Astro 404

Lecture 41: Course Finale

December 8, 2021

Announcements:

- Final Exam Mon Dec 13, 1:30–4:30 pm
  info is on Canvas
- **please fill out ICES form!**
- Participation scores: many posted, a few yet to go

Last time: binary star–Type Ia supernovae

Q: What is exploding? What are dominant elements produced?

Type Ia Supernovae: White Dwarf Explosions

all viable scenarios invoke:

⋆ *binary system*

⋆ a *white dwarf*, usually a CO dwarf

if WD in close binary/merger:

- companion donates mass
- when $M_{\rm WD} > M_{\rm Chandra}$: unstable
- WD detonates, most of star $\rightarrow$ *iron group elements*

white dwarf entirely unbound, disrupted, ejected

- Type Ia should leave *no compact remnant*
- all nucleosynthesis products ejected

Summary: 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, ^{32}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
  $\rightarrow \sim 300$ events/yr $\rightarrow$ about 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
- *sky locations* only known to within $\sim 1^\circ$
  $\rightarrow$ too big a region to quickly search with telescopes
  $\rightarrow$ no counterparts seen at any other wavelengths!

What are they?!?

GRB Distance Scale and Sources

Galactic models: (favored pre-BATSE)
$\sim$ all observed bursts within our Galaxy
energetics requirements modest $\rightarrow$ neutron stars?
event rates high: many sources needed
  bursts a very common, frequent occurrence in a galaxy

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

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 $\rightarrow$ arise in Milky Way

B most events come from all directions $\rightarrow$ isotropic $\rightarrow$ 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

1997: cosmological origin confirmed
- X-ray "afterglow" detected following γ-rays
- distant galaxy seen as host!

GRB Populations: Two Classes

BATSE bursts show:

- clear bimodal separation in timescale
  separation at $T_{90} \simeq 2$ sec
- **two GRB populations**
  ⋆ **short bursts** ⋆ **long bursts**

Extras today summarize detective work:

- long bursts – most (all?) from *rare supernova explosions*
- short bursts – likely from mergers of two neutron stars

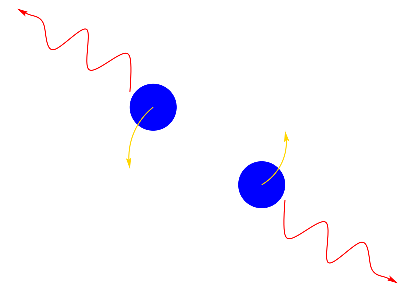
GRAVITY AND LIGHT

GW 170817 and GRB 180817A

GW 170817

LIGO: Laser Interferomert Gravitational Observatory `www: LIGO`

first gravitational wave events discovered
were BH-BH mergers $\sim 30 M_\odot$ binaries (!!!)



August 17, 2017: event seen by LIGO-Virgo

gravitational wave signal detected for $\sim$ 100 sec

`www: observed gravitational radiation signal`

- longest gravitational wave duration seen to date
- inspiral phase, frequency increases until out of bandpass
  gravity waves did not observe coalescence
- initial mass estimates: $0.86 - 2.26 M_\odot$ $\rightarrow$ neutron stars!

GRB 170817A

Fermi satellite detected gamma ray burst

- ~ 2 sec after LIGO signal
- duration ~ 2 sec

other telescopes found event in direction of the GRB
distance: 40 Mpc, consistent with gravity waves!
blue point source in outskirts of elliptical galaxy NGC 4993
`www: discovery images`

implications:

- off axis view of GRB jet
- lower-energy EM emission not from jet
  but from the merged NSs: **kilonova/macronova**

Kilonova/Macronova

theory predictions for binary neutron star merger outcome
merger matter sorted by angular momentum

- **central object:** lowest angular momentum matter
- **black hole**, or
  rotationally supported **hypermassive neutron star**
- magnetized, spinning $\rightarrow$ **relativistic magnetized jet**

- **accretion disk:** drives hot, low-density wind
  of expanding neutron star matter: expected EM signal!

