Astro 404

Lecture 36

Nov. 20, 2019

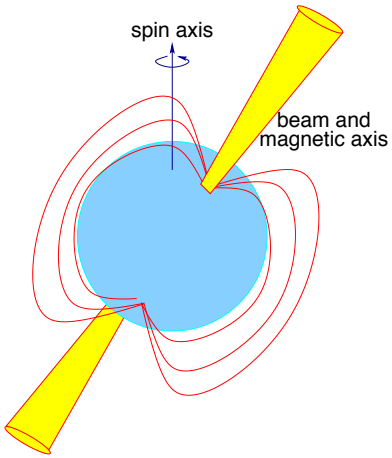
- **Problem Set 11 due date extended to Wed Nov 27**
  but do yourself a favor and turn it in this Friday!
- **No class meeting Friday Nov 22**

Upgrade continues: guest lecturer Prof. Leslie Looney

Last time: neutron stars *Q: what are they? how do we get them?*
Q: why were they feared to be undetectable?
pulsars
Q: what are they? how were they discovered?

if pulsar are spinning stars:
simplest interpretation: *pulse period = spin period* P

this means pulsar emission is *not isotropic*
not the same in all directions



Lighthouse Model of Pulsars

- *radio emission is beamed!*
- beam axis is not aligned with rotation axis
- we see pulses when (and if!) beam sweeps over us

equatorial rotation speeds up to 1000 km/sec!
stability: $v_{\rm esc} < v_{\rm rot}$:

$$\rho_{\rm avg} \; > \; \frac{3\pi}{GP^2} \; \sim \; 10^{14} \; {\rm g/cm^3} \qquad (1)$$

huge density! near that of nuclei!

Q: and so what does this mean? how to test?

Neutron Stars and Pulsars

Bell and Hewish suggest *pulsars are spinning neutron stars*

How can we test this?

the most direct method:
look for pulsars in remnants of core-collapse supernovae!

- found! brightest and best studied: **Crab** pulsar
  found at heart of SN 1054 (Crab Nebula)
  period $P = 0.033$ sec! $\rightarrow$ spin frequency $f = 30$ Hz!
  `www: Crab pulsar in X-rays--images and movies`
- X-ray point source also seen in Cas A remnant `www: Cas A`

Antony Hewish shares 1974 Nobel Prize for Physics.
Jocelyn Bell doesn't. The Nobel Prize has issues.

some pulsars not found in SN remnants, and have high speeds
Q: what could explain this?

Neutron Star Kicks

We observe pulsars (and thus neutrons stars)
to have a wide range of velocities
up to many 100 km/sec; some nearly 1000 km/sec! $\rightarrow$ the fastest ones will escape our Galaxy!

still a research topic why, but:

if supernova explosions perfectly spherical
then they should produce a neutron star at rest in the remnant

but if the explosion is even a little *asymmetric*
if the collapse more violent in one hemisphere
then neutron star can recoil against collapse
and be "kicked" out of remnant!

`www: runaway neutron stars observed`

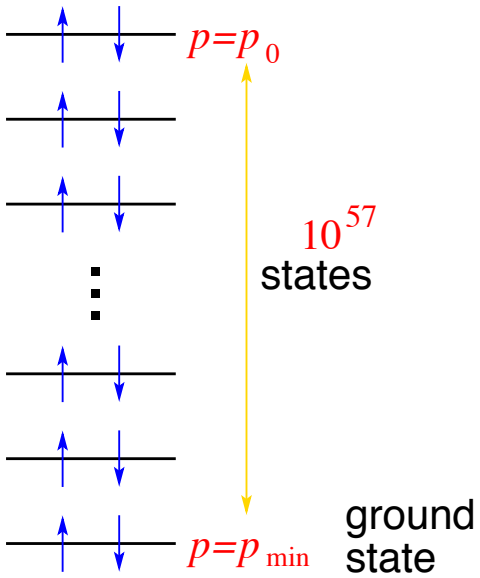
Neutron Stars: Theory

consider *degenerate star made of neutrons*
closely related to white dwarfs: degenerate electron star

recall how degeneracy works:
Pauli: no two identical Fermions in same quantum state
Heisenberg: $\Delta x\ \Delta p \geq \hbar/2$,
so confinement to small region Δx
means high momentum Δp and energy

Taken together:
a star made of identical Fermions
confined to stellar radius R
forms quantum states, max 2 per level: $\uparrow\downarrow$

- the more particles added...
- the higher the last filled level
  the Fermi level, with Fermi momentum p_0



White Dwarfs vs Neutron Stars

white dwarfs:
mass density provided by protons
degeneracy pressure provided by electrons
- relativistic quantum scale: Compton wavelength $h/m_e c$
- leads to minimum size of Chandra white dwarf
- and to escape speed large but $v_{\rm esc} \ll c$

neutron stars:
neutrons provide both mass density and degeneracy
- relativistic quantum scale $h/m_n c$ much smaller!
  by a factor $m_n/m_e \simeq 2000$!
- neutron stars much more compact
- escape speed $v \sim c/3$!

neutron stars are densest known objects other than black holes!

