GAMMA RAYS

PROBLEM SET #6 ON WEBWORK – DUE WEDNESDAY AT MIDNIGHT

EXAM #2 ON THURSDAY

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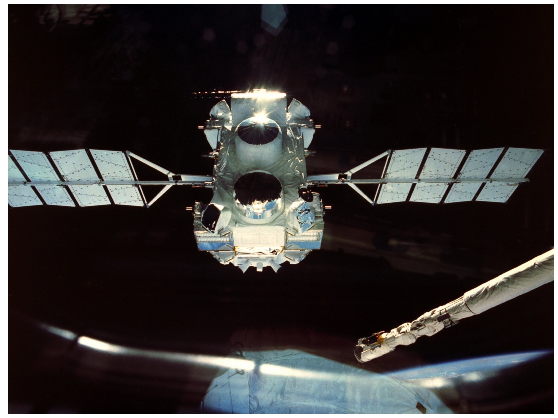
- 1 hr 15 min exam in class, open book and open notes
- Things that you should DEFINITELY bring with you:
  - Writing utensil (pencil or pen – blue or black ink)
  - Calculator
- Things that you should probably bring with you:
  - Lecture notes
  - Laptop or tablet (so that you can access the WeBWorK homework problems and the “How Big is That?” sheet on the class website)
- Practice exam available on WeBWorK – email me when you want solutions
- REVIEW SESSION – Wednesday, 11/6, at 7:30pm in B&L 372

GAMMA RAYS

Gamma-ray bursts: a longtime mystery, now seen as black hole formation



The NASA Compton Gamma-Ray Observatory (GRO) shortly after deployment in 1991 by the crew of the space shuttle Atlantis (NASA/Marshall Space Flight Center)

GAMMA-RAY BURSTS

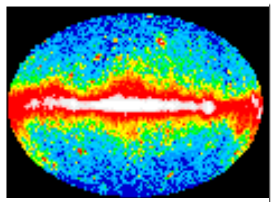
In the mid-1960s, after ratification of the Nuclear Test-Ban Treaty, the US and USSR each put up satellites (the *Vela* and *Konos* satellite groups, respectively) with X- and γ-ray detectors to monitor the other's compliance with the treaty.

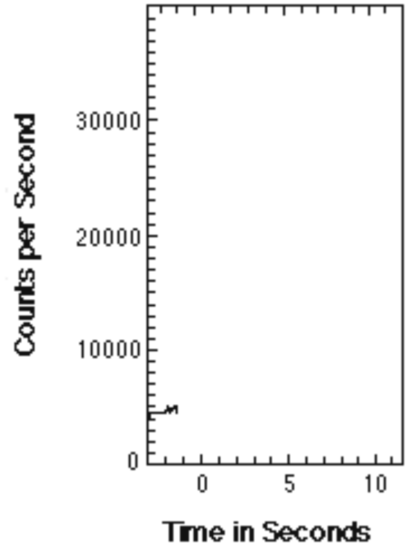
- These instruments immediately detected many brief, bright **bursts** of γ-rays, similar to the expectations for above-ground nuclear detonations. Naturally, this worried all concerned, even though the bursts were not correlated with seismic events.
- The satellites could not determine the direction from which the γ-rays came very well, so it took some time to determine that they actually came from outer space rather than Earth. (Even then, the data remained top secret until the mid-1970s.)

TYPICAL "LONG" GAMMA-RAY BURST

Detections of many brief, bright **bursts** of γ-rays.

Full-sky γ-ray image, arranged so that the Milky Way lies along the "equator." (CGRO/NASA)

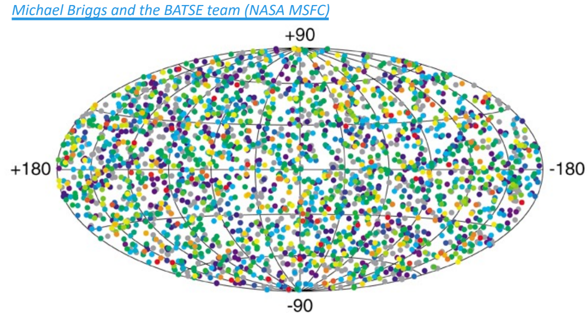


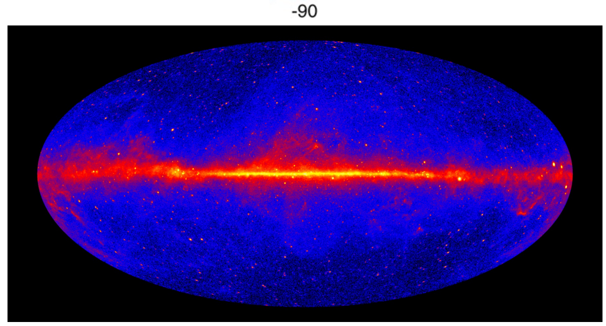


GAMMA-RAY BURSTS

- The γ-ray bursts come from locations spread randomly and uniformly all over the sky. This is very different from non-burst γ-ray sources.
- Bright sources of γ-rays: neutron stars or black holes?
- There is no tendency for the γ-ray bursts to cluster in the Milky Way, which would be the case if their sources were stellar remnants.

