Astro 404

Lecture 35

Nov. 18, 2019

- **Problem Set 11 (penultimate!) due Fri 22**
- **No class meeting Friday Nov 22**

Upgrade: guest lecturer Prof. Leslie Looney

Last time: consequences of supernova explosions

Q: how much of a massive star is ejecte in explosion?

Q: what is this ejecta made of? why do we care?

Q: effects if a supernova is too close?

Supernova Search Engines

modern telescopes (so far!) have *tiny* fields of view!
Hubble: single image ~ 1 arcmin $\times$ 1 arcmin $\sim 10^{-7}$ sky
priority has been to deeply study small regions of sky

But a revolution is coming...

Large Synoptic Survey Telescope `www: LSST`

- site: Cerro Pachón ridge, Andes mountains, Chile
- primary mirror diameter $D = 8.4$ m: large but not unusual
- field of view 10 deg^2 **enormous!**
  requires 3.2 Gigapixel camera!
  first telescope to have such a large field of view
- Illinois is LSST member; Astronomy, Physics, NCSA involved

Q: why is such a large field of view useful? what does this allow?

Coming Soon–Cosmic Movie & Wallpaper

thanks to large field of view
LSST can **scan entire night sky** in a few days!
and then **repeat** this scan for ≈ 10 years

result: ≈ 1000 deep digital images of *every point* on the southern celestial sphere, spanning 10 years!

Strategy: *compare* images of *same* region

- some things won't show any change *Q: like?*
  add exposures to get *very* deep images
  "The Sky: The Wallpaper"
- other things *will* show change! *Q: like?*
  subtract exposures to find & monitor changes
  $\rightarrow$ reveal celestial variability over timescales $\sim$hours to years
  "The Sky: The Movie"
  $\Rightarrow$ this has never been done on such a huge scale!

LSST and Supernovae

every year, LSST expected to see:

- $\sim 300,000$ core-collapse supernovae!
  more than all discoveries in recorded history
  from 185 AD to present day
- nearly all supernovae in local Universe
- distant events out to $z > 1$

over 10-year LSST lifetime: *millions of supernovae!*
unusual events will still be numerous
and surprises likely!

opportunities for clever ideas on supernova discovery
classification, and science questions
see Director's Cut Extras for one idea

The Central Object

in core-collapse supernovæ:
most of progenitor mass ejected in wind or explosion

but what about the central object – the star's core

Q: properties before and during collapse?

Q: properties after collapse?

Q: what if pre-collapse star was rotating? spoiler–it was!

Q: what if pre-collapse star was magnetized?

The Ultra-Compact Remains

massive star collapse begins when iron core mass $> M_{\mathrm{Chandra}}$
collapse accelerated during neutronization: $e^- + p \to \nu_e + n$
finally halted when core $\to$ degenerate

result: star core is degenerate gas of neutrons

Baade & Zwicky (1934 PNAS 5, 259):

> With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the gravitational packing energy in a cold neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such.

Note: the neutron was only discovered by Chadwick in 1932!

Interlude: Pulsar Discovery

neutron stars studied from 1930's onward
but viewed as theoretical curiosity

even if they existed, too small to ever observe
since $L = 4\pi R^2 \sigma T^4$

1968: Antony Hewish radio astronomy group in Cambridge UK
graduate student Jocelyn Bell [Burnell] notices variable radio sources

- pointlike, pulsing with regular periods $P \sim 1$ sec
- extraterrestrial, but no obvious counterparts for first discoveries

cosmic lighthouses! aliens? joking name LGM = little green men
named **pulsars**: pulsating stars

What Makes a Pulsar?

now thousands of radio pulsars found
periods down to $P \sim 1 \text{ ms} = 10^{-3} \text{ sec}$
pulses also seen at other wavelengths, out to gamma-rays
`www: radio pulses sonified`

imagine pulsars are *spinning stars*

Q: what sets the pulse period?

Q: why would we see pulses at all?
Q: what is the star doing between pulses?

Q: if this is true, what are biases in pulsar observations?

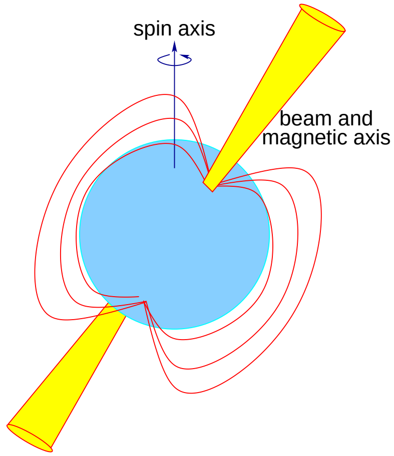
∞

Q: implications of high spin rate?

Pulsars as Spinning Stars: Lighthouse Model

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

if true: we are biased against observations of pulsars
whose beams don't point to us!
$\rightarrow$ observed pulsar counts are *underestimate* of true numbers

Pulsar Spin Rates and Stability

stability a challenge with these huge spin periods

if mass M and radius R

escape speed at surface: set by energy conservation

$$\frac{1}{2}mv_{\rm esc}^2 - \frac{GMm}{R} = \frac{1}{2}mv_\infty^2 = 0 \quad (1)$$

$$v_{\rm esc}^2 = \frac{GM}{R} \quad (2)$$

at equator, rotation speed $v_{\rm rot} = \omega R = 2\pi R/P$

Q: condition for stability?

