Gamma-Ray Astronomy

Gamma-ray photons are the most energetic ones of the whole electromagnetic spectrum. Like all photons with wavelengths shorter than 10 nm, they are absorbed by the Earth's atmosphere. Detection of γ-ray emission from space requires then the use of stratospheric balloons, rockets and satellites, which became feasible only with the advent of the space era.

The borderline between the spectral regions of x-rays and γ-rays is sometimes placed at an energy of $E \sim 30$ keV (wavelength $\lambda \sim 4.13 \times 10^{-9}$ cm or a frequency of $\nu \sim 7.2 \times 10^{18}$ Hz). At lower energies, radiation from astrophysical sources is dominated by thermal emission (i.e. resulting from radiation in equilibrium with matter, in optically thick media), while at higher energies non-thermal emission prevails. Alternatively, the x–γ-ray borderline may be placed at 511 keV (the energy equivalent of the electron rest mass); above this 'limit' electrons behave relativistically. In any case, the use of large photon collectors becomes impossible above a few tens of keV: photons have wavelengths smaller than typical interatomic distances in solids and cannot be reflected by any kind of mirror (contrary to what happens at longer wavelengths).

The γ-ray domain extends over 12 decades in energy, as much as all other spectral regions put together. However, above a few tens of GeV, the number of photons received from even the brightest sources is so small that their observation during the limited lifetime of a satellite is no longer possible (see VERY-HIGH-ENERGY GAMMA-RAY SOURCES). Those very high energy (VHE) photons are detected through their interaction with the Earth's atmosphere, producing cascades of secondary particles.

Astronomy in the γ-ray domain faces several serious handicaps.

- The impossibility of using large collectors to focus the γ-ray photons implies that the detector itself should be as large as possible.
- A detector placed outside the Earth's atmosphere is constantly bombarded by energetic cosmic ray particles, coming from the outer space or trapped in the Van Allen radiation belts. The interactions of these particles with the detector induces very high backgrounds, which are difficult to attenuate with passive or active shielding. As a result, the sensitivity of γ-ray detectors increases only as the square root of their collecting area.
- Astrophysical sources emit generally very small numbers of γ-ray photons. Statistically significant detections then require very long exposures, which are not always compatible with the generally short lifetime (a few years) of an observatory in space.

These difficulties explain why γ-ray astronomy is the last window of the electromagnetic spectrum to be opened to our observation of the universe. However, it has undergone a spectacular development in the 1990s and has grown to a mature astrophysical discipline. It offers information that is impossible to obtain in other wavelengths, allowing us to probe the close surroundings of a black hole or the interiors of a supernova, to identify nuclear isotopes and to obtain clues to the origin and acceleration of cosmic rays, either in our Galaxy or in the very active central regions of remote galaxies.

A short history of γ-ray astronomy

The opening of the γ-ray window was preceded by a relatively long period of theoretical studies concerning the γ-emissivity of potential astrophysical sources. Most of these ideas were put forward by scientists working in fields other than astronomy (particle and nuclear physics and cosmic ray physics). Following the detection of atomic hydrogen in the Galaxy (through its characteristic 21 cm line; see RADIOASTRONOMY) Hayakawa realized in 1952 that the interaction of COSMIC RAYS with the hydrogen atoms of the interstellar medium should give rise to γ-ray emission. Six years later, Morisson suggested two known radiosources (the CRAB NEBULA and CYGNUS A) as possible γ-ray emitters. Thus, theoreticians realized quite early that relativistic particles could generate photon emission in both extremes of the electromagnetic spectrum.

Progress in observational γ-ray astronomy has been too slow to test those ideas, because of the smallness of early detectors and underestimated background fluxes. The first γ-ray emission of extraterrestrial origin was detected during the solar flare of March 1958. However, it was only 10 yr later that γ-ray emitters outside our solar system were detected: the US satellite OSO-3 (launched in 1961) recorded a few hundred photons of energy $>$50 MeV from the inner Galaxy, while a balloon-borne experiment detected photons in the 100–300 keV range from the direction of the Crab nebula. A few months later, radioastronomers discovered the CRAB PULSAR; subsequent analysis of the γ-emission from the Crab revealed a periodicity similar to that in the radio band. During a solar flare in August 1972, a spectrometer aboard the US satellite OSO-7 recorded the first γ-ray spectrum of the Sun, revealing several lines of nuclear origin, as well as the electron–positron annihilation line at 511 keV. Also, the following year a US team reported the detection of γ-ray bursts of extraterrestrial origin by the military satellites of the Vela series (launched to monitor the Earth's atmosphere for nuclear explosions).

