miles

B $10 \text{ miles} < r_{\text{thanks}} < 100$ miles

C $100 \text{ miles} < r_{\text{thanks}} < 1000$ miles

D $r_{\text{thanks}} > 1000$ miles

Go forth, eat well, have fun, get rest, return safely!