

**SAO Essay Cover Page**

**Essay Title** The Mystery of Gamma Ray Bursts

## The Mystery of Gamma Ray Bursts

This essay discusses the observational history and discovery of gamma ray bursts (GRBs), and some current theories and research about their origin and form.

Discovered around 1900 by French chemist Paul Villard (Becquerel 1901), and probably named by Ernest Rutherford in 1903 (Gerward 1999), gamma rays are an electromagnetic radiation with wavelength less than about  $10^{-11}\text{m}$ , frequency more than about  $10^{19}\text{Hz}$ , and energy more than about 0.1 MeV (EAAweb, Imagineweb). There's some overlap of hard X-rays with soft gamma rays, and cosmic rays are over 100MeV (Caltechweb).

As the name suggests, a gamma ray *burst* is a short-lived emission of these high energy photons from somewhere in space. We now know that GRBs can release more energy than our Sun will produce in its lifetime, they occur about once a day, in any part of the sky, at enormous distances, and last from just a few milliseconds up to an hour and a half (Swiftweb, INTEGRALweb1). As cosmic gamma radiation is absorbed by the Earth's atmosphere (EAAweb), it must be observed from space, the first GRBs being accidentally discovered by a US military satellite in 1967 (Cline et al 1973). The findings were published six years later, describing short-duration and long-duration bursts of around 1MeV, which were proven to be non-terrestrial (Klebesadel et al 1973). The light curve for the first event discovered is shown in Fig. 1(Gammahistweb). The subsequent few decades saw continued research of gamma rays in general, as well as those of cosmic origin, but the specific phenomenon of the GRB was difficult to study due to their unpredictable location and short lifetime.

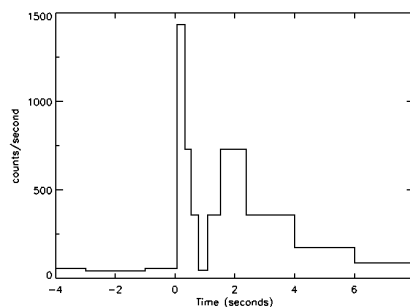


Fig. 1 Light curve of the first GRB, detected by Vela 4 in 1967. Credit NASA

Around 1968, NASA's Orbiting Solar Observatory discovered the general galactic gamma ray background which results from interactions of cosmic rays (mostly hydrogen and helium nuclei) with the interstellar medium, recording a paltry 621 gamma photons. The Apollo 15 and 16 moon missions (1971 & 1972 respectively) also recorded soft gamma ray background as well as emissions from the Moon. In 1972, NASA's Small Astronomy Satellite-2 found a point source of gamma rays coming from the constellation Gemini, and dubbed it Geminga, for "gemini gamma ray source". That source is now known to be a neutron star, and the second brightest gamma ray source known (Darlingweb).

Over a six year period from 1975, the European COS-B satellite searched for gamma rays up to 5GeV, discovering another couple of dozen point gamma ray sources including pulsars and quasars, and then around 1980 NASA's High-Energy Astrophysics Observatory-3 recorded gamma rays coming from the galactic centre (GLASTweb, HEASARCweb). But GRBs were still not commonly observed or studied.

In the 1980s, NASA's Solar Maximum Mission recorded GRBs accidentally while observing the Sun (SMMweb) and later in the 80s, the US and USSR deploy several missions specifically to look for GRBs, finding a few more, and spawning new theoretical development (GLASTweb). But it wasn't until 1991 that deliberate and successful observation of GRBs was accomplished with the Burst and

Transient Source Experiment (BATSE), aboard NASA's Compton Gamma-ray Observatory. When on-board sensors detected an increase in gamma photon counts over and above the background level, an event was 'triggered', and several instruments on the satellite would swing into action, pointing at the source and recording its light curve. Of the over 8000 triggered, impulsive events recorded in its nine year mission, BATSE confirmed 2,704 GRBs (BATSEweb). They were spread over all parts of the sky, two categories later being described from the returned data: long GRBs lasting for more than two seconds, and short lasting for less than two seconds. GRB light curves have a wide range of forms as illustrated in Fig. 2.

