Astro 404
Lecture 40
Dec. 11, 2019

- Good news: no more problem sets!
- Bad news: **Final Exam Next Friday, Dec 13, 7:00-10:00pm**
  info on Compass
- graded Hour Exams available

Finale this week: binary stars and stellar explosions

most dramatic effect of binaries: mass transfer
Q: how can this occur?

Type Ia Supernovae

Type Ia Supernovae Observed

- *SN Type I* → *no hydrogen* in spectrum
- **Type Ia**: He, Si lines *are* seen
- peak luminosity: $\sim 1^{\rm mag}$ = factor 2.5 brighter than SN II
  → easier to find, probe larger distances (higher z)
- ejecta 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 can be long-lived: low/intermediate mass stars

- faster ejecta, brighter events → progenitors less massive

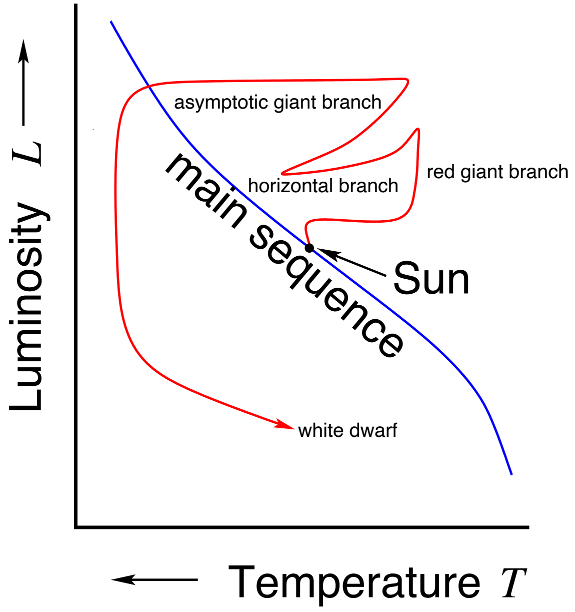
- regularity of light curves → fairly uniform path to formation

☞ 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 sequence:
1. H shell burn → red giant
2. He ignition: degenerate → explosive: *helium flash*
3. core expands, burns He → C+O
4. CO white dwarf forms (for $1 - 4 M_{\odot}$; see Director's Cut)

SN Ia: Thermonuclear Explosions

companion donates mass to white dwarf
- WD becomes denser, more relativistic
- when $M_{\rm WD} > M_{\rm Chandra}$: unstable! collapse begins
  ignites degenerate C burning ("carbon flash")

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

energy release:
- *nuclear burning* $^{12}{\rm C} \rightarrow {}^{56}{\rm Fe}$ gives
  $Q = B_{56}/56 - B_{12}/12 = 0.86$ MeV per nucleon
  if inner 50% of $M_{\rm Chandra}$ is carbon, then
  release $E_{\rm nuke} \sim QM_{\rm core}/m_u \sim 1.6 \times 10^{51}$ erg $= 1.6$ foe
- compare to core *gravitational binding:*
  for uniform sphere $E_{\rm grav} = 3/5\ GM_{\rm core}^2/R \sim 10^{50}$ 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 thermonuclear explosion:
all nucleosynthesis is from *explosive burning*
(in contrast to core-collapse case)
most of star "cooked" to $T \sim 1\text{MeV}$
driven to nuclear statistical equilibrium

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

- yields peak at $m_{\text{Ia,ej}}(^{56}\text{Fe}) \sim 0.5 M_{\odot}$
  $\sim 5 - 10$ 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

iClicker Poll: Progenitors of Type Ia Supernovae

All answers count! Your chance to prognosticate!

Which best describes the origin of Type Ia supernovae?

A single degenerate (giant companion) $> 80\%$ of SNIa

B single degenerate 50 to 80% of SNIa

C double degenerate (merging white dwarfs) 50 to 80% of SNIa

D double degenerate $> 80\%$ of SNIa

E none of the above

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

Supernovae and Abundance Signatures

Core collapse supernovae: massive star explosions

- observed as Type II, Ib, Ic events
- ejecta dominated by α-elements
  ^{16}O, ^{12}C, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{22}S
- less but still significant Fe group (Ca, Fe, Ni)

Thermonuclear supernovae: exploding white dwarfs

- observed as Type Ia events
- ejecta dominated by Fe group: Ca, Fe, Ni

Q: so what is the role of stars in making the periodic table?

Stellar Nucleosynthesis: Updated Scorecard

a good thing to take away from ASTR404 - hint!

element origins: the story thus far:

- *intermediate-mass stars:* $0.9 M_\odot \lesssim M \lesssim 8 M_\odot$
  sources of carbon (C)
  ejected in planetary nebulae
- *high mass stars*: $M \gtrsim 8 M_\odot$
  sources of α-elements O, Si, Mg, S
  ejected in core-collapse supernova explosions
- *exploding white dwarfs*:
  sources of iron-peak elements Ca, Fe, Ni
  ejected in thermonuclear supernova explosions

`www: periodic table and stellar origins`

Gamma-Ray Bursts

Gamma-Ray Bursts: Discovery

historical context: in late 1960's: *Cold War*

Nuclear Test Ban treaty–no explosions in atmosphere or space

US military: *Vela* satellites to monitor for air blast γ-rays

discovered signals at a huge rate: 10–20/year!

