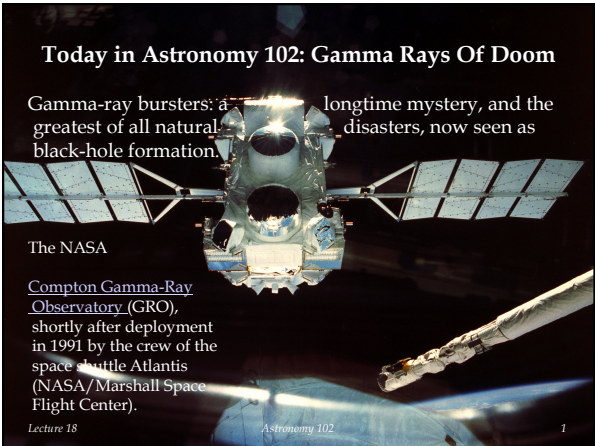**Today in Astronomy 102: Gamma Rays Of Doom**

Gamma-ray bursters: a   longtime mystery, and the greatest of all natural-   disasters, 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).

Lecture 18   *Astronomy 102*   *1*

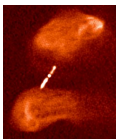**Distinctive features that can indicate the presence of a black hole (review from last three lectures)**

Observe **two or more** of these features to find a black hole:

❑ **Gravitational deflection of light**, by an amount requiring black hole masses and sizes.

❑ **X-ray and/or γ-ray emission** from ionized gas falling into the black hole.

❑ **Orbital motion of nearby stars or gas clouds** that can be used to infer the mass of (perhaps invisible) companions: a mass too large to be a white dwarf or a neutron star might correspond to a black hole.

❑ **Motion close to the speed of light**, or apparently greater than the speed of light ("superluminal motion").

❑ **Extremely large luminosity** that cannot be explained easily by normal stellar energy generation.

❑ Direct observation of a large, massive **accretion disk**.

Lecture 18   *Astronomy 102*   *2*

🛈   **Find the active galaxy**

Which of these is a visible-light picture of a radio galaxy?
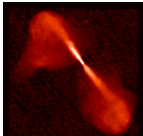
A.   B.   C.   D.

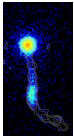*Lecture 18*   *Astronomy 102*   *3*

Find the active galaxy

Which of these is a radio image of a radio galaxy?

A.   B.   C.   D.

Find the active galaxy

Which of these is a visible-light picture of a Seyfert galaxy?

A.   B.   C.   D.

Gamma-ray bursters

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.

❑ Immediately these instruments 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 very well the direction from which the γ rays came, so it took a while 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

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

Gamma-ray bursters (continued)

Soon it became possible to measure the directions of the γ rays well enough to show that the bursts came 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?
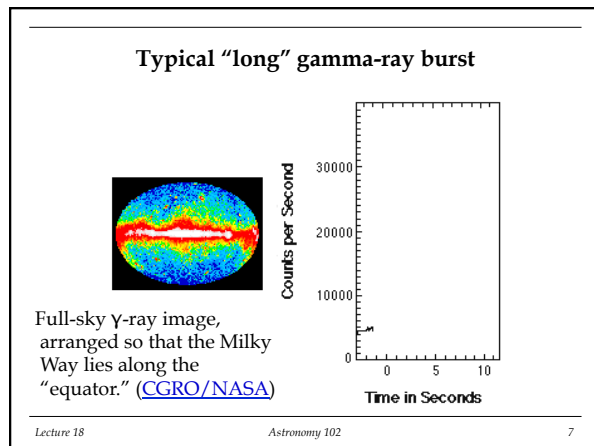❑ The nearest stars also appear to be randomly and uniformly spread all over the sky. Are the γ bursters just remnants of nearby dead stars?

γ-ray burst locations and sequence ([CGRO/NASA MSFC](#))

Gamma-ray bursters (continued)

Still, it was not possible to measure the position of any of the γ -ray bursters precisely enough to observe them at any other wavelength.

❑ One can't really make γ ray telescopes with which this could be done. γ rays do not reflect or refract significantly.
❑ The original determinations of γ -ray burster locations on the sky were made by **triangulation** among different satellites, using the different arrival times of the burst at each satellite.
❑ The longest bursts only last about 30 or 40 seconds, and it can take hours to notify ground-based observers that a burst has occurred.

So years passed without any explanation of their nature.

The BATSE instrument on the Compton Gamma-Ray Observatory

In 1991, the NASA Compton Gamma-Ray Observatory (GRO) was deployed. It included the Burst and Transient Source Experiment (BATSE), designed to detect more and fainter γ ray bursts, and measure their locations more precisely, than was possible hitherto.

❑ The expectation was that the distribution of fainter γ ray bursters would look more like the Milky Way.
  • Just like stars do: the brighter nearby ones are evenly distributed in the sky, but the more distant, fainter ones comprise the Milky Way.

❑ The expectation was not borne out, though – the γ ray bursters still looked uniform on the sky, even at faint levels.

A BATSE gamma-ray burster sky map.