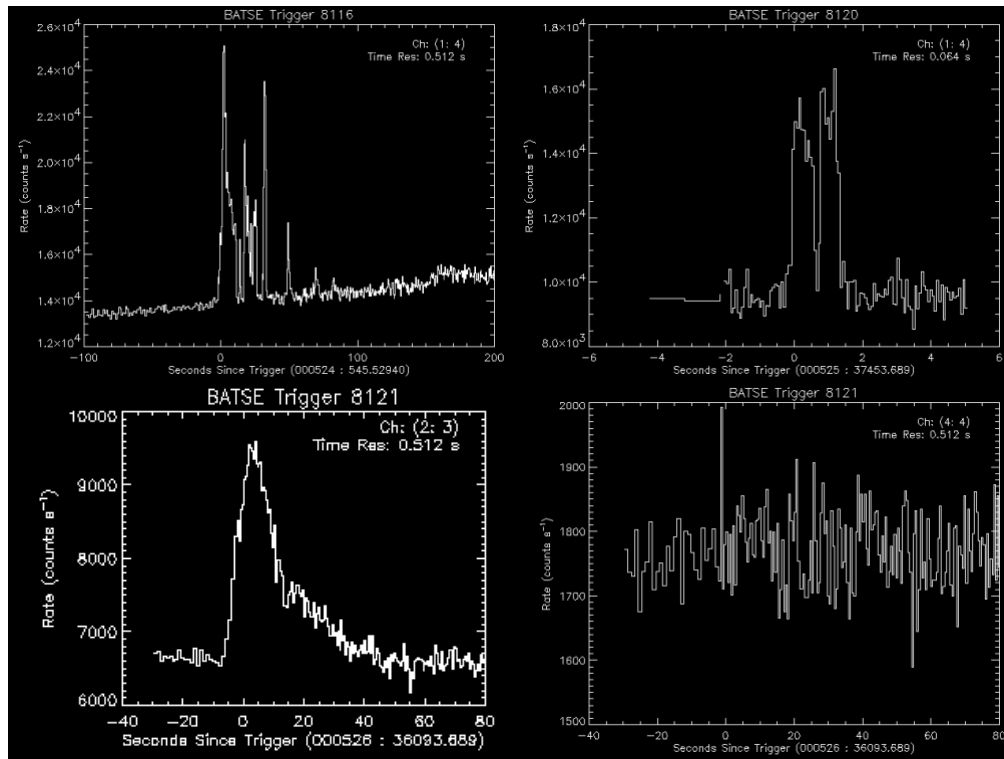


Fig. 2 A variety of gamma ray light curves from BATSE. Credit: NASA

But calculating the distance to these events required the accuracy of the Italian-Dutch BeppoSAX satellite launched in 1997, which could detect GRBs to within an arcminute, allowing astronomers to train optical telescopes on the afterglow, also recording iron and magnesium absorption lines. These lines were redshifted to a large degree, corresponding to a distance of at least 7 billion light years (Freedman & Kaufmann 2005).

Information from recent missions has helped develop theory on GRBs. NASA's High-Energy Transient satellite confirmed the connection between long GRBs and supernovae, and the Reuven Ramaty High Energy Solar Spectroscopic Imager satellite, though primarily looking at gamma rays in solar flares, also observed GRBs and has shown polarized light due to magnetic fields associated with GRBs (RHESSIweb). In the last five years, NASA's Swift satellite, with its ability to quickly turn towards an identified GRB, has detected about 100 each year, showing they come from a variety of sources including neutron star/black hole mergers (GLASTweb).