Q: should NSs hava a maximum mass?

Neutron Stars: Maximum Mass

recall why white dwarfs have maximum mass

as add mass to degenerate star:
- number of particles increases
- have to add to ever higher Fermi level
- so average particle momentum and energy goes up
- and star radius goes down due to huge gravity

for very massive degenerate stars
size becomes so small that essentially all particles relativisitic
and $P = K\rho^{4/3}$: unstable!

all of these effects are true for *both* neutron stars
and white dwarfs: neutron stars do have maximum mass!
more than white dwarfs because all NS particles add degeneracy
and extra compression includes new gravity effects
estimated max mass $M_{\rm NS} < 3M_\odot$

Beyond Newtonian Gravity

neutron stars extremely dense $\rightarrow$ strong gravity
escape speed $v_{\rm esc} \sim 1/3\ c$!

Newtonian dynamics, gravity:
ok if $v \ll c$

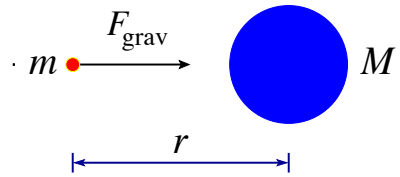
but this won't do for neutrons stars!
can't get structure right without going beyond Newton

This is a job for Einstein!
...though neutron stars unknown when we did this work!

Gravitation Revisited

Newton gravity force law

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



implies that *if M moves* and thus r *changes:*

→ *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 1905: **Special Relativity**

- rewrote dynamics to include motions with speeds near c
- Maxwell's Equations already have signal speed $= c$
  no need to revise E&M! automatically relativistic!
- but did not include gravity

The Democracy of Gravity

How to go about revising gravity? Where to start?

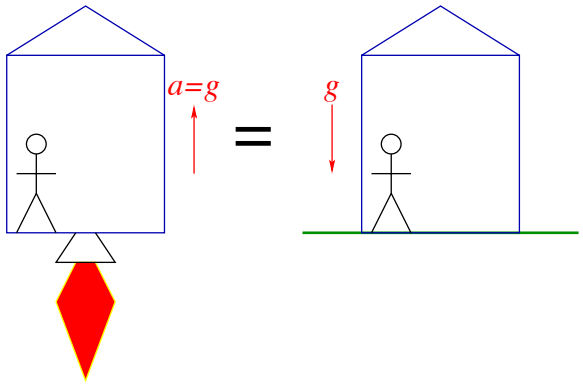
Recall Galileo atop the Tower of Pisa:
gravity $\rightarrow$ all objects move (accelerate) the same way in free fall
  regardless of object mass, shape, composition not new result,
but different explanations...

Newton sez:
it just so happens that gravitational mass
  the way objects "feel" or "couple to" gravity $F_{\text{grav}} = m_{\text{grav}} g$
is always exactly the same as inertial mass
  the way objects resist acceleration $a = F/m_{\text{inert}}$

Einstein sez:
too amazing to be a coincidence, must be deeper...

Gravity and Acceleration are One

Einstein 1905-1915: struggled to reconcile
special relativity and *gravity*



Key step:
Einstein's Equivalence Principle:
in a closed room
no experiment can distinguish
gravity-free acceleration vs *gravity and no acceleration*

Q: explain apple weight–Earth's surface
vs rocket accelerating $a = g$*?*
Q: explain apple drop–Earth's surface vs rocket with $a = g$*?*

Newton's Apple Experiment: Two Views

Isaac Newton on Earth's surface:

- holds an apple in his hand, **pushes up with force** $F = mg$
  says: must oppose weight so net force zero
- releases apple, **observes downward acceleration**
  says: motion due to net gravity force

Albert Einstein in rocket with constant acceleration $a = g$:

- holds apple in hand, **pushes up with force** $F = mg$
  says: to keep apple in my non-inertial accelerating hand must push so it accelerates too
- releases apple, **observes downward acceleration**
  says: motion due to my non-inertial frame

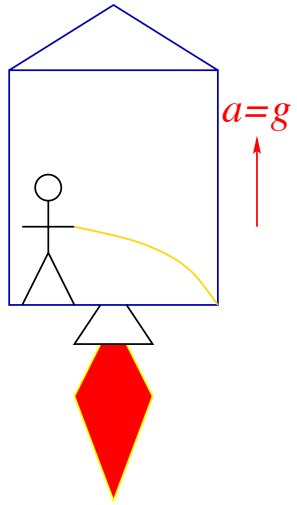
Note: identical physical results, radically different explanations

Q: what about horizontal ball toss?
Q: what about horizontal light beam?