After these early discoveries, the γ-ray sky was explored in some detail in the 1970s by the US SAS-2 and the European COS-B satellites, which provided the first high-energy images of the Milky Way, detailed observations of the first known γ-ray pulsars and the first detection of extragalactic γ-ray sources. Extrasolar γ-ray spectroscopy started in the same period, with the discovery of the electron–positron annihilation line from the galactic centre direction by a balloon-borne spectrometer. This discovery was confirmed in the early 1980s by a γ spectrometer aboard the US HEAO-3 satellite, which discovered also the first extrasolar γ-ray

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line emission of nuclear origin, namely the 1.8 MeV line of the radioactive nucleus ^{26}Al.

The pace of discoveries slowed down in the 1980s, as a result mainly of the lack of dedicated γ-ray satellites. The explosion of the supernova SN1987A in the nearby galaxy of the Large Magellanic Cloud on February 23 1987 offered the γ-ray community an unprecedented opportunity: the SMM (Solar Maximum Mission) satellite, as well as several balloon borne instruments, detected γ-ray lines from the decay of radioactive ^{56}Co (predicted long ago to be the source of power for the late optical light curves of supernovae). Finally, the early 1990s constitute the golden era of γ-ray astronomy, thanks to the discoveries of the Soviet–French SIGMA mission (see GRANAT) and the US COMPTON GAMMA RAY OBSERVATORY (CGRO).

Emission processes of γ-ray photons

Nature creates γ-ray photons in a variety of ways. If the temperature of the environment is high enough ($>10^8$ K), γ-photons are produced as thermal emission of the astrophysical PLASMA and they generally have a blackbody spectrum. The interiors of stars in their advanced evolutionary stages reach such high temperatures, but they cannot be observed, because the star's dense material makes it opaque to photons of all wavelengths.

The close neighborhood of a strongly gravitating body, such as a black hole accreting matter from a companion star, may also reach high temperatures, as the gravitational energy of accreted matter turns into heat. The detection of γ-ray photons produced in this way is a unique tool for studying the interactions of compact objects with their environment as well as their energetics.

However, astrophysical γ-rays are mainly produced by various non-thermal processes, involving in general the interactions of high-energy particles. For instance, high-energy electrons radiate γ-rays by interacting electromagnetically with nuclei, photons or intense magnetic fields; the corresponding processes are known as bremsstrahlung, inverse Compton emission and synchroton emission, respectively, and they can obviously take place also in a high-temperature plasma. In addition nuclear interactions of protons with energies higher than $\sim$1.2 GeV produce secondary unstable particles, pions and mesons; γ-ray photons are produced by the decay of some of these particles, the most prolific producers being the π^0 pions. The resulting γ-ray spectrum has a characteristic maximum around 70 MeV (corresponding to half the rest-mass energy of π^0).

All these thermal and non-thermal processes give rise to the emission of γ-rays with a continuous spectrum of energy. There are also processes producing γ-rays with discrete energies, involving in general the de-excitation of atomic nuclei. Just as the more familiar optical lines are caused by the electron transitions in atoms, nuclear lines result from the much more energetic transitions (typically, in the MeV range) between energy levels of the atomic nuclei. This makes γ-ray spectroscopy an invaluable diagnostic tool for nuclear astrophysics, since it allows for an unambiguous identification of isotopic species (radiation originating from electrons enables one in general, to identify chemical elements, but not isotopes).

The excited nuclear states are populated either through the decay of an unstable nucleus or through high-energy nuclear interactions. In the former case, we obtain information about the synthesis of radioactive nuclei in various sites (mostly explosive ones such as supernovae) and the physics of these sites. In the latter case, we learn about the nature of the energetic particles (e.g. their composition, spectrum, acceleration mechanism etc). γ-ray lines from the de-excitation of nuclei are routinely observed in the Sun's photosphere during solar eruptions; in some cases, the nuclei are produced through neutron captures, in a medium sufficiently dense to favor these reactions, but also sufficiently thin to allow γ-rays to escape.

