Astro 404
Lecture 40
December 6, 2021

Announcements:

- Good news: no homework this week!
  can still make predictions for bonus points
- Bad news: Final Exam Mon Dec 13, 1:30–4:30 pm
  info is on Canvas
- **please fill out ICES form!**

Last time:
right now is a golden age of black hole astrophysics

- M87* event horizon imaged! SgrA* soon!
- gravitational wave astronomy under way!
  LIGO/Virgo have seen 90 merger event!

Update: LIGO/Virgo Black Holes

LIGO/Virgo ran until COVID shutdown
to date: *90 gravitational wave events detected!*
upgrades underway, Dec 2022 restart planned

signal is strongest for nearest, most massive events
→ biased towards binary black holes (BH-BH) mergers

`www: LIGO/Virgo detections`

detected black hole masses before merger:

- lowest: $5.9^{+4.4}_{-1.3} M_{\odot}$
  consistent with origin in core-collapse explosion
- highest: $106.9^{+41.6}_{-25.2} M_{\odot}$ – very massive!
  could this be the result of a prior merger?

Gravitational Wave Astronomy: Open Questions

To name just a few:

- how and where are stellar mass BH binaries formed?
- what is the (unbiased) distribution of black hole masses?
- do BH mergers have a detectable electromagnetic signal?
- does the BH formation rate follow the rate of massive stars?
  what is the delay between a BH binary formation and merger?

Stay tuned!

Binary Systems and Stellar Explosions

Evolution of Binary Stars

for most of this course: considered evolution of stars that are
- non-rotating
- non-magnetic
- in isolation – **no binary partner**

for many stars, these are good or even excellent approximations
but *there are stars where these features a critical!*

for the rest of the course: binary stars that evolve explosively!

recall: most stars are in binaries!
observed separations span a few AUs to fractions of parsecs
and orbital eccentricities vary widely

iClicker Poll: Evolution of Binary Stars

consider two stars in a binary

which of these will evolve most differently
compared to the same two stars in isolation

- A two *main sequence stars*, with *wide* separation
- B two *main sequence stars*, with *close* separation
- C 1 or 2 *post-main-sequence stars*, with *wide* separation
- D 1 or 2 *post-main-sequence stars*, with *close* separation

Binary Stars and Mass Transfer

binarity effect are most drastic when there is *mass transfer*

- one star loses mass by giving it to the other
- for this to occur, matter must become unbound in one star and move to the other

this happens when

- one star becomes a giant → atmosphere loosely bound
- two stars orbit decays until they merge

  Q: how can orbits decay?

Binar Star Orbit Decay

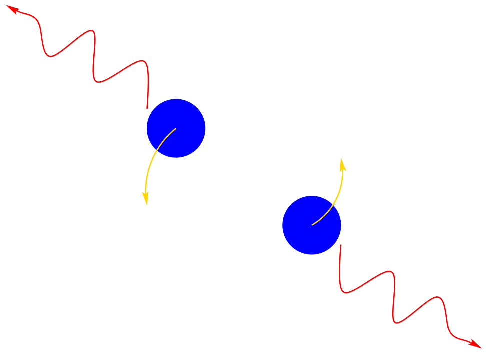
In *Newtonian* gravity, *point mass* binary orbits *in vacuum*

- are perfect ellipses
- never change in time

but orbits *do change* if one of these conditions is violated

- *one star becomes giant*, other moves in its atmosphere
  slows down due to drag forces

- *two white* dwarfs, no atmosphere
  but energy lost due to General Relativity effect:
  gravitational radiation
  acceleration launches spacetime ripples
  that carry away energy and angular momentum
  shrinks binary orbit: *inspiral*



Binary Stars: Type Ia Supernovae

Type Ia Supernovae Observed

- SN Type I → no H in spectrum
- Type Ia: He, Si lines *are* seen
- peak luminosity: $\sim 1^{\text{mag}}$ = factor 2.5 brighter than SN II
  → easier to find, probe larger distances (higher z)
- ejecta somewhat faster than Type II events
- blast energies ~ 1 foe $= 10^{51}$ erg
- host galaxies: all types, including "red and dead" elliptical
- observed Type Ia rate $\sim 20\% - 50\%$ of Type II
  but beware selection effects: easier to see Type Ia

Q: what physical ingredients needed to produce SN Ia?

Type Ia Supernovae: Ingredients

- no hydrogen → "stripped" star
  need either wind or companion
- found in all galaxies
  → not correlated with active in star formation
  → progenitors not short-lived: low/intermediate mass stars
- faster ejecta, brighter events → progenitors less massive
- regularity of light curves → fairly uniform path to formation

putting it all together... *Q: what do you think?*

Type Ia Supernovae: White Dwarf Explosions

all viable scenarios invoke:

⋆ *binary system*

⋆ a *white dwarf*, usually a CO dwarf

What's a CO white dwarf?

→ end-product of intermediate-mass star

recall – after main seq:

1. H shell burn → red giant
2. He ignition: degenerate → explosive: *helium flash*
3. core expands, burns He → C+O

Q: and what happens when core is CO? Hint: it depends!

4(a). if $M \lesssim 4 M_\odot$, CO core supported by e^- degeneracy pressure
never contracts, remains as CO *white dwarf*

4(b). if $M \sim 4 - 8 M_\odot$, shell He burning increases CO core mass
until $M_{\text{core}} > M_{\text{Chandra}}$: core contracts, burn to O, Ne, Mg
results in ONeMg white dwarf

thus: CO white dwarfs are outcomes of $\sim 1 - 4 M_\odot$ evolution
but lower-mass stars are the most abundant
$\rightarrow$ CO white dwarfs are the most common type

Q: so what if WD has binary companion which donates mass?

