Astro 596/496 NPA

Lecture 35

Nov. 16, 2009

Announcements:

- Preflight 6 was due at noon today
  last preflight! party like it's 1999!

Last time: Type Ia Supernovae

Q: how are they similar to core-collapse supernovae?

Q: how are they different?

Q: what are the main theoretical uncertainties about Type Ia progenitors?

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 lost to winds and/or Roche lobe overflow
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
  $\rightarrow$ limits imply companion must be dim $\rightarrow$ 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 $\tau_{\text{inspiral}} < t_0$
  ...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 $-$ 8$M_\odot$ star death rate

but SNIa candidates

- *must* (?) be in binaries ... and can't double-count: $\leq$ 1 SN Ia per binary! and so $\leq$ 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 $\sim$ 100% 3 $-$ 8$M_\odot$ close binaries $> M_{\text{Chandra}}$!

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

$\longrightarrow$ strains all models!

LISA and the Coming Binary White Dwarf Revolution

close WD-WD binaries have significant energy loss
by **gravitational radiation**
signal frequency $\sim$ orbit frequency
close binaries $\rightarrow$ short period $P \sim$ minutes–hours
$\Rightarrow$ gravity wave frequencies $\nu_{\rm gw} \sim P^{-1} \sim 10^{-4} - 10^{-2}$ Hz
$\Rightarrow$ out of ground-based (LIGO) range,
but detectable in space by *LISA* (launch in 10 yrs?)

LISA WD-WD binary forecast (R. Webbink et al)

- $\sim$ 3600 close WD-WD binaries seen
- parameters (mass, binary orbits) found for each
- WD-WD population statistics measured
  $\Rightarrow$ *check feasibility of WD-WD $\rightarrow$ SN Ia !*
- near-merger events should produce strongest signal
- can forecast next merger to within $\sim \pm 1$ year!
  SN Ia "early warning system" ?!

Supernovae and Abundance Signatures

Core collapse:
α-elements (^{16}O, ^{12}C, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{22}S)
Fe group (Ca, Fe, Ni)

Thermonuke:
dominated by Fe group

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

 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 $\rightarrow$ intermediate mass $\rightarrow$ longer lived

$\Rightarrow$ time ordering: first SN II, then later SN Ia

Solar system: mix of both `www: Solar Abundances`
Halo stars: old $\rightarrow$ SN II only and so expect

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

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

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!

Beyond the Iron Peak

Beyond the Iron Peak

`www: Solar Abundances`

if all heavy elements made only in
burning to nuclear statistical equilibrium
then should follow Fe peak, fall dramatically at high A
$\longrightarrow$ would have much less of the very heavy elements

How to synthesize nuclei with $A >$ iron peak?
- Coulomb barrier $\propto Z^2$ prohibitive
- fusion reaction *not* exothermic

Yet silver, gold, lead, uranium, ... all exist!
$\longrightarrow$ nature has found a way

Q: Suggestions?

Solution: **neutrons**

- no Coulomb barrier
- capture reactions occur even at small thermal speeds

Today: nuclear physics of n capture processes

Then: astrophysics

Neutron Capture Processes

To see basic physics:

(1) "let there be neutrons"

(2) assume a heavy "seed" nucleus (e.g., ^{56}Fe)

(3) ignore charged particle rxns (Coulomb suppressed)

Q: if add n to seeds, expect...?

`www: chart of nuclides`

Neutron capture physics set by competition

- neutron capture $n + (A, Z) \rightarrow (A+1, Z) + \gamma$
- β decay $(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$

Two regimes (BBFH 1957; Cameron 1957):

capture rate $\gg$ decay rate

$\Rightarrow$ rapid capture: *r*-process

decay rate $\gg$ capture rate

$\rightarrow$ slow capture: *s*-process

Detective story:

- do these limiting cases occur? (*Yes!*)
- what are astrophysical sites?

n Capture Rates

n-capture cross sections:

typically, $\sigma \propto 1/v$

- enhanced at low energies!
- $\sigma v = \langle \sigma v \rangle = const$ $\rightarrow$ T-indep!
- fails for magic nuclei:

  tightly bound $\rightarrow$ small σ

Implications?