Finally, the annihilation of an electron and a positron also gives rise to emission in the γ-ray domain. Positrons may be produced in astrophysical sites through the decay of π^+ pions or through the β^+ decay of radioactive nuclei. Depending on the conditions they may annihilate directly with electrons or combine first with them to form positronium. In the former case (at high temperatures, $T > 10^6$ K) two γ-ray photons of energy 0.511 MeV are produced. In the latter case, the resulting emission depends on the state of positronium: in 25% of the cases it is formed in the *para* (singlet, $^1S_0$) state and two photons of 0.511 MeV are again emitted; in 75% of the cases it is formed in the *ortho* (triplet, $^3S_1$) state and a continuous spectrum of three photons, each with an energy of $\leq$0.511 MeV, is then produced.

The γ-ray sky

The poor resolving power of current γ-ray instruments is one of the main problems in γ-ray astronomy (see GAMMA-RAY TELESCOPES). Observations in this energy range usually define 'error boxes', regions of the sky where the source most probably lies. Instruments launched in the 1990s provide error boxes of $\sim$1 arc min at low energies (the SIGMA telescope) and $\sim$5—10 arc min at higher energies (the EGRET instrument aboard CGRO), to be compared with, for instance, $\sim$0.1 arc sec in the visible. Identifying a source in these conditions is much more difficult than at other wavelengths. In the case of a variable source, the time-scale of variability sets an upper limit to the dimensions of the source (which cannot be larger than the distance light travels during this time-scale).

The sources of the γ-ray sky are extremely varied: some of them appear as 'points' (i.e. with angular dimensions smaller than the resolution of γ-detectors) and others as extended sources, both in our Galaxy and in the remote universe.

Stars on the main sequence (i.e. burning hydrogen in their cores) do not, in principle, radiate γ-rays and only the Sun has been observed to do so sporadically. During their advanced evolutionary stages, some stars may eject radioactive isotopes through their powerful stellar winds and become γ-ray emitters (red giants, Wolf–Rayet stars). However, radioactivity is mostly produced during stellar explosions (supernovae and, to a lesser extent, novae). On the other hand, stellar remnants may produce copious amounts of γ-rays in several cases: rotating neutron stars may convert a fraction of their rotational energy into high-energy photons (γ-ray pulsars), while accreting black holes convert the energy of accreted matter into low-energy γ-rays in their vicinity and present a steady or variable emission. Some of these objects produce jets of high-energy particles which interact with their environment to produce γ-rays. Finally, the emission mechanism of the mysterious γ-ray bursts is not understood yet, although it—most probably—involves compact objects (neutron stars and black holes).

The Sun

Since the first detection of its γ-ray emission, in 1958, the Sun has been regularly monitored by US, Soviet and Japanese satellites (OSO, HEAO, Prognoz, SMM, Hinotori, Yohkoh, CGRO). γ-rays are emitted continuously, but particularly during a brief period of intense activity, associated with the 11 yr cycle of solar flares (see SOLAR FLARES: GAMMA RAYS). During this period the energy stored in unstable magnetic configurations of the solar surface layers is suddenly liberated; particles are accelerated to high energies and their interactions produce γ-rays. The study of the γ-ray emission provides information on the acceleration sites, their physical conditions and their composition.

The low-energy part of the continuum γ-ray spectrum of the Sun results from bremsstrahlung emission of accelerated electrons interacting with the solar atmosphere. At higher energies (100 MeV) part of the emission is due to the decay of π^0s produced by the interactions of high-energy accelerated protons.

The de-excitation of atomic nuclei (excited by high-energy collisions) gives rise to prompt γ-ray lines, which may be narrow (when ambient nuclei are excited by energetic protons and α particles) or broad (when fast nuclei are excited by ambient protons and α particles). The most intense narrow lines are those at 4.438 MeV and 6.129 MeV, resulting from the de-excitation of the abundant ^{12}C and ^{16}O nuclei, respectively; the lines of several other nuclei (^{15}N, ^{20}Ne, ^{24}Mg, ^{28}Si and ^{56}Fe) have also been detected (figure 1). The relative intensities of these lines provide information on the isotopic composition of the Sun's surface.

