Astro 404

Lecture 34

Nov. 15, 2021

Announcements:

- **PS11 due Friday**

  uses data from `www: Open Supernova Catalog`

Last Time:

core-collapse supernovae: observations

Q: types based on spectra?

Q: lessons for supernova origin?

Type I: **hydrogen** totally or nearly *absent*

subclasses: Type Ia: silicon present, iron-peak elements

Types Ib and Ic: helium and oxygen present

Type II: **hydrogen present** in spectrum and ejecta

elliptical/early-type galaxies: no/little ongoing star formation

- only have Type Ia explosions
- no progenitors seen to date–must be faint, not massive stars!

spiral and irregular galaxies: star formation ongoing

- Type II are most numerous, Types Ib, Ic also found

Supernovae have two distinct physical origins

massive stars explode as Type II, Ib, Ic events

white dwarfs explode as Type Ia events: discussed later

Nearby Supernovae: How close is too close?

today: ready for another supernova!
explosions unpredictable, effectively random

expected distance of next event: ~ 10 kpc
rougly sun's distance to Milky Way center

but don't get too close!
minimum safe distance to supernova: $\sim$ 8 pc
Q: why would this ruin your whole day?
Q: should we alert Homeland Security today?

Supernova Threat

explosion produces *high-energy photons:*
extreme UV, X-ray, γ-rays
ionizing radiation – can tear apart atoms

we on Earth's surface: shielded by atmosphere
but: ionizing photons alter atmospheric chemistry
tears apart $N_2 \rightarrow$ highly reactive $\rightarrow$ destroys ozone O_3

this is bad.
no stratospheric ozone: UV from Sun unfiltered
you and I: wear hats and sunblock SPF 2000
species at bottom of food chain: no escape!
damage propagates up: could trigger biological mass extinction!

Q: how can we identify a nearby supernova in the distant past?

Nearby Supernova Detection: Live Radioactivity

if supernova exploded in distant past
evidence on sky may be gone
have to look on Earth

if explosion near enough: blast wave engulfs the Earth
supernova debris literally rains on our heads
signature: newly-produced supernovae elements

- stable: *can't distinguish from terrestrial matter*
- live (not decayed) radioactivity: none found on Earth!
  if half-life $<$ age: cosmic "green bananas" (unripe)

radioactive ^{60}Fe found on Earth! half-life $t_{1/2} = 2.6$ Myr

- in deep ocean, in Antarctic snow, and on Moon too!
- two pulses: one 2–3 Myr ago, another 7 Myr ago
- two nearby supernovae! very close–near misses!
- no mass extinction, but possible extinctions under investigation

Supernova Discovery: The Future

supernova discovery pioneered **multimessenger astronomy:**
collecting signals from all fundamental forces

messenger: *neutrinos*
emitted from neutrinosphere $\rightarrow$ probe proto-neutron star

messenger: *gravitational radiation*
spoiler alert–ripples in space, propagate at c
created by rapid aspherical motions of large masses
should arise in collapse, escape immediately

messenger: *photons*
arise from photosphere once blast wave arrives there

Poll: Messenger Choreography

a supernova explodes nearby, with little dust obscuration

In what order do we see the messengers?

given from first to last

A neutrinos, gravitational radiation, photons

B gravitational radiation, neutrinos, photons

C gravitational radiation, photons, neutrinos

D gravitational radiation and neutrinos tied, then photons

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 $> M_{\text{Chandra}}$

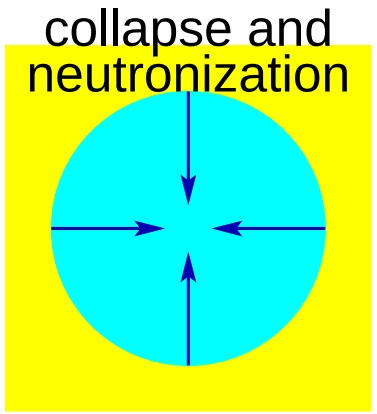
collapse accelerated during neutronization:

$e^- + p \rightarrow \nu_e + n$

finally halted when core $\rightarrow$ degenerate

result:

star core is degenerate gas of neutrons



...explosion...

Prescience

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

belief was: even if they existed, the would be
too small to ever observe, since $L = 4\pi R^2 \sigma T^4$

1968: Antony Hewish radio astronomy group in Cambridge UK
systematically surveying the radio sky
grad student Jocelyn Bell [Burnell] finds 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 $P \sim 1$ ms $= 10^{-3}$ 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?