Michael Briggs and the BATSE team (NASA MSFC)



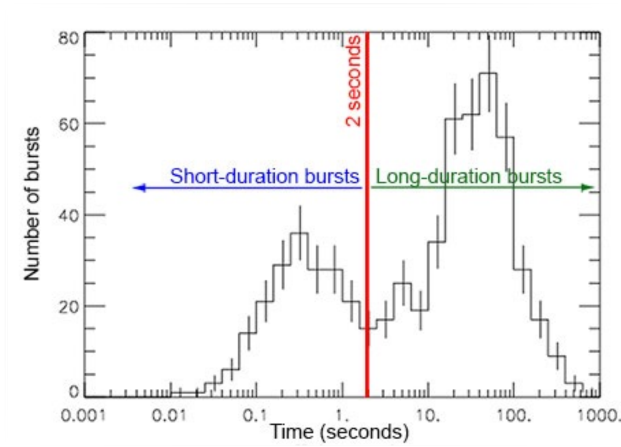


The sky in γ-rays (NASA/DOE/Fermi LAT collaboration)

TWO TYPES OF γ-RAY BURSTS

The γ-ray bursts come in two major varieties: long (> 2 s, typically 30 s) and short (typically 0.01-0.1 s).

- The short bursts are also less luminous and emit a larger fraction of their γ-rays at the highest energies observed than the long bursts.



Histogram of BATSE γ-ray bursts

ANALYSIS OF THE GAMMA-RAY BURST DISTRIBUTION

Obviously, γ-ray bursts are not as numerously distributed throughout our galaxy as the stars are. What other explanations are there?

- **Very nearby objects** that are evenly distributed on the sky, like the very nearest stars, or the cloud of comets surrounding the Solar System.
  - But how would these objects emit γ-rays?
- **Very distant objects.** Distant galaxies and galaxy clusters are evenly distributed on the sky.
  - But if the γ-ray bursts are *that* far away, their energy outputs are (problematically) enormous.

THE BEPPOSAX AND *SWIFT* SATELLITES

In 1996, the Italian and Dutch space agencies launched BeppoSAX, a satellite observatory designed (in part) to detect X-rays from some γ-ray bursts.

- X-ray telescopes *can* be made, though with difficulty. (As you know, X-rays are good at passing unhindered through matter, too, so they are also difficult to reflect or refract.)
- The hope was that, for each γ-ray burst, they could find a corresponding, bursting or fading, X-ray source and measure its position.
- It worked. About 1 out of every 20 γ-ray bursts found by BATSE were also detected and localized by BeppoSAX, and the position was made available to observers on the ground within hours.

RESULTS OF VISIBLE-LIGHT OBSERVATIONS OF BEPPOSAX POSITIONS

Follow-up observations showed that the sources of γ-ray bursts live in distant galaxies.