The most intense solar γ-ray line, at an energy of 2.223 MeV, results from the de-excitation of deuterium nuclei (D), produced by neutron captures on protons; since free neutrons are unstable (they decay to protons within 10 min) the ones involved in the formation of deuterium are ejected by accelerated heavy nuclei. The ejected neutrons have to slow down to the thermal velocities of the ambient medium before being captured by the protons and thus they give rise to delayed γ-ray line emission. The delay time (about 100 s) provides information on the ambient density ($\sim 10^{17}$ particles cm^{-3}) and the location of the emission site in the solar photosphere (at a depth of $\sim$300 km).

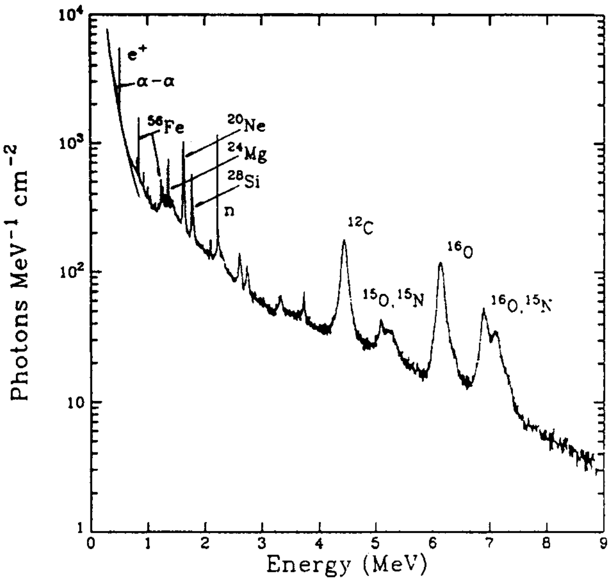

Figure 1. γ-ray spectrum of a solar flare modeled by Murphy *et al* (1991).

The second most intense line observed in the solar γ-ray spectrum results from the annihilation of positrons with electrons. Positrons are produced by β^+ decay of short-lived radioactive nuclei and of π^+ pions (both produced in high-energy interactions). Before annihilating, positrons have to slow down and their γ-ray emission is delayed (as in the case of neutrons).

Stellar explosions and remnants

Radioactive nuclei are produced by thermonuclear reactions in high-density environments, which are opaque to γ-rays. The photons of the radioactive decays interact with the ambient electrons and lose energy via Compton scattering; the medium is heated and the energy is ultimately radiated at longer wavelengths. Only in the case of a site violently expanding after an explosion (SUPERNOVAE, NOVAE) or suffering mass loss through a stellar wind (WOLF–RAYET STARS or stars in the asymptotic giant branch stage) can the γ-ray photons escape, since the opacity decreases with decreasing density.

The characteristic energy of escaping γ-ray lines enables one to identify isotopic species, while their intensity provides information on the amounts that have been synthesized and on the physical conditions of the corresponding stellar zones. The shape of the lines may give information on the structure (velocity and density profiles) of the stellar ejecta. These properties make γ-ray spectroscopy a unique tool for nuclear and stellar astrophysics.

These theoretical ideas, put forward mostly by D D Clayton in the 1960s, were spectacularly confirmed in 1987: the 0.847 MeV and 1.238 MeV lines of the decay of ^{56}Co were observed in SUPERNOVA 1987A, a massive star ($20M_\odot$) that exploded in the nearby galaxy of the Large Magellanic Cloud. Their detection confirmed that ^{56}Fe, the most strongly bound stable nucleus in nature, is produced in the form of unstable ^{56}Ni (through the decay chain $^{56}\mathrm{Ni} \longrightarrow {}^{56}\mathrm{Co} \longrightarrow {}^{56}\mathrm{Fe}$). It also confirmed that the observed late optical luminosity of supernovae (decreasing by a factor of $\sim$2 every 75 days) is due to the energy released by the radioactive decay of ^{56}Co (which has a half-life of 77 days). Finally, the appearance of the γ-ray lines about 6 months earlier than expected from theoretical models suggested that some of the ^{56}Ni nuclei, produced in the dense inner zones of the star, had been mixed into the outer layers.