Gravity Bends Light

Rocket Experiment: `www: illuminating animation`
in accelerating rocket, shoot a horizontal beam

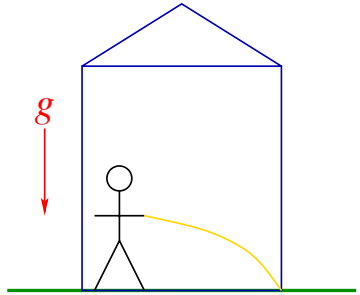
- ⋆ light ray deflected
- ⋆ entire light path bent (in fact, a parabola!)
  "gravity's rainbow"



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

- ⋆ gravity bends light rays

gravitational lensing



iClicker Poll: Rocket Lasers

Install lasers and detectors in rocket basement and attic measure λ_{obs} during acceleration

Resulting effect on photons?

A no effect: λ unchanged if emitter and detector both accelerate with rocket

B attic detectors see *blueshift*
basement detectors see *redshift*

C attic detectors see *redshift*
basement detectors see *blueshift*

D both detectors see *redshift*

E both detectors see *blueshift*

Gravitational Redshifting

Rocket experiment:
- light bending
- as photon travels, acceleration changes detector v relative to emitter
  upgoing (downgoing) photon seen to redshift (blueshift)

But by equivalence principle:
must find *same result due to gravity*, so:
⋆ gravity bends light rays
gravitational lensing
⋆ observers in basement see blueshift of attic photons!
and observers in attic see redshift of basement photons!
gravitational redshift/blueshift

Note: gravitational red/blueshift confirmed in lab!
Q: how would you do the experiment? what are you looking for?
`www: Pound-Rebka expt`

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

Q: and so?

Gravitational Time Dilation

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

viewed from attic, basement clocks appear slower by

$$\Delta t = t_{\text{basement}} - t_{\text{attic}} = \frac{gh}{c^2} = \frac{\phi}{c^2} \qquad (2)$$

where $\phi = gh$ is gravitational potential

⋆ time "warping" due to gravity:
"**gravitational time dilation**"
⋆ gravity influences "flow" of time!
deeper potential $\rightarrow$ slower apparent "time flow"
Q: so which clock is really right?

Who's right–attic or basement observers?

⋆ *both* are reporting accurately

⋆ *both* see their own clocks tick normally

experiment: Alicia and Beyoncé start at same place
- Alicia remains still
- Beyoncé goes deeper in potential, hangs out, then returns

They meet again at starting point and compare clocks:
Q: how do the tick rates compare?
Q: how do the elapsed times compare?

when they meet again:

- *both* clocks tick at same rate
- but total elapsed time is larger for Alicia!

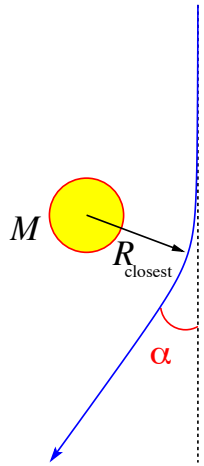
Q: how to test these effects in real world?

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
- the stronger the gravity along the path
  the bigger the deflection
  bending angle $\alpha = 4GM_\odot/R_{\text{closest}}c^2$



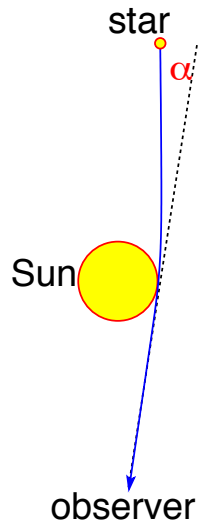
biggest effect for starlight "grazing" Sun edge: $R_{\text{closest}} = R_\odot$
Q: why is this technically challenging to see?
Q: how to get around the problem?

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

`www: expedition results paper to Royal Society`



★ starlight bent! Woo hoo!

★ relativistic gravity confirmed!

★ Einstein an instant celebrity

`www: NY Times announcement`

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

`www: HST gravitational lens Abell 2218`

• all starlight bending experiments confirm Einstein!