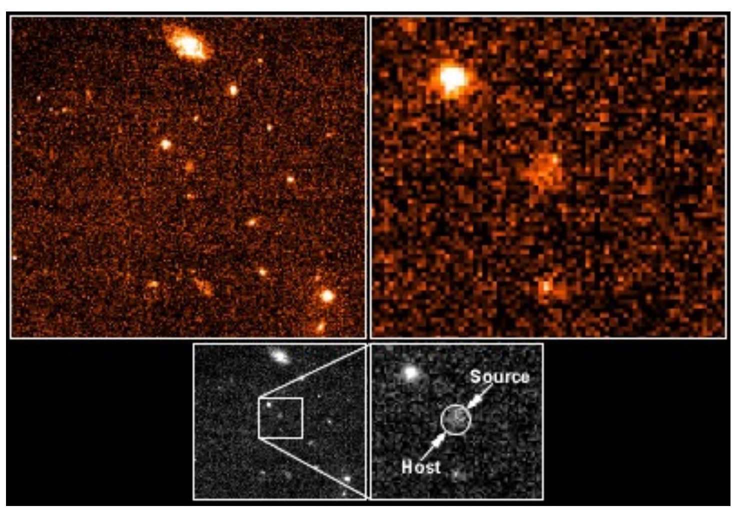
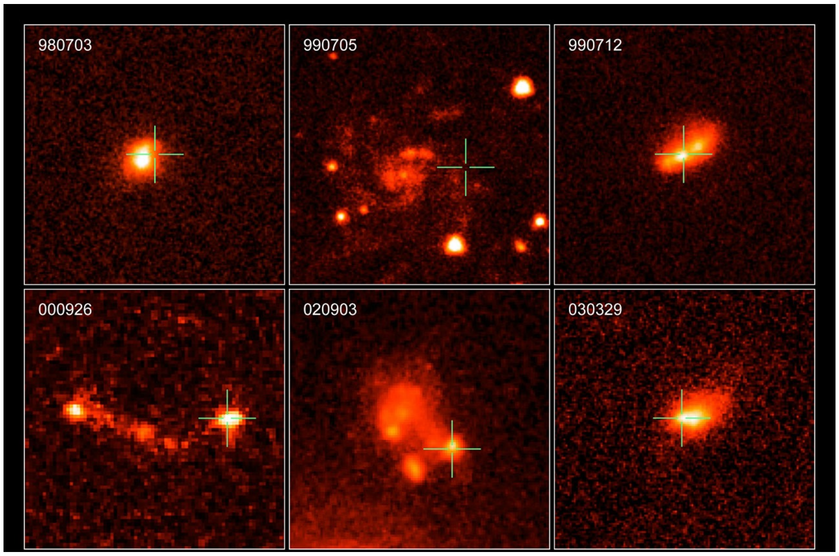


Image of the γ-ray burst of February 28, 1997, taken with the STIS instrument on the HST on September 5, 1997 ([Andy Fruchter, STScI/NASA]())



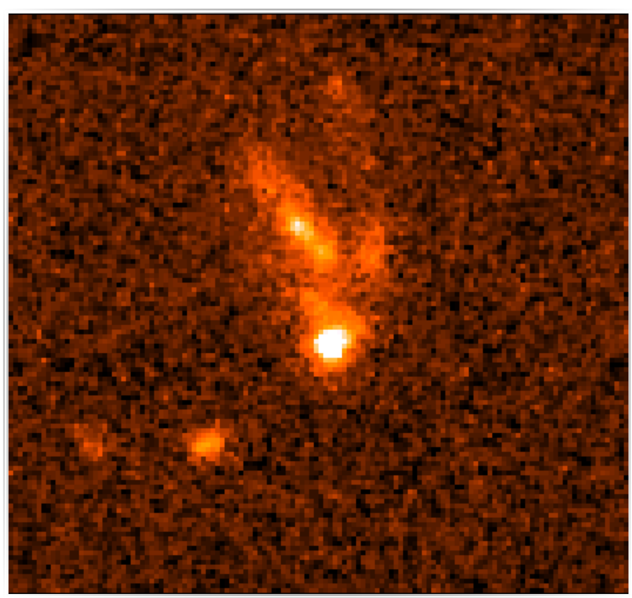
γ-RAY BURSTS ORIGINATE IN DISTANT GALAXIES

Green crosses indicate where the bursts were seen; all lie within distant galaxies (Andy Fruchter, STScI)

LONG BURSTS OCCUR IN STAR-FORMING REGIONS

Their afterglow resemble supernovae.

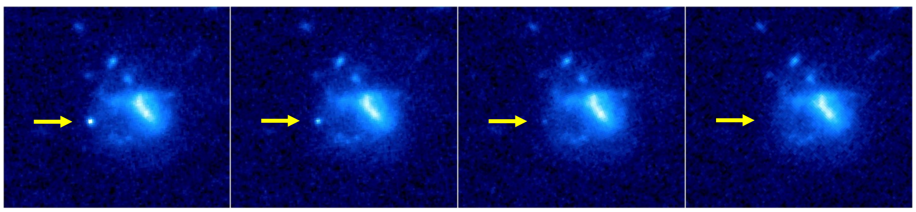
Images of the γ-ray burst of January 23, 1999, taken with the STIS instrument on the HST 16, 59, and 380 days after the outburst (Andy Fruchter, STScI). It faded at the same pace supernovae do.



SHORT BURSTS DO NOT

The NASA *Swift* satellite, launched in 2004, was built with visible-UV (UVOT) and X-ray (RAT) telescopes along with a γ-ray detector (BAT) that can sort more finely by burst duration.

- *Swift* has found and localized many more GRBs than was previously possible, including examples at the greatest distances at which galaxies have been detected.
- *Swift* also localized short bursts for the first time and showed that they do *not* resemble supernovae.