This is a map of the whole sky, displayed so that the Milky Way lies along the equator. The positions of 2704 BATSE detections are plotted. Note that there is no tendency for the γ-ray bursters to cluster in the Milky Way.

Image:

Michael Briggs and the BATSE team, NASA MSFC.
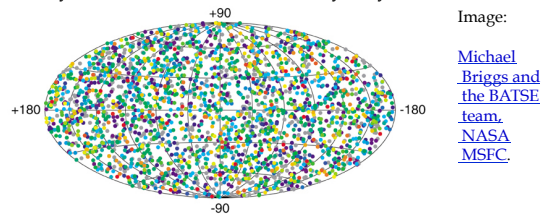
Two types of γ-ray bursters. Or maybe three…

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

❑ 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.

❑ There is also evidence of a third type, intermediate in duration and luminosity, and with a preponderance of lower-energy ("softer") γ rays.

Histogram of BATSE γ-ray bursts (Mukherjee et al. 1998).

log(Burst duration, sec)
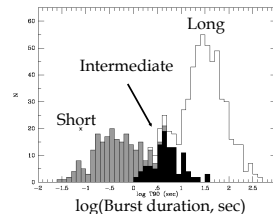
Analysis of the BATSE results

Obviously γ-ray bursters are not numerously distributed throughout our galaxy, as 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 ɣ rays?

❑ **Very distant objects.** Distant galaxies and galaxy clusters are evenly distributed on the sky.

  • But if the ɣ ray bursters are *that* far away, their energy outputs are (problematically) enormous.
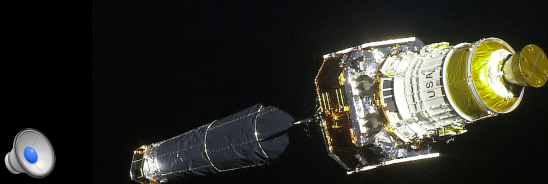
Mid-lecture Break (2 min. 47 s.)

❑ Exam #2 is Thursday 3/31. You may take it in any 75-minute block between 12 PM and 6 PM.
❑ Material on Exam # 2 will be reviewed on Wednesday.
❑ No recitations and office hours on Thursday and Friday.

The Chandra X-ray Observatory, launched in 1999 (CfA/NASA).

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 bursters.

❑ X-ray telescopes *can* be made, though with difficulty. (As you know, X-rays are good at passing unhindered through matter, too, so they're hard to reflect or refract.)

❑ The hope was that for each ɣ-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 ɣ-ray bursters found by BATSE was also detected and localized by BeppoSAX, and the position is made available to observers on the ground within hours.
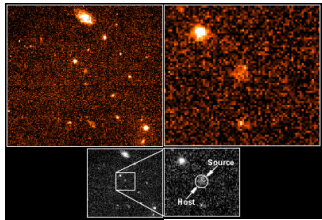
Results of visible-light observations of BeppoSAX positions: γ ray bursters live in distant galaxies

Image of the γ ray burst of 28 February 1997, taken with the STIS instrument on the Hubble Space Telescope on 5 September 1997 (Andy Fruchter, STScI/NASA).

Lecture 18   *Astronomy 102*   16

γ ray bursters live in distant galaxies (continued)
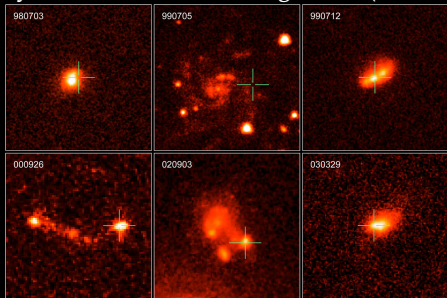
Green crosses indicate where the bursts were seen; all lie within distant galaxies (Andy Fruchter, STScI).

Lecture 18   *Astronomy 102*   17

Long bursts occur in star-formation regions, and their afterglows resemble supernovae…

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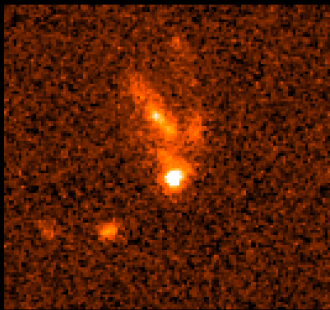

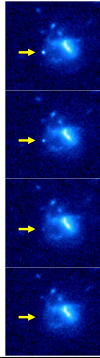*Lecture 18*   *Astronomy 102*   18

…but short bursts do not.

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

❑ Thus *Swift* has found and localized many more GRBs than was possible with BeppoSAX, 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.

Images: 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.)

Lecture 18 — Astronomy 102 — 19

Extragalactic origin: γ-ray bursters are *extremely energetic*.

The spectrum of the galaxy in which the γ-ray burst of 23 January 1999 lives indicates that its distance is 39 billion light years.

❑ At that distance, the γ-ray burst amounted to an energy of **3×10^{54} erg** in γ rays alone, if it emitted its energy uniformly in all directions.

