Gamma-ray bursts: observations

Photons with $E > 100$ keV are typically called gamma rays (no *physical* distinction between gamma rays and hard X-rays though need different detectors for each) - absorbed by atmosphere so only detectable from space.

Gamma ray sky first studied in the 1960s, in part initially by the Vela satellites - monitoring treaty forbidding nuclear tests in space.

Several reasonably well-understood sources of γ-rays:
  • Diffuse component which tracks the gas in the Milky Way
  • Point sources which can be identified with known locations of pulsars (i.e. Galactic neutron stars)

Also detect extremely bright, short-lived transient sources of gamma-ray emission - **gamma-ray bursts**.
Properties of GRBs

**Durations:** $10^{-2}$ to $10^3$ s
**Variability:** as short as ms
**Time-integrated flux:** up to $10^{-4}$ erg cm$^{-2}$
**Photon energies:** broad range, 0.1 MeV to 1 MeV typical

Note: $1$ eV = $1.6 \times 10^{-12}$ erg. Using: $E = h\nu$

1 MeV corresponds to a frequency $2.4 \times 10^{20}$ Hz

If these photons arose from a **thermal** process, then:

$$E \sim kT,$$ with $k$ Boltzmann’s constant $T \sim 10^{10}$ K

Gamma-rays are produced only from very energetic, normally **non-thermal** processes.
Example of burst `light curve’ in gamma-rays

Large range of durations, evidence for bimodal distribution of bursts - `short’ bursts lasting ~ 0.1 s and `long’ bursts lasting ~ 10 s.

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Initial models

Until late 1990’s, distance scale to GRBs was unknown. If we assume isotropic emission, then a source emitting energy E in gamma-rays at distance d would give a time integrated flux S:

\[ S = \frac{E}{4\pi d^2} \]

Suggested models:

• Comets: \( d \sim 100 \text{ au} \): \( E \sim 10^{27} \) erg

• Events on surface of Galactic neutron stars
  \( d \sim 1 \text{ kpc} \): \( E \sim 10^{40} \) erg

• Cataclysmic events in distant external galaxies
  \( d \sim 1 \text{ Gpc} \): E as large as \( 10^{52} \) erg
Most popular models in the early 1990s involved explosive events on the surfaces of Galactic neutron stars:

- analogy with X-ray bursts
- modest energetics
- apparent observation of cyclotron lines in one source
- similarity to soft gamma-ray repeaters

Observations with the Compton Gamma Ray Observatory provided the first hint this consensus was wrong.
Distribution of integrated flux from the bursts

Even if we have no idea of the distance to any burst, can learn something by comparing the number of faint bursts to the number of bright ones.

Consider a population of sources uniformly distributed in space. Each source emits energy (in some waveband) E isotropically in a burst:

Integrated flux detected at distance $d$:

$$ S = \frac{E}{4\pi d^2} $$

All sources with $S > S_{\text{min}}$ will be detected out to a maximum distance:

$$ d_{\text{max}} = \sqrt{\frac{E}{4\pi S_{\text{min}}}} $$
Volume in which sources with $S > S_{\text{min}}$ are detectable is thus:

$$V = \frac{4}{3} d_{\text{max}}^3$$

If number density of sources is $n$, number in that volume is:

$$N = nV = n \frac{4}{3} \sqrt[3/2]{\frac{E}{4 S_{\text{min}}}}$$

If we plot the number of bursts $N$ with integrated flux above some threshold $S_{\text{min}}$ on a log-log plot, expect a straight line with a slope of -1.5.

$log N - log S$ test of whether distribution of unknown sources is homogenous
BATSE results showed that a slope of -1.5 fit the distribution of the brightest bursts, but that there were fewer faint bursts. We can see the `edge’ of the distribution.
If GRBs originated on Galactic neutron stars, the `edge’ of the population would be defined by the size of the Galaxy. Since the Sun is not in the Galactic center, expect an anisotropic distribution of bursts on the sky (more towards the Galactic center).

Actual spatial distribution is perfectly isotropic:

With log N - log S results, inconsistent with Galactic origin.

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Conclusion:
• Distribution on the sky is isotropic because bursts arise in distant galaxies, far enough away that the Universe is almost homogenous.
• See an edge to the distribution because the Universe is:
  (a) finite - at large enough distances reach very early time before galaxies had formed - no bursts
  (b) evolving - rate of GRBs was probably different in the past as compared to today
  (c) can have a non-Euclidean geometry

Cosmological distance scale implies very large energies, comparable or larger than supernovae but with much of the energy in gamma-rays.
Gamma-ray bursts: afterglows

Cosmological origin of gamma-ray bursts was definitively established in 1997, following launch of Italian X-ray satellite BeppoSAX:

- Wide field X-ray imager detected X-ray emission from location where GRB had been seen in gamma-rays
- **Much** more precise positions
- Made possible follow-up observations in other wavebands
- Detection of fading **afterglows** in the optical and radio for some (not all) GRBs
Once the afterglow has faded, host galaxies are typically found to be faint, distant galaxies.

Afterglows are not found only in galactic nuclei, but may be preferentially associated with regions of star formation.