Visible afterglow of the short γ-ray burst of 7/9/2005, pictured by HST 6, 10, 19, and 35 days after Swift discovered it. It fades too fast to be a supernova. (Derek Fox, Penn State U.)

EXTRAGALACTIC ORIGIN: γ-RAY BURSTS ARE EXTREMELY ENERGETIC

The spectrum of the galaxy at which the γ-ray burst of January 23, 1999 lives indicates that its distance is 9 billion light years.

- At that distance, the γ-ray burst amounted to an energy of $\mathbf{3{\times}10^{54}}$ **erg** in γ-rays along, if it emitted its energy uniformly in all directions.
- For scale: that is equivalent to a mass of

$$M = \frac{3{\times}10^{54}\,\mathrm{erg}}{c^2} = 3.3{\times}10^{33}\,\mathrm{g} = 1.7M_{\odot}$$

suddenly (in a span of about 40 seconds) converted completely into γ-rays.

γ-RAY ENERGY IS PROBABLY LESS THAN THAT…

- The most efficient way to produce lots of γ-rays quickly is in **shock waves** within exploding relativistic jets.
- Assuming, therefore, an explosion violent enough to be relativistic, and noting that relativistic objects tend to emit light mostly in the direction they are going…
  - As is the case with quasar / radio galaxy radio jets.
- …the same brightness could be produced with a smaller energy: smaller by a factor of about $1-\frac{V^2}{c^2}$, where V is the outward speed of the explosion.
- That reduces the energy requirement to about **10^{52} erg**. Still a huge amount of energy, considering the short time and the fact that it is **all γ-rays**.

WHAT ARE THE SOURCES OF γ-RAY BURSTS?

10^{52} erg is an awful lot of energy to release in less than one minute, and γ-rays are an extreme form for the energy to assume.

- 10 ordinary supernovae account for this much emitted light, but it would take months and would do so at much longer wavelengths.
- The entire Milky Way galaxy emits this much light in about 10 years, but it also does so with much longer wavelength light.

So, it is difficult to imagine how to do this with normal stellar processes. But, now we know about more powerful tools. How about:

- **Accretion of a very massive compact object by a black hole** (compact, so the accretion does not take very long) and radiation of much of its mass energy?
- **Formation of a rapidly-spinning black hole,** and driving a relativistic expansion with its ergosphere? (Requires strong magnetic fields threading the ergosphere.)

LEADING CONTENDERS FOR THE SOURCES OF γ-RAY BURSTS

- **Binary neutron stars,** coalescing to form a black hole? *Observationally confirmed as a source of short bursts.*
- **Neutron star – black hole binary,** with the neutron star captured by the black hole?
- **Hypernova (a.k.a. Collapsar)**: collapse of a very massive $(50 - 120M_\odot)$ star to form a black hole, accompanied by a supernova-like explosion?
  - *Currently-favored model for long bursts*
  - Works even better with collapse that follows soon after a binary-star merger

Maybe all three mechanisms are represented among the sources. All involve black hole formation or growth. All three naturally produce rapidly spinning black holes. **All should be rare processes.**

FATES OF THE MOST MASSIVE STARS

CXO/CfA/NASA

$150M_\odot$

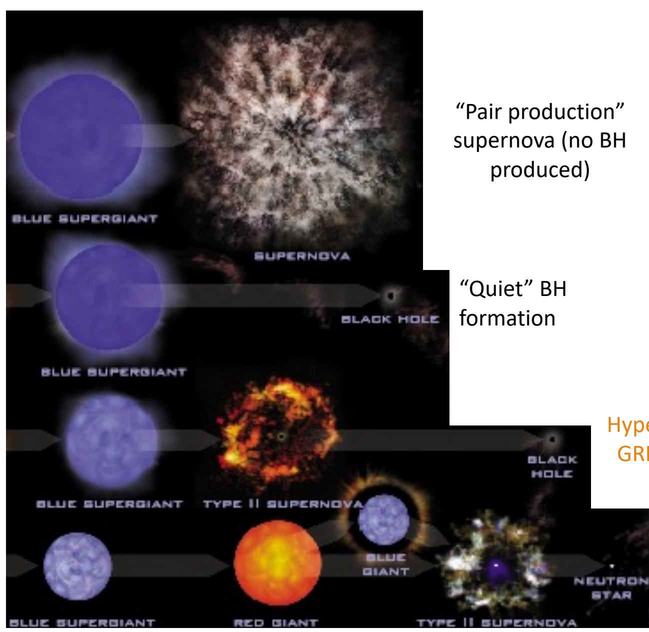
$120M_\odot$

$100M_\odot$

$50M_\odot$

$20M_\odot$

$10M_\odot$



"Pair production" supernova (no BH produced)