huge worry but quickly realized events are
extraterrestrial and indeed extrasolar

1973: Los Alamos *Vela* Group finally went public

"Observations of Gamma-Ray Bursts of Cosmic Origin"
Klebesadel, Strong, & Olsen 1973 ApJL 182, L85

hundreds (!) of different theories proposed over the decades

Gamma-Ray Bursts in the Compton Era

major advance: *Compton Gamma-Ray Observatory* 1991-2000
Burst And Transient Source Experiment (BATSE)
monitored all sky for ≈ 9 years, found:

- *event rate*: 2704 BATSE bursts seen
  → ~ 300 events/yr → 1 GRB/day!
- *no repeat events* from same direction
- *duration* (time above background): ~ 0.1 sec to $\sim 10^2$ sec
- time history (*lightcurves*): highly nonuniform
  some highly variable: 100% modulation on < 0.1 sec timescales!
  but others fairly smoothly varying
  `www: BATSE lightcurve sampler`
- *energy spectra*: typically $\epsilon_{\rm peak} \sim few \times 100$ keV
- *sky locations* only known to within $\sim 1^\circ$
  → too big a region to quickly search with telescopes
  → no counterparts seen at any other wavelengths!

What are they?!?

GRB Distance Scale and Sources

most models have either GRBs very local or very distant

Galactic models:
$\sim$ all observed bursts within our Galaxy

energetics requirements modest → neutron stars?

event rates high: many sources needed to give
$\sim$ daily, non-repeating event rate
bursts a very common, frequent occurrence in a galaxy

this was the favored model pre-BATSE

GRB Distance Scale and Sources

Galactic models: (favored pre-BATSE)
$\sim$ all observed bursts within our Galaxy
energetics requirements modest → neutron stars?
event rates high: many sources needed
  bursts a very common, frequent occurrence in a galaxy
compare: novae (accreting white dwarfs) $\sim$ 50 events/yr
  Galactic population, similar rate

Cosmological models:
bursts come from other galaxies, typically very distant:
  substantial fraction of max distance $\sim d_H$ *energetics* requirements enormous! $\gg$ SN baryonic energies
event rates low: only 1 GRB/day/observable Universe
  bursts a very rare occurrence in a galaxy

rate per galaxy $\sim 3 \times 10^{-5}$ GRB/century
compare: core-collapse supernova rate $\sim few$/century

Q: what information (from BATSE alone) would discriminate the Galactic vs cosmo pictures?

Implications of Variability

GRBs can be highly variable, with $\delta F/F \sim 1$
on the smallest observable timescales, $\delta t \sim 1$ msec

but if entire signal varies, has to reflect
coordinated behavior of *entire source*
i.e., source luminosity has $L = F_{\rm surface} A_{\rm emit}$
and so $\delta L/L \sim \delta A_{\rm emit}/A_{\rm emit} \sim 2\delta R_{\rm emit}/R_{\rm emit}$

in time δt, max change in emitting region $R_{\rm emit}$
is $\delta R \leq \delta R_{\rm max} = c\ \delta t$
and so given observed variability, can put *upper limit*
on source size: $\delta R_{\rm max}/R \geq \delta R/R \leq 1/2\ \delta L/L \sim 1/2$

$$R_{\rm emit} \lesssim 2R_{\rm max} = \frac{c\ \delta t}{2} \simeq 6 \times 10^7\ {\rm cm} = 600\ {\rm km} \ll R_\oplus, R_\odot$$

emitting region must be *tiny*!
compact source required – neutron star?! black hole?!

Implications of Sky Distribution

GRB positions not well-determined by gamma-ray data (BATSE)
localized to $\sim 1^\circ$

But for > 4700 bursts, *sky distribution* of events
carries important information

Q: expected distribution in Galactic model (very nearby, all-Galaxy)?

Q: expected distribution in cosmological model?

iClicker Poll: GRB Sky Distribution

All answers count! Your chance to prognosticate!

Which will best describe the GRB sky distribution?

A most events trace Galactic plane → arise in Milky Way

B most events come from all directions → isotropic → cosmological

C will see two components: plane and isotropic

D none of the above

Observed GRB Sky Distribution

`www:  BATSE sky distribution`

isotropic to very high precision
no correlation with Galactic plane

much more simply explained in cosmological model
thanks to Cosmological Principle

in Galactic model: very difficult to avoid anisotropy

- either sources *very* close: $d \ll$ disk scale height ~ 100 pc
- or sources in Galactic "halo"
  spherical configuration, much larger than $R_\odot \sim 10$ kpc
  … but must avoid signal from M31…

Director’s Cut Extras

Fate of a CO Core

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

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

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

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

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 $> M_{\text{Chandra}}$!

Type Ia path must be dominant $3-8M_\odot$ endpoint!

→ strains all models!

History of Nucleosynthesis

Composition of an astrophysical object
gives clue to supernova contributors → past evolution

abundances encode nucleosynthesis history

compare the two supernova classes:
- core-collapse (Type II, Ib, Ic)
- thermonuclear (Type Ia)

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

Evolution 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 SN II patterns in heavy elements (high O/Fe)
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!