The extraordinary opportunity offered by SN1987A was due to its proximity; indeed, it was the first supernova visible to the naked eye in the past four centuries, since supernovae are mostly detected in distant galaxies. Moreover, theory suggests that exploding massive stars (characterized as supernovae of type II or SNII) produce moderate amounts of ^{56}Ni ($\sim 0.1M_\odot$) and remain opaque to γ-rays for a long time ($\sim$1 yr, i.e. until the radioactivity of ^{56}Co has dropped to low levels). Supernovae of another class, SNIa, are much brighter γ-ray line emitters. They are white dwarfs in binary systems, undergoing a thermonuclear explosion, which is triggered by the accretion of mass from their companion star; they produce $\sim$10 times more ^{56}Ni and become transparent to γ-rays much earlier than SNII, because of their smaller envelope mass. Unfortunately, observations show that SNIa are less frequent than SNII and their occurrence in a closeby galaxy is unexpected, on statistical grounds. The first SNIa to be (marginally) detected in the light of the ^{56}Co lines was SN1991T in the Virgo cluster of galaxies, at an estimated distance of 55 million light- years (by CGRO). Future γ-ray line observations of extragalactic SNIa will provide important information on the physics of those poorly understood objects.

Long-lived radioactive nuclei can emit characteristic γ-ray lines hundreds or thousands of years after the supernova explosion, while they are evolving in an environment transparent to γ-rays. The 1.156 line of ^{44}Ti (half-life 60 yr) has been detected by CGRO in the remnant of Cas-A, presumably a massive star that exploded about 300 yr ago, at a distance of 7000 light-years from the Earth. The ^{44}Ti emission may help to reveal remnants of recent supernova explosions that are unobserved in other wavelengths, because of obscuration by surrounding material (i.e. dense molecular clouds or layers of dust).

Finally, for tens of thousands of years after the explosion the SUPERNOVA REMNANT may radiate high-energy γ-rays, produced by accelerated electrons and protons interacting with the ambient medium. The Crab remnant, observed since the late 1960s, as well as five other sources detected by CGRO, belongs to this class of γ-ray emitters.

γ-ray pulsars

PULSARS are rapidly rotating neutron stars, first detected in the late 1960s through their periodic radioemission. More than 550 radio pulsars are known to day, with periods ranging from a few ms to several seconds. Before the launch of CGRO, only the Crab and VELA PULSARS were known to emit periodically in the γ-ray domain. Since then five more objects have been added to the list and all of them (except Geminga) emit also in the radiofrequencies (figure 2).

The fact that only a small fraction of the radio pulsars emits in γ-rays suggests that a special environment is required for γ-rays to be produced. The required energy is presumably provided by the rotational energy of the neutron star, which slows down in the process; however, the emission mechanism as well as the role of the magnetic field and of the pulsar environment are not well understood. A hint may lie in the fact that the younger pulsars are more active in the low-energy ($\sim$1 MeV) domain than the older ones, which have in general weaker magnetic fields and emit essentially in the $>$100 MeV range.

GEMINGA is the only known pulsar with no detectable radio emission. Many years after its detection in γ-rays (by SAS-2), it represented an enigma, since it had not a counterpart in any other wavelength. Its period ($\sim$0.237 s) was first measured in x-rays by the German satellite ROSAT and confirmed in γ-rays by CGRO. Its distance, evaluated in the early 1990s to $\sim$100 light-years, makes it the closest known neutron star.

Accreting compact objects

NEUTRON STARS and BLACK HOLES are the end products of the evolution of massive stars and they may be found in binary systems (as happens with about half of the stars we observe in the Galaxy). Matter from the companion star may then be accreted onto the compact object, forming around it an ACCRETION DISK. As matter spirals in, heat is generated at the expense of gravitational energy and the inner disk may reach high temperatures. According to theory, disks around neutron stars may never reach temperatures higher than $T \sim 10^8$ K (corresponding to thermal emission in the x-rays), whereas disks around black holes may become much hotter ($T \sim 10^9$ K) and radiate in the low-energy γ-ray domain, up to a few hundreds of keV. γ-ray observations would allow then neutron stars to be distinguished from stellar black holes.

Observations with SIGMA and CGRO allowed a few black hole candidates in our Galaxy to be identified, on the basis of their γ-ray signature. Some of the sources show steady emission, while others present a variable behaviour (presumably as a result of variation in the accretion rate or of instabilities developed in their accretion disk). A typical example of this class of transient sources (or γ-ray novae) is the source GRS 1124-68, alias Nova Muscae. Detected in January 1991, it has been observed in radio, x-rays and γ-rays, its luminosity in the last of these energy ranges exceeding that of the Crab (which is the strongest γ-ray source in the sky).