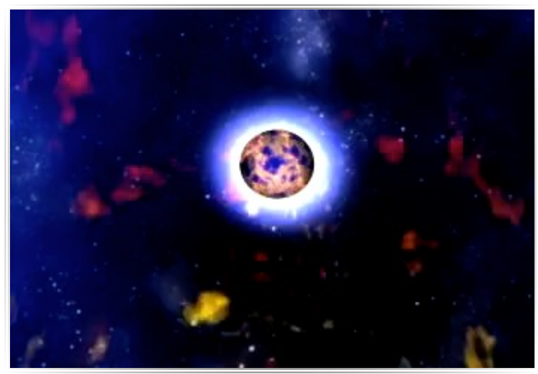
"Quiet" BH formation

Hypernova/ GRB/SN II

Ordinary SN II

GW170817 – A NS-NS MERGER

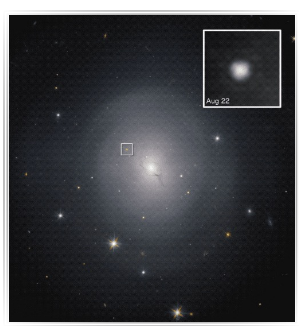
- On August 17, 2017, LIGO and VIRGO detected a gravitational wave signal, the intensity and frequency of which matched the theoretical values for a NS-NS merger.
- 1.7 seconds after the GW reached us, Fermi and *INTEGRAL* detected a short GRB coming from the same region in the sky.

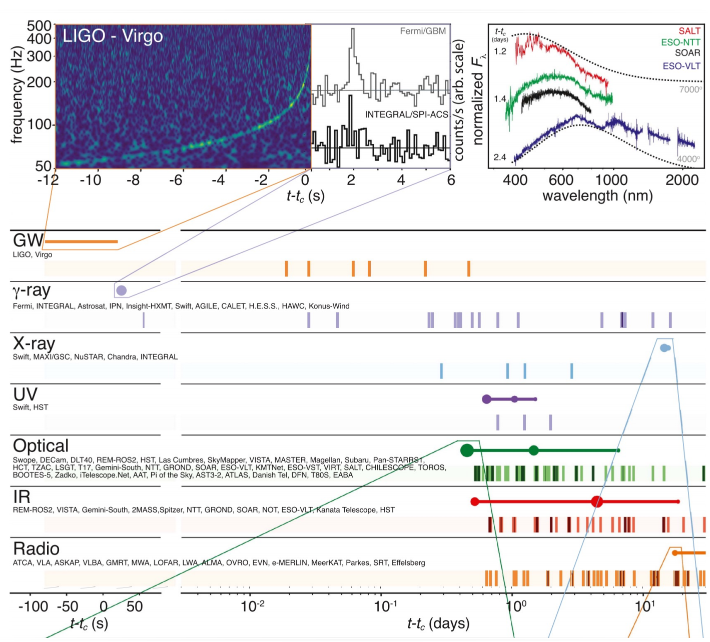


Artist's impression of a NS-NS merger (Dana Berry, NASA)

GW170817 – A NS-NS MERGER

Follow-up observations were made with numerous telescopes over the following hours, days, and weeks across the EM spectrum. These observations were consistent with the debris ejected from a NS-NS merger (a fast-moving, rapidly-cooling cloud of neutron-rich material).





BLACK HOLE FORMATION?

SN 2006gy, in NGC 1260 (238 Mly away) was the most luminous supernova ever observed (100 times more luminous than the naked-eye SN 1987a, a Type II SN). *Swift* detected no γ-ray burst, but a relatively weak X-ray emission is seen in the afterglow.

Which of the following is SN 2006gy most likely to be?

A. An ordinary (I or II) supernova

B. A NS-NS or NS-BH merger

C. BH formation from stellar collapse (plus hypernova)

D. An extraordinary supernova, but not linked to BH formation

BLACK HOLE FORMATION?

On March 19, 2008, a simultaneous burst was seen by *Swift* at γ, X, and UV wavelengths, and by the Pi of the Sky camera at visible wavelengths. The brightest part of the burst – bright enough to have been seen with the naked eye – was about 30 seconds long.

Which of the following events is this most likely to be?

A. An ordinary (I or II) supernova

B. A NS-NS or NS-BH merger

C. BH formation from stellar collapse (plus hypernova)

D. An extraordinary supernova, but not linked to BH formation