❑ For scale: that's equivalent to a mass of

$$M = \frac{3\times10^{54} \text{ erg}}{c^2} = 3.3\times10^{33} \text{ gm} = 1.7 M_\odot,$$

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

Lecture 18 — Astronomy 102 — 20

Well, maybe a little relief on that energy…

❑ 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're going…

• …as in the case of quasar/radio galaxy radio jets…

❑ …the same brightness could be produced with a smaller energy: smaller by a factor of about $1 - V^2/c^2$, 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's **all γ rays**.

Lecture 18 — Astronomy 102 — 21

So what are γ-ray bursters?

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

❑ 10 ordinary supernovae account for this much emitted light, but take months and do so at much longer wavelengths.

❑ The entire Milky Way emits this much light in about 10 years, but it also does so with much longer wavelength light.

That is to say, it's difficult to imagine how to do it with normal stellar processes.

So what are γ-ray bursters?

But now you know about more powerful tools.
How about:

❑ **Accretion of a very massive compact object by a black hole** (compact, so the accretion doesn't 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.)
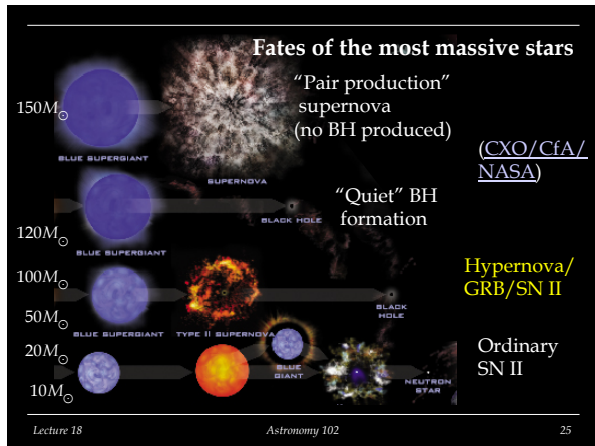
Leading possibilities for γ-ray bursters

❑ **Binary neutron stars**, coalescing to form a black hole?
❑ **Neutron star-black hole binary**, with the neutron star captured by the black hole? Currently-favored model for short bursts, though NS-NS coalescence is much the same.
❑ **Hypernova (a.k.a. Collapsar)**: collapse of a very massive (50-120 $M_\odot$) 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 bursters. All involve black hole formation or growth. All three naturally produce rapidly spinning black holes. **All should be rare processes.** And that's good…

Fates of the most massive stars

$150M_\odot$ — BLUE SUPERGIANT

"Pair production" supernova (no BH produced)

(CXO/CfA/NASA)

$120M_\odot$ — BLUE SUPERGIANT — SUPERNOVA — BLACK HOLE

"Quiet" BH formation

$100M_\odot$

$50M_\odot$ — BLUE SUPERGIANT — TYPE II SUPERNOVA — BLACK HOLE

Hypernova/ GRB/SN II

$20M_\odot$ — BLUE GIANT — NEUTRON STAR

$10M_\odot$

Ordinary SN II

Lecture 18   *Astronomy 102*   25

Talk about weapons of mass destruction!

A γ-ray burst like that on 23 January 1999 would destroy all life within **several thousand light years** of the burster. If it were 5,000 ly away and pointed at Earth:

- ❑ The γ rays would ionize Earth's atmosphere; the gas would recombine to form nitric oxides, which in turn would eliminate the ozone layer.
- ❑ If the γ rays are followed by a month-long blast of cosmic rays (as models predict), everything within 200 m of the surface would receive a lethal dose of radiation.
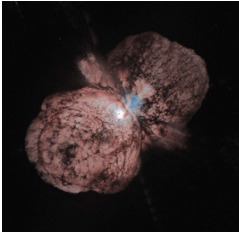
Sky and Telescope, February 1998

Lecture 18   *Astronomy 102*   26

And we even know where some of them are hidden. Here is *our* cherry-picked intelligence:

Nearest binary neutron star: PSR J0737-3039, 1,500 light years away, and due to merge 85 million years from now. See Kramer & Stairs 2008.

Nearest neutron star – black hole pair: none known. This doesn't mean there aren't any.

Nearest >$50M_\odot$ star: η Carinae, 7500 light years away, but could blow up any minute. (It's already tried several times, most recently about 170 years ago.)

η Carinae, surrounded by the expanding debris from its outburst of 1820-1840 (HST image by Jon Morse and Kris Davidson).

Lecture 18   *Astronomy 102*   27

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-visible SN 1987a (a Type II SN). *Swift* detected no γ-ray burst, but relatively weak X-ray emission is seen in the afterglow.

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.

Lecture 18   *Astronomy 102*   *28*

Black-hole formation?

On 3/19/08, 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 that it could have been seen with the naked eye – was about 30 sec long.

Is this event 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.

Lecture 18   *Astronomy 102*   *29*

Done. Next: Exam # 2.
Creature Aurora Over Norway.

Image Credit & Copyright:
Ole C. Salomonsen
(Arctic Light Photo)

Lecture 18   *Astronomy 102*   *30*