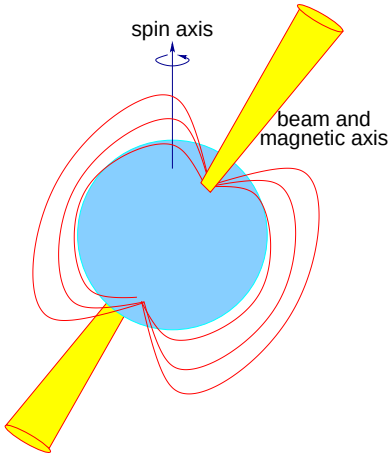
Q: if this is true, what are biases in pulsar observations?

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:

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

equatorial rotation speed:

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

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

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

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

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

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`

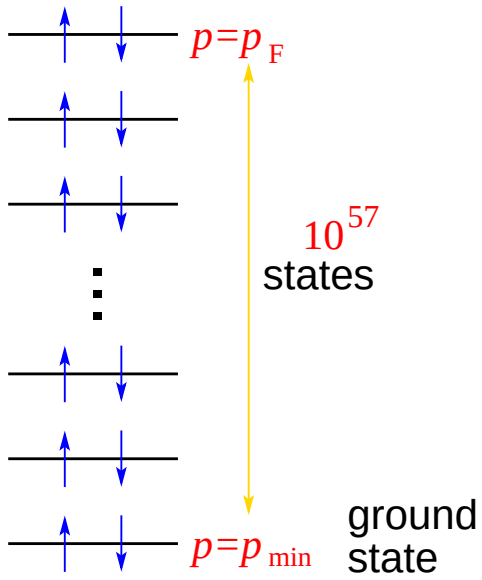
Neutron Stars: Theory

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_F



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

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

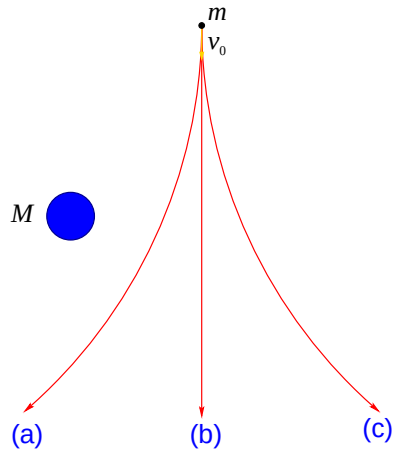
but this won't do for neutrons stars!
can't get structure right without going beyond Newton

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

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

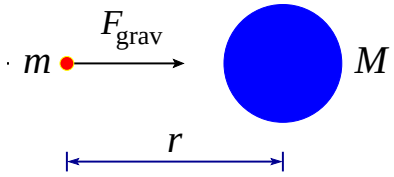
C deflected away from M

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!

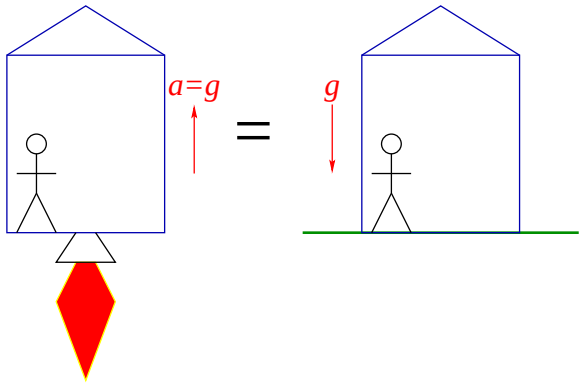
violates basic principles of special relativity

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?

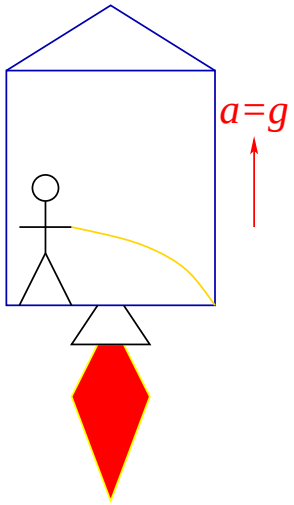
Q: what about horizontal ball toss?

Q: what about horizontal light beam?

Gravity Bends Light

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

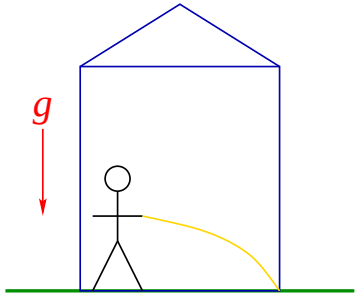
- ⋆ light ray deflected
- ⋆ entire light path bent (in fact, a parabola!)



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?