The stars which cause GRBs are the first, supermassive stars formed early in the universe's life, and have long since died (INTEGRALweb2). They're too far away to be observed by telescope, but the current theory is that a Wolf-Rayet star (old, massive star with extreme mass loss from stellar wind) explodes in a hypernova (a type Ibc supernova where the star has lost all of its hydrogen and helium), the core collapsing rapidly into a black hole. This is the "collapsar/hypernova" model proposed by Woosley's team at the University of California (Woosley 1993). As well as gamma photons being produced by radioactive decay during the explosion, this model proposes shock waves travelling

outwards from the hyper-giant's collapsing core, and interacting with the outer layers to produce gamma photons. As the shock wave develops, it loses energy to the surrounding stellar material, producing progressively less energetic photons such as X-rays, then UV, then visible, then IR, then radio photons. This manifests as an observed afterglow of increasing wavelengths. Free electrons spiral around strong magnetic field lines, to produce this synchrotron radiation, mostly in the optical range, and visible for a number of days after the actual event (COSMOSweb) (Fig. 3).

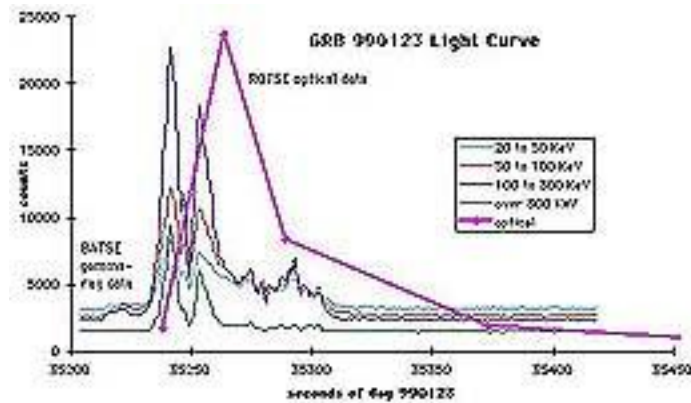


Fig. 3 Optical light (purple line) peaks some time after gamma photon peak. Credit NASA

This energy is ejected at the magnetic poles, in collimated jets, and is therefore directional, enabling us to see only those pointed at Earth. An alternative to the collapsar/hypernova model, the 'cannonball' model proposes that lumps of material in the outcoming blast hit the ISM, releasing gamma rays - this could account for some of the variation in shapes observed in the light curves (Imagineweb).

A GRB afterglow (980425) was first linked to a supernova (1998bw) in 1998. Then in 2003, GRB 030329 had an optical and X-ray spectrograph almost identical to the supernova that created it, sealing the case for a causal relationship between supernovae and long GRBs (Imagineweb).

Short GRBs have minimal afterglow and appear to be caused by a different mechanism, such as a neutron star or black hole merger. They're also only 1/10 as bright as long GRBs, and have more high energy gamma rays. Some astronomers suggest that a short GRB may simply be an observational artefact - recording the edge of the energy cone from a long GRB. X-ray flashes are also observed, and may be classified as 'soft' gamma ray bursts, perhaps also seen as the edge of a long GRB cone (Imagineweb). In fact, the brightest extra-galactic X-ray burst ever recorded, from GRB 100621A, recently overwhelmed the sensors on NASA's Swift satellite (Pennweb).

In mid 2005, NASA's Swift and HETE satellites both recorded separate short GRBs at the edge of galaxies billions of light years away. One was a neutron star/neutron star collision, the other was a neutron star falling into a black hole. Various telescopes around the world made observations of the afterglow in progressively longer wavelengths (Fox et al 2005, Gehrels et al 2005, Villasenor et al 2005, Hjorth et al 2005), and also excluded the possibility of a supernova cause (Fox et al 2005). This supported the neutron star/black hole theory well. Mergers like this can cause ripples in space-time gravitational waves, which could be detected if close enough to Earth (Shortburstweb).

Because GRBs are short-lived, several networks have been setup to quickly train telescopes to look at the optical afterglow of observed long GRBs. The Interplanetary Gamma-Ray Burst Timing Network (IPN), uses existing probes located at different points in the Solar System, cobbled together to allow triangulation and location of GRBs, alerting astronomers to make observations. Contributing satellites include NASA's Ulysses, Wind and Mars Odyssey, and the internationally operated HETE2 satellite (IPNweb). Also, the Gamma-ray Burst Coordinates Network (GCN) links space-borne and terrestrial observations so that researchers can access data seconds after a GRB is detected (Fig. 4) (GCNweb).

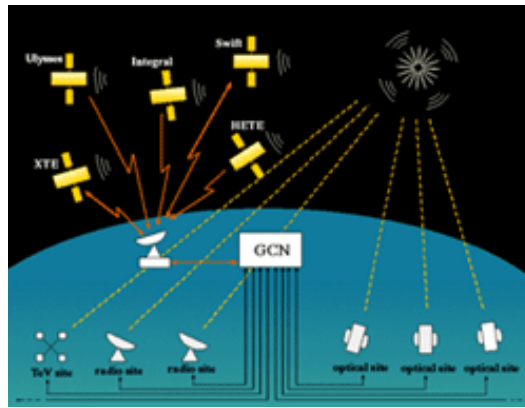


Fig. 4 Gamma-ray Burst Coordinates Network. Credit: NASA

In 2002, the ESA launched its INTEGRAL satellite, carrying the Integral Burst Alert System which can detect gamma, X-ray and visible light simultaneously. GRB's can be detected even when the instrument isn't pointing at the source, and can relay the event to a ground network within a few seconds. An interesting event was observed by IBAS in 2004, when GRB 041219A recorded one of the brightest explosions ever. Polarization of light from these events is related to the structure of their magnetic fields, so analysis of such big bursts allows astronomers to theorise about the causes of the emanating shockwave. Four scenarios have been postulated: the burst could break off a section of the magnetic field and push it out into space, or it could generate a new magnetic field at some distance from the GRB source, or it could (amazingly) consist of pure magnetic energy without any particles, or it could impact with an extant magnetic field. Götz et al (2009) showed that the best model to fit the data was synchrotron radiation from a detached magnetic field.

Swift was launched by NASA in 2004, and can turn towards an afterglow in under a minute, observing in X-ray and UV energies and looking for supernova light curves. A sample of the exciting theory coming out of GRB research at telescopes around the world suggests the infant nature of this field, and the reliance on orbiting platforms like Swift. Becker et al (2010) have analysed data from several events detected by the GBM detector on NASA's Fermi Gamma-ray Space Telescope, and concluded that GRBs have sufficient energy to be responsible for at least some of the extremely high energy, cosmic rays coming from cosmological distances in space. The ground-based Solar Tower Atmospheric Cherenkov Effect Experiment was located near Albuquerque, New Mexico and until 2007, looked at very high energy transient events over 150GeV (Jarvis et al 2010). The University of Western Australia's Zadko Telescope near Gingin in WA, fills a niche at that latitude, for observing afterglows of triggered GRBs from orbiting satellites and looked at six Swift transients over a twelve month period (Zadkoweb, Coward et al 2010). The Tsinghua University-National Astronomical Observatory of China Telescope and the Mt Lemmon Optical Astronomy Observatory's LOAO telescope collaborated recently to conclude that the source of the short GRB090426 detected by Swift, was probably a collapsing massive star (Xin et al 2010). Perhaps surprisingly, Kann et al (2010) very recently concluded from a study of all Swift data, that there's a continuous range of luminosities and red-shifts for long GRBs, contrary to the established theory that they clustered around two maxima.

## Summary

This brief summary of some history and science around the most energetic events known, has revealed a very young research area based on a highly tuned network of space, and terrestrial telescopes. Gamma ray bursts are a more complex phenomenon than the generalised description of a simple peak followed by an afterglow. They range widely in intensity and duration, and their progenitors may be any one of a number of cosmic events like neutron star/black hole mergers, or hypernova from collapsing massive stars. Study of these amazing events has far reaching

implications for expanding our knowledge of particle physics, stellar evolution, space weather, cosmology and many other fields.

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