SN Ia: Thermonuclear Explosions

if WD in close binary/merger:

- companion donates mass
- when $M_{\text{WD}} > M_{\text{Chandra}}$: star contracts
  ignites degenerate C burning ("carbon flash")

runaway nucleosynthesis → WD detonates
heated → achieve *nuclear statistical equilibrium*
Q: which will make what?

energy release:

- ^{12}C→ ^{56}Fe burning gives
  $Q = B_{56}/56 - B_{12}/12 = 0.86$ MeV per nucleon
  if inner 50% of M_{Chandra} is carbon, then
  release $E_{\text{nuke}} \sim QM_{\text{core}}/m_u \sim 1.6 \times 10^{51}$ erg $= 0.6$ foe
- compare to core gravitational binding:
  for uniform sphere $E_{\text{grav}} = 3/5\ GM^2_{\text{core}}/R \sim 10^{50}$ erg $= 0.1$ foe

Q: and so?

Type Ia Explosion Physics

thermonuclear energy powers explosion

not gravitational energy!

`www: Type Ia simulation movie, Chicago group`

white dwarf entirely unbound, disrupted, ejected
- Type Ia should leave *no compact remnant*
- all nucleosynthesis products ejected

Neutrinos?
- expect some relatively low-energy ~ 3 MeV emission from β decays, but a "fizzle" compared to core-collapse

Type Ia Supernova Nucleosynthesis

in thermonuke explosion:

all nucleosynthesis is from *explosive burning*

(in contrast to core-collapse case)

most of star “cooked” to $T \sim 1$MeV

driven to nuclear statistical equilibrium

- favors most tightly-bound elements: *iron peak*

- yields peak at $m_{\rm Ia,ej}(^{56}\text{Fe}) \sim 0.5 M_\odot$
  $\sim 5 - 10$ times more than typical core-collapse Fe yields
  also large amounts of Cr–Ni

- but traces of Mg Si, S, Ca observed: not all star in NSE
  requires some burning occur at lower T:
  “deflagration–detonation” transition

Type Ia Supernovae: Whodunit?

general agreement: SN Ia require white dwarf & companion
good news: binary systems common
bad news: *still* no consensus, and no direct evidence,
on nature of binary companion

single degenerate

binary companion is a star in giant phase
mass transfer to white dwarf
companion survives explosion

double degenerate

binary companion is another white dwarf
merge after inspiral due to gravitational radiation

Problems with either!

Single-Degenerate:

- explosion should evaporate some of companion atmosphere
  why no H seen in supernova spectrum?
- No success (yet?) in direct searches for runaway companions
  in Type Ia SN remnants
  → limits imply companion must be dim → low mass
  but then must be very close binary to transfer mass
  so why no H in spectrum?

Double-Degenerate:

- WD-WD inspiral times long unless very close binary
  no WD binaries seen with $\tau_{\rm inspiral} < t_0$
  ...but could this be a selection effect?
- WD-WD merger could lead to neutron star formation
  "accretion induced collapse," inward burning

SN Ia Population Studies: Everybody Does It?

SN Ia population constraints: (Maoz 2008)
observed SNIa rate ≈ 15% *all* $3-8M_{\odot}$ star death rate

but SNIa candidates

- *must* (?) be in binaries ... and can't double-count:
  ≤ 1 SN Ia per binary! and so ≤ 0.5 SN Ia/star,
- *and must* have total mass $m_{\text{tot}} > M_{\text{Chandra}}$,
- *and must* have short periods = close orbits

Relevant comparison:
SNIa ∼ 100% $3-8M_{\odot}$ close binaries $> M_{\text{Chandra}}$!

$\boxed{\text{Type Ia path must be dominant } 3-8M_{\odot} \text{ endpoint!}}$

→ strains all models!

Supernovae and Abundance Signatures

Core collapse:
  α-elements (^{16}O, ^{12}C, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S)
  Fe group (Ca, Fe, Ni)

Thermonuke:
  dominated by Fe group

Composition of an astrophysical object
gives clue to supernova contributors → past evolution
→ *abundances encode nucleosynthesis history*

Q: which occurs first in the universe? testable consequences?

Cosmic History of Supernova Nucleosynthesis

Evolution timescales very different:

- SN II: massive stars, short lived
- SN Ia: need WD → intermediate mass → longer lived

⇒ time ordering: first SN II, then later SN Ia

Solar system: mix of both `www: Solar Abundances`

oldest stars (globular clusters and "halo stars"):

→ SN II only and so expect

$$\left(\frac{\mathrm{O}}{\mathrm{Fe}}\right)_{\odot} = \frac{\mathrm{O}_{\mathrm{II}}}{\mathrm{Fe}_{\mathrm{II}}+\mathrm{Fe}_{\mathrm{Ia}}} \tag{1}$$

$$\left(\frac{\mathrm{O}}{\mathrm{Fe}}\right)_{\mathrm{halo}\star} = \frac{\mathrm{O}_{\mathrm{II}}}{\mathrm{Fe}_{\mathrm{II}}} > \left(\frac{\mathrm{O}}{\mathrm{Fe}}\right)_{\odot} \tag{2}$$

Observed!

also expect $(\mathrm{O/Si})_\odot \simeq (\mathrm{O/Si})_{\mathrm{II}}$

and so $(\mathrm{O/Si})_{\mathrm{halo}} \simeq (\mathrm{O/Si})_\odot$

Observed!