- **dynamically ejected matter**: $v \sim 0.10 - 0.3c$
  expanding neutron star matter: expected EM signal!

- kilonova powered by decompressing neutron star matter
  likely in the process of forming the heaviest elements!

Gravitational Wave Emitters–Summary

LIGO has detected gravitational radiation bursts since 2015 and found 3 classes of sources `www: LIGO summary`

- **binary black holes** - first source detected, Nobel Prize 2017
  mergers of $\sim 30 M_\odot$ black hole pairs!
  by far these are most LIGO sources, found about 1 per week

- **binary neutron stars** - first found 2017
  two solid detections so far

- **neutron star–black hole binaries**
  first found in 2019
  one solid detection so far

many open questions: what sources make $30 M_\odot$ black holes?
what is the EM signal from a NS-BH binary?
is there an EM signal from a BH-BH binary

Finale

Stellar Nucleosynthesis: Final Scorecard

a good thing to take away from ASTR404 - hint!

stars make most of the periodic table:

- *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
- *neutron star mergers*:
  important sources of heaviest elements: Pt, Au

`www: periodic table and stellar origins`

The Next Ten Years in Stellar Astrophysics

Your predictions were great! Sampler follows–sorry not time to mention everyone's.

⋆ We [will have] higher resolution image of black holes

⋆ With Vera Rubin/LSST and the James Webb telescope, supernovae questions will be answered. We could hopefully have more observations of failed supernovae ... and FRBs (fast radio bursts) could also be precisely localized in the sky.

⋆ [T]ens of habitable planets or moons, new exoplanets, stars and planetary systems, and what is truly on the other side of a black hole

⋆ [*Gaia* will] gain insight into the history of stars in our galaxy. Maybe it will also some questions about dark matter

⋆ Tthe next decade will see an explosion of black hole and planetary detection. ... [We]will see an image of SgrA* ... at the end of 20 years, an inkling of a quantum gravity theory will emerge.

⋆ I think the future of stellar astrophysics is going to be influenced by alternative methods of stellar observation. With the Hyper-Kamiokande and KM3NeT being built, I see us better understanding neutrinos and their properties. With these neutrino detectors, they can warn us about imminent supernovae.

⋆ I think the future of stellar astrophysics can be dominated by multi-messenger studies... LSST will allow us to look into the time-domain... And with neutrinos and gravity waves, we can even "listen" to the stars in another way.

★ *Gaia* [will] provide the positions and radial velocities of most or all stars in the Local Group.

★ Event Horizon Telescope expands on the potential of observing black holes on future research... Since black holes have just been able to be observed by mankind, I expect there will be surprising discoveries on the identity and physical properties of black holes

★ We will discover new gravitational waves from merger events that we would have never thought of ... we will learn the most about the remnants of supernovae like black holes. [...] The possibilities are endless for what we would discover in the next 10 to 20 years, this is really exciting.

★ I suspect that some will be surprised how everything ties to the formation and evolution of stars. Stars are after all the "star" of the show!

Thank You!

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 $M_{\text{core}} > M_{\text{Chandra}}$: core contracts, burn to O, Ne, Mg results in ONeMg white dwarf

thus: CO white dwarfs are outcomes of $\sim 1-4M_{\odot}$ 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 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 $m_{\mathrm{tot}} > M_{\mathrm{Chandra}}$,
- *and must* have short periods = close orbits

Relevant comparison:

SNIa ∼ 100% $3-8M_{\odot}$ close binaries $> M_{\mathrm{Chandra}}$!

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

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

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

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

$\rightarrow$ SN II only and so expect SN II patterns in heavy elements (high O/Fe)

Observed!

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

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

Observed!

Implications of GRB 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 $L = F_{\text{surface}} A_{\text{emit}}$
and so $\delta L/L \sim \delta A_{\text{emit}}/A_{\text{emit}} \sim 2\delta R_{\text{emit}}/R_{\text{emit}}$

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

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

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