escape speed:

$$v_{\mathrm{esc}}^2 = \frac{GM}{R} \tag{3}$$

equatorial rotation speed:

$$v_{\mathrm{rot}} = \frac{2\pi R}{P} \tag{4}$$

stability: $v_{\mathrm{esc}} < v_{\mathrm{rot}}$:

$$\frac{GM}{R} > \frac{4\pi^2 R^2}{P^2} \tag{5}$$

$$\frac{GM}{R^3} \sim G\rho_{\mathrm{avg}} > \frac{4\pi^2}{P^2} \tag{6}$$

$$\rho_{\mathrm{avg}} > \frac{3\pi}{GP^2} \sim 10^{14}\ \mathrm{g/cm^3} \tag{7}$$

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`

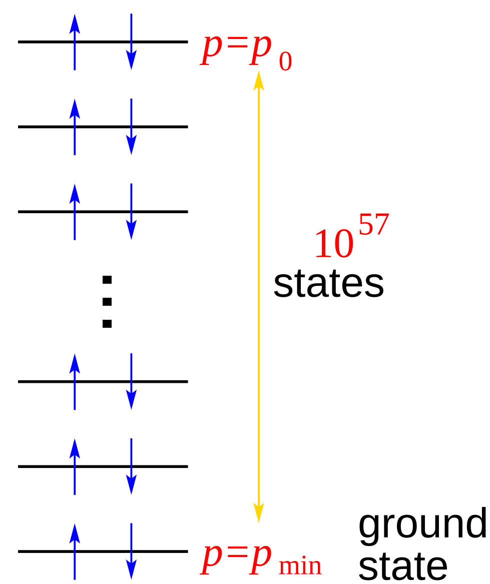
Neutron Stars: Theory

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

- relativisitic 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 Fermil 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 maximium 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 $\longrightarrow$ strong gravity
escape speed $v_{\text{esc}} \sim 1/3\ c$!

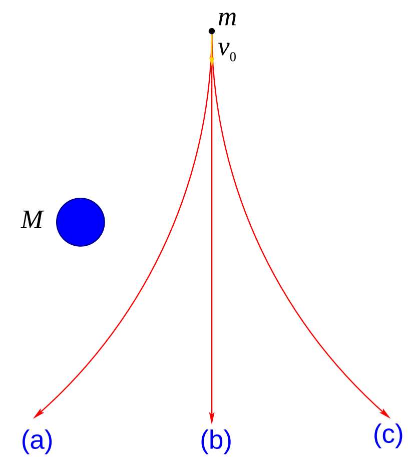
Newtonian dynamics, gravity:
ok if $v \ll c$

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!

iClicker Polls: Gravitation Warmup Twofer

Recall your (Newtonian) gravitation



a test particle, mass m,
launched from "infinity" with *speed* $v_0 > 0$
passes gravitating mass M

What is the path of the particle?

A deflected towards M

B no deflection: straight line

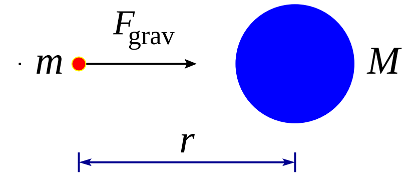
C deflected away from M

Twofer! Same, but for *massless* test particle, $m = 0$

Gravitation Revisited

Newton gravity force law

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



implies that *if M moves* and thus *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!

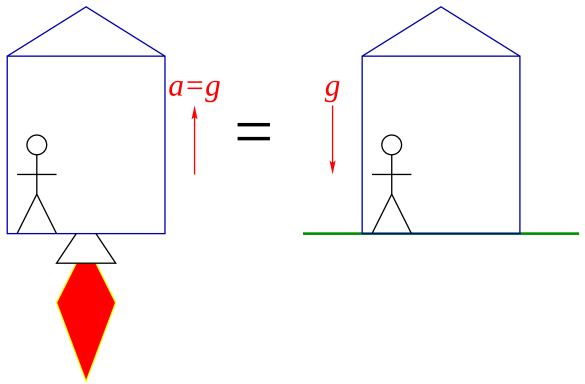
violates basic principles of special relativity

Einstein 1905: **Special Relativity**

- rewrote dynamics to include motions with speeds near c
- but did not include gravity

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 ball weight–Earth's surface vs accelerating rocket?

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

Q: what about horizontal ball toss?

Q: what about horizontal light beam?

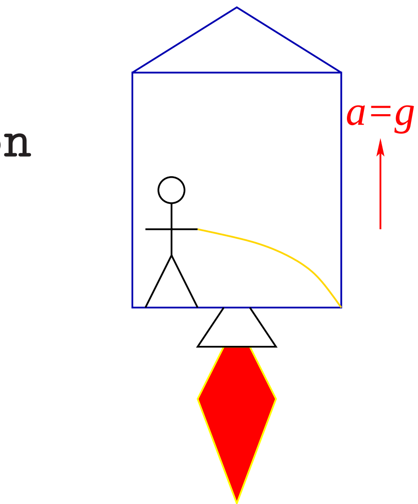
Gravity Bends Light

Rocket Experiment: `www: illuminating animation`

in accelerating rocket, shoot a horizontal beam

★ light ray deflected

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

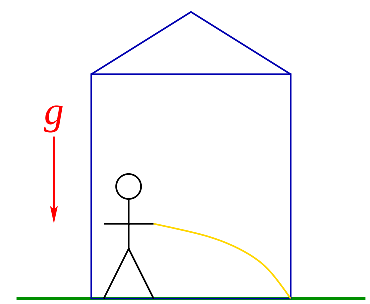


But by equivalence principle:

must find same result due to gravity, so:

★ gravity bends light rays

gravitational lensing



Q: what if shine light from basement to attic?