Astro 404

Lecture 41: **The Final Frontier**

Dec. 11, 2019

- **Final Exam Next Friday, Dec 13, 7:00-10:00pm**
  info on Compass
- graded Hour Exams available
- Problem Sets will all be graded soon

Today: Sprint to the Finish!

Last time: gamma-ray bursts (GRBs)

Q: what are their key observed properties: observed rate flux vs time (light curve), spectrum, duration?

Q: implications of Galactic vs extragalactic GRB origins?

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
  `www: BATSE lightcurve sampler`
- *energy spectra*: typically $\epsilon_{\rm peak} \sim few \times 100$ keV
- *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 $\sim d_H$ *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

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: $\delta R_{\rm max}/R \geq \delta R/R \leq 1/2\ \delta L/L \sim 1/2$

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

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

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**

host galaxy correlations:

- long bursts found in regions of active star formation
- short bursts found in elliptical galaxies

∞ *Q: and so?*

Long GRBs and Supernovae

hints of supernova association with long-soft bursts:

- given beaming; long-soft burst energetics, rate in line with supernova blasts
- long-soft bursts found in regions of active star formation

direct evidence: supernova outbursts seen in GRB afterglows!

- SN 1998bw seen in unusually low-energy GRB 980326
- SN 2003dh seen in "vanilla" GRB 030329
- supernova spectra derived → no H, He I, Si II; lines all broad consistent with relativistic ejecta

all GRB-linked supernovae are Type Ic

very massive star, winds/companion remove outer layers

...but not all Type Ic make GRBs

Collapsar Model

How does a supernova make a GRB?

collapsar model (Woosley)

- very massive progenitor, rapid rotation
- black hole formed in core, ang momentum $\rightarrow$ accretion disk
- relativistic jet created, punctures star `www: jet simulation`

What makes the jet?

magnetohydrodynamic effects in GR?

`www: Illinois Shapiro group GR magnetohydrodynamic collapse simulati`

Short Bursts: Status Before 2017

short 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

GRAVITY AND LIGHT

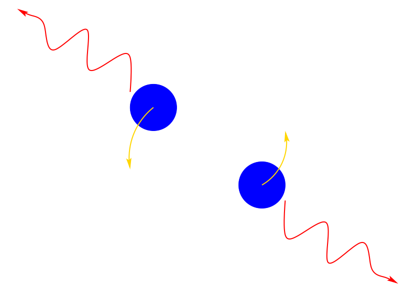
GW 170817 and GRB 180817A

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/GBM detected gamma ray burst

- ~ 2 sec after LIGO signal
- duration ~ 2 sec
- hard-ish spectrum
- with some evidence of another gamma outburst 2 sec later

Swift: behind Earth during event

isotropic energy: 2 orders of magnitude smaller
than any other GRB with measured distance
Q: implications?

with gamma-rays localization drastically improved!
launched EM followup at other wavelengths

EM Counterpart

LIGO+*Fermi* location errorbox searched by many telescopes
prioritized by nearby star-forming galaxies with high stellar mass

electromagnetic event discovered independently by many groups
blue point source in outskirts of elliptical galaxy NGC 4993
`www: discovery images`

distance: 40 Mpc, consistent with gravity waves!

EM emission much brighter than known short GRB afterglows

implications:
- off axis view of GRB jet
- lower-energy EM emission not from jet
  but fron central engine: **kilonova/macronova**

Neutron Star Mergers and Gamma-Ray Bursts

production: two scenarios (at least)

- binary massive stars, neutron stars survive explosions
- in star cluster, single neutron stars gravitationally settle to center, then become bound

evolution:

orbit inspiral - decay via gravity wave emission

known progenitor: binary pulsar

orbit decay observed, matches gravitational wave prediction

Nobel Prize 1993: Hulse and Taylor

fate:

coalescence: hypermassive neutron star? black hole?
gravitational wave amplitude rises to burst
then decays in "ringdown"

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:* $0.9M_\odot \lesssim M \lesssim 8M_\odot$
  sources of carbon (C)
  ejected in planetary nebulae
- *high mass stars*: $M \gtrsim 8M_\odot$
  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`

Prognostications: The Next Galactic Supernova

There will be a next Galactic supernova. When?

A 2019 to 2029

B 2030 to 2049

C 2050 to 2079

D 2080 or after

Answers will be archived for later bragging rights!

The Next Ten Years in Stellar Astrophysics

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

⋆ EHT will produce images of SgrA*

⋆ confirmation or denouncement of the "supernova imposter" that arises from incredibly massive stars.

⋆ Maybe stellar astrophysics, especially black holes, will be a way to probe/confirm theories that include a particle explanation for gravity.

★ *Gaia* might help astrophysicists in delving deeper into the galactic structures by providing detailed information about the parallaxes and by mapping the structure and composition of galaxies.

★ I think we will have a lot more information about supernovae, because of the upcoming LSST pictures of the sky.

★ With the success of the EHT, I would expect the next decade to be a period of discovery for black hole physics.

★ I think that coronal heating problem regarding why the Sun has a corona that is far hotter than its surface will solved, since NASA is taking steps to observe the causes behind it experimentally.

$\star$ LSST will be used to look at the Milky Way– specifically the interplay between galactic evolution and stellar evolution through metallicity will be probed by looking at the galactic center.

$\star$ I expect (or at least hope) that stellar astrophysics will become a necessary complement to particle physics because stars are a display of all four fundamental forces and a range of energy scales.

$\star$ a core-collapse supernova will explode in the Milky Way!
multimessenger detections: gravity waves, neutrinos, radio to γ-ray photons

$\star$ Unexpected discovery makes our predictions look quaint
"I have no idea what surprises are in store (that's what makes them surprises!)."

Thank You!