An extremely important manifestation of variable γ-ray activity is the excess emission detected in the 300–600 keV range from the source 1E1740.7-2942, located

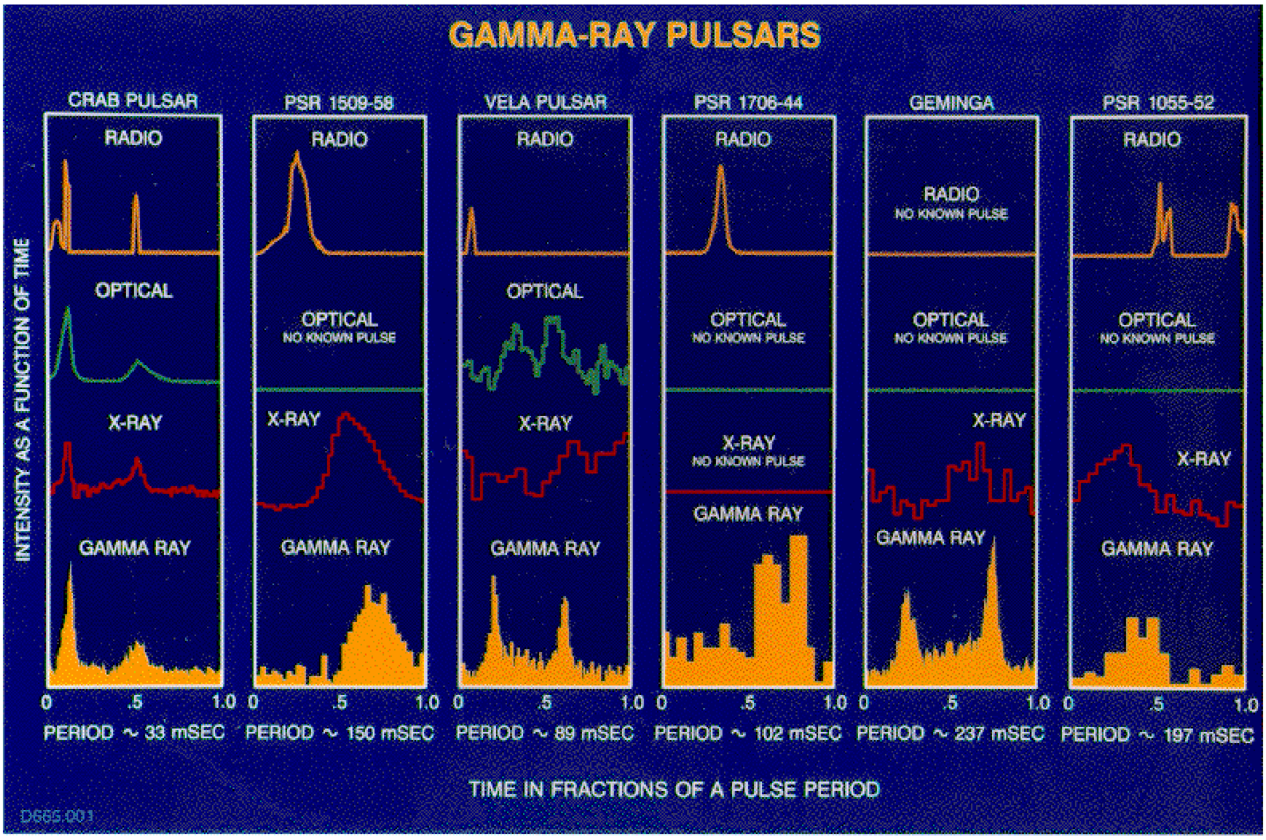

Figure 2. The folded light curves (intensity as a function of time) of various γ-ray pulsars at different energies (from radiowaves to γ-rays). A straight line means no known pulses. Explaining the variety of pulse shapes and energy dependences is a challenge to theorists.

in the galactic center region; observed for 2 days in October 1990 by SIGMA, this 'paroxysmic' activity has been interpreted in terms of electron–positron annihilation in the vicinity of a stellar mass black hole. Follow up radio-observations of the source revealed radio-emitting jets, presