Astronomy 1Bh *The New Astronomies* **Spring 2001**

Gamma-ray & Cosmic-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. The nature of these sources was destined to provide one of the longest-standing astronomical puzzles, which only began to be resolved at the very end of the 20th century, more than 30 years on.

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)

COSMIC RAYS

'Something' that makes air electrically conducting (we should say ionized) was known 100 years ago. C.T.R. WILSON (1901) found no change inside a railway tunnel near Peebles; 'something' could penetrate rock. HESS (1912) inferred cosmic rays from the increase of ionization in the upper atmosphere (balloon flights). If you don't like radiation, don't fly.

The ionization was eventually ascribed to (mainly) positively charged particles: the primary particles have energies $> 10^4$ MeV, and in traversing the atmosphere they create secondary particles, still of high energy. Spacecraft experiments of the 1970s established that the primary cosmic rays are charged nuclei of the same elements that are widespread in the Solar System, plus some electrons.

Above 5000 MeV the particle abundance at energy E is proportional to $E^{-2.6}$: at the very highest energies observed (10^{20} eV) the flux is only a few particles per square kilometre per year. Being charged particles, cosmic rays are deflected by the magnetic fields of the Galaxy (and of the Earth), so they carry no trace of their point of origin. Below 10^6 MeV they are confined by the Galaxy's magnetic fields.

Cosmic rays are also affected by the Earth's magnetic field, which traps the particles and prevents most of them from reaching the ground (a good thing for life on Earth). The VAN ALLEN BELTS were found by the first US satellite, and represent a significant hazard for manned spacecraft (or even electronic equipment on unmanned craft). There is archaeological evidence (e.g. ^{14}C in coral reefs) that cosmic-ray activity was higher 20,000 years ago, which means that the Earth's shielding magnetic field was weaker then.

Cosmic rays are interstellar gas particles that are believed to have been accelerated by supernova explosions, and possibly by pulsars and X-ray binary stars. Cosmic rays $>$ 10^6 MeV would be little affected by our Galaxy's magnetic fields, and may be extragalactic. The acceleration mechanism for ultra high energies up to 10^{20} eV is unknown. If theorists had their way, such high-energy particles would not exist. The problem is that all known acceleration mechanisms involve the cosmic rays being deflected by fast-moving plasma containing magnetic fields – but the deflection produced by a magnetic field falls with increasing particle energy, so ultra high-energy cosmic rays would pass through such plasma without noticing.

COSMIC-RAY TELESCOPES

Cosmic rays are observed at ground level via the extensive **air showers** they provoke in the atmosphere. An incoming cosmic ray is a highly relativistic particle; when it hits an atom in he atmosphere, nuclear reactions readily generate many new particles (such as muons, symbolized μ – heavy versions of electrons), which are also relativistic. These in turn create further sets of particles. The result at ground level is a shower of thousands of particles, all from the one initial cosmic ray.

Arrays of particle detectors are used to detect these air showers, employing similar technology to that used in X-ray and gamma-ray satellites. The one at Haverah Park near Leeds covers 12 square kilometres. See Sky & Telescope, September 1995. By the numbers of particles detected, the energy of the initial event can be estimated. The air-shower phenomenon is also produced by gamma-ray photons; these can have energies similar to those of cosmic rays, and their effect on the upper atmosphere is similar. However, the detailed mixture of particles detected in the shower can discriminate between gamma-ray events and cosmic-ray events.

Ground-based gamma-ray & cosmic-ray telescopes can also detect **Cerenkov radiation**: this is the analogue of the 'sonic boom' from particles travelling faster than the speed of light in air, producing detectable flashes of light. This information is useful because it gives the direction of the incoming particle (by triangulation – using a number of telescopes spread out over a wide area). The most ambitious such telescope is AUGER, now under construction in Chile: this aims to study just the most energetic (10^{20} eV) events, hoping to solve the mystery of their origin.

GAMMA-RAY ASTRONOMY

(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. 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.

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.

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.