Astro 596/496 NPA

Lecture 34

Nov. 13, 2009

Announcements:

- Preflight 6 due *Monday* noon

Last time: gamma-ray burst populations and physics

Q: what evidence is there for two GRB populations?

Q: how are the populations different?

Q: what's the observed GRB–supernova association?

Q: what's the leading theory model for this?

Q: what should go into a theory model for the other GRB class?

Short-Hard Bursts

short-hard bursts:

- fewer bursts seen: $\sim 30\%$ of BATSE catalog
  closer? intrinsically fainter? both?
- few afterglows seen, not in active star-forming regions
  and many seen in elliptical galaxies
  $\rightarrow$ come from older population

What are the astrophysical sources?

neutron star mergers with other neutron stars or black holes

`www: Illinois Shapiro group GR merger simulation`

- neutron star "kicks": up to $\sim few \times 100$ km/s at explosion
  $\rightarrow$ ejected from disk
- gravitational inspiral time long
  $\rightarrow$ mergers not connected to star formation
- possible sources of gravitational radiation

GRBs as Cosmic Engines and Probes

⋆ GRB prompt emission and afterglow as searchlights:
like quasars, but temporary, and more democratically distributed
$\longrightarrow$ probe of galactic, intergalactic medium at high z

⋆ long-soft bursts connected with supernovae/star formation
$\longrightarrow$ tracers of cosmic star-formation rate at high redshift?

⋆ GRBs could be sources of high-energy ($\gtrsim$ 1TeV) neutrinos

⋆ GRBs could be sources of ultra-high-energy
($\gtrsim 10^{19}$ eV) cosmic rays

Gamma-Ray Bursts: Open Questions

much recent progress, but still many open questions

- what are the "central engines" of short-hard bursts?
- are all long-soft bursts connected with supernovae?
  are there long-lived signatures of these? elements? remnants?
- why don't all supernovae make bursts?
- what drives the relativistic jets?
- what is emission mechanism for the γ-rays? still unclear!
- *Swift* afterglow lightcurves show great diversity
  and unexpected color-dependent breaks–what's going on?

Job security! Stay tuned!

Type Ia Supernovae

Type Ia Supernovae

Thus far:

core collapse/ "Type II" SN (massive star)

but also: "Type Ia"

Light curves (brightness vs time):

- good news: all roughly similar
- bad news: real variations seen

  `www: SN Ia light curves`
- good news: peak luminosity, decay timescale *correlated*

$\longrightarrow$ given timescale, infer luminosity

$\longrightarrow$ *standard(izable) candle*! enormously important for cosmology

Type Ia Supernovae Observed

- SN Type I $\rightarrow$ no H in spectrum
- Type Ia: He, Si lines *are* seen
- peak luminosity: $\sim 1^{\mathrm{mag}}$ = factor 2.5 brighter than SN II
  $\rightarrow$ easier to find, probe larger distances (higher z)
- ejecta somewhat faster than Type II events
- blast energies ~ 1 foe
- 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 $\rightarrow$ "stripped" star
  need either wind or companion
- found in all galaxies
  $\rightarrow$ not correlated with active in star formation
  $\rightarrow$ progenitors not short-lived: low/intermediate mass stars
- faster ejecta, brighter events $\rightarrow$ progenitors less massive
- regularity of light curves $\rightarrow$ 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

after main seq:

1. H shell burn → RGB
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:

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