Gamma-ray astronomy

This is the 'last frontier' of electromagnetic radiation, comprising photon energies spanning the immense range from 0.1 MeV to 10^{20} eV or more. Gamma-rays of ultra high energy are exceedingly infrequent! There is no possibility for matter to be hot enough to radiate black-body photons of such energy. They must be generated individually by other processes, involving the release of nuclear or gravitational energy:

- transitions between nuclear (not electron) energy levels
- particle/antiparticle annihilation
- decay of elementary particles; radioactive decay
- acceleration of charged particles (by black holes?)

Most of these processes produce a wide spread of photon energies. Some however produce definite gamma-ray energies ('lines') characteristic of specific events, e.g.

- electron/positron annihilation, $e^- + e^+ \rightarrow 2\gamma$ ($h\nu = 0.511$ MeV for each photon)
- specific radioactive events, e.g. the decay of ^{26}Al, 1.808 MeV.

GAMMA-RAY DETECTORS: Gamma-rays are too energetic to be focused, so there is difficulty in determining their direction.

Scintillation counters, crystals of material such as sodium iodide, emit detectable flashes of visible light when gamma-rays of low energy (< 10 MeV) are absorbed in them. Directional determination is poor – you won't see any gamma-ray pictures.

Spark chamber telescopes give fairly good directions (if you can call a few degrees good!) for higher-energy gamma-rays. High voltages are applied to interleaved metal plates in a box filled with argon and neon gas. Incoming gamma-rays produce electron/positron pairs which travel through the gas and cause sparks, which are recorded, between the plates.

DISCOVERY OF COSMIC GAMMA-RAYS: These were detected in various balloon and rocket experiments during the 1960s. Progress was slower than that of X-ray astronomy. The flux is weak, and there is difficulty in allowing for local gamma-rays created in and around the detector by cosmic-ray particles (see below). Military surveillance satellites (monitoring possible H-bomb tests) picked up cosmic **gamma-ray bursts** of unknown origin. Early gamma-ray sky mapping was done by the American SAS-2 (1972) and the European COS-B (1975-82) spacecraft, both using spark-chamber telescopes. COS-B had a spatial resolution no better than 2°, and even from a 'bright' source like the Crab Nebula (supernova remnant) the flux was only one or two γ-photons per hour! Gamma-ray detectors flew on some other spacecraft. A major injection of new data has been coming from NASA's second 'Great Observatory', the Compton Gamma Ray Observatory (1991); at 16 tonnes, it is the heaviest scientific satellite launched by Space Shuttle. GRO's instruments, covering 20 keV to 30 GeV (3×10^{10} eV), are:

OSSE:	Oriented Scintillation Spectrometer Experiment (steerable)
COMPTEL:	Imaging Compton Telescope (multiple detectors, accuracy 1/8 degree)
EGRET:	Energetic Gamma Ray Experiment Telescope (20 MeV−−30 GeV)
BATSE:	Burst and Transient Source Experiment (8 separate telescopes)

GAMMA-RAY OBSERVATIONS:

(1) THE SUN: while you wouldn't expect much gamma (or radio) flux from a black-body at 6000 K, gamma-rays have been detected from solar flares associated with sunspot groups. Intense local magnetic fields in flares accelerate particles to high energies. The 0.511 MeV electron/positron annihilation line has been observed. GRO has obtained detailed gamma-ray spectra of flares over the range 20 keV to 1 GeV (range of 1:50,000 in energy!).

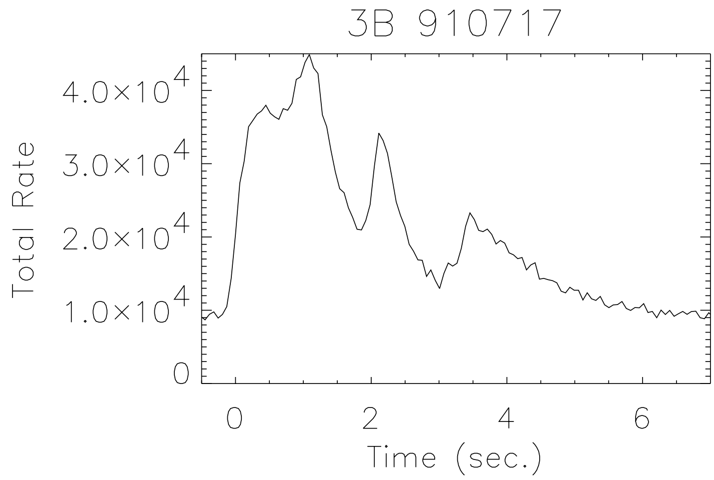
(2) THE MILKY WAY: is the dominant feature of COS-B sky-maps (as it is of radio maps). Gamma-rays are generated by collisions between cosmic-ray nuclei (particles, not photons) and nuclei in the interstellar gas. The collisions produce intermediate-mass particles called neutral pions which decay into gamma-rays. [For example, $p+p \rightarrow p+p+\pi^0$, $\pi^0 \rightarrow 2\gamma$].

(3) POINT SOURCES: gamma-rays from highly-accelerated particles in pulsars and supernova remnants; the Vela pulsar (neutron star) is the brightest 'star' in the gamma-ray sky. SNRs are the dispersed remnants of past supernova explosions, in which it is believed that heavy elements are created by nucleosynthesis. Gamma-ray lines corresponding to radioactive decay of specific synthesized nuclei have not yet been identified in individual SNRs. The ^{26}Al line at 1.808 MeV has however been found in the direction of the Galactic Centre; because ^{26}Al has a mean lifetime of only 10^6 years, it must have been formed in a number of 'recent' supernovae. BATSE and EGRET have recorded gamma-rays from several pulsars; these will provide clues to particle acceleration in the vicinity of neutron stars.

(4) EXTRAGALACTIC: gamma-rays from active galactic nuclei and QSOs. EGRET has recorded high-energy gamma-rays form a number of distant galaxies. One QSO emits most of its energy in the X-ray/gamma-ray region!

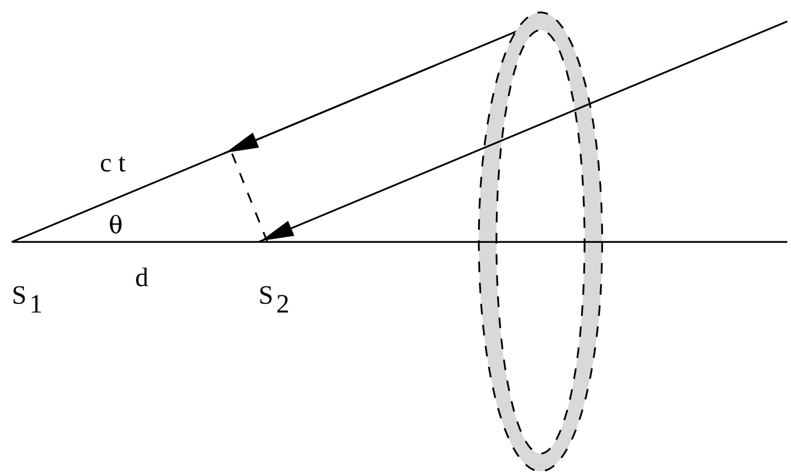
Ground-based gamma-ray telescopes can detect **Cerenkov radiation**, visible light emitted in the atmosphere when an incoming high-energy photon or particle hits an air molecule to create an **air shower** of relativistic subatomic particles. We get the analogue of the 'sonic boom' from particles travelling faster than the speed of light in air, producing detectable flashes of light. A giant elliptical galaxy emitting 10^{12}-eV gamma rays has been detected; more evidence for infall onto a back hole?

(5) GAMMA-RAY BURSTS: Vela military satellites detected gamma-ray bursts in the 1960s, and it was clear even with poor directional accuracy that they were of cosmic origin. They occur randomly over the whole sky and come in many different classes, from single spikes lasting only 0.02 s, to events with complex time structure lasting up to 1000 s.



The spiky time structure of a typical gamma-ray burst.

There is a way to get rather accurate directions to bursters that have been observed by several spacecraft in interplanetary orbit (by as many as nine, in one case!).



The time difference t between arrivals of the burst at spacecraft S_1 and S_2 gives the angle θ, from $d \cos\theta = ct$.

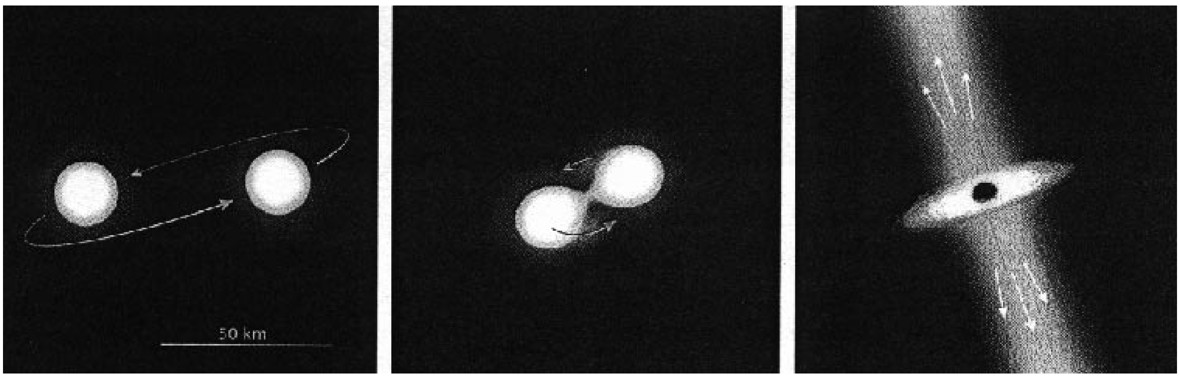
So, the burster direction, taking into account all planes through S_1S_2, lies somewhere on a cone of semi-angle θ centred on the line S_1S_2. If the burst has been observed by another spacecraft S_3, then the burster direction also lies on another cone centred on the line S_2S_3. The intersections of these cones (which project as two circles on the sky) give two possible directions for the burster. A fourth spacecraft will enable us to pick the correct value, with a possible precision of one arc-minute. Spacecraft networks have been set up internationally from time to time. Positions for about 200 bursters were known prior to GRO.

In its first year BATSE recorded positions of 261 bursts, and the surprise is that they are all over the sky. Their distribution is not associated with the large-scale structure of the

Galaxy (cf. X-ray sources, many of which do concentrate towards the galactic plane). This suggests that bursters are either local, perhaps associated with the outer reaches of the Solar System (but what??), or very distant, outside our Galaxy altogether – that would make them exceedingly energetic.

In order to make the critical leap of working out what sort of objects the gamma-ray bursters are, an optical counterpart needs to be found, and this is difficult to achieve with the low-accuracy gamma-ray positions. The real breakthrough was the Italian BeppoSAX satellite. This contains a $1 - 200$ keV X-ray camera that is able to be pointed rapidly in the general direction of a gamma-ray burst. If a transient X-ray source is found, this is almost certainly associated with the burst; the X-ray position is good to better than 1 arcminute, so that an optical image can be taken. In this way, the optical counterparts of many gamma-ray bursts have been found, proving that the bursts take place in faint galaxies at very high redshifts. The bursts are therefore the most *visibly* energetic events in the universe: they manage to release roughly the same energy as a supernova (10^{45} J), but they put it all into radiation. A recent burst from a galaxy at redshift 1 peaked at 9th magnitude - almost bright enough for the naked eye, from the other side of the universe. We should keep our fingers crossed that one doesn't go off in the Milky Way...

The favoured theoretical idea for how gamma-ray bursts can liberate so much energy is via the merger of two neutron stars. As it happens, such an event would also be an effective source of gravity waves (see below), so there is some chance that this theory may get tested one day.



The last few seconds of the life of a neutron-star binary. The two stars lose orbital energy via gravitational radiation, until they merge into a black hole surrounded by a disk. The disk is heated so much in the process that it emits gamma rays.

For a review of the Compton Gamma Ray Observatory's work, see Sky & Telescope, December 1992. The impact of BeppoSAX on solving the gamma-ray burst mystery is described in Sky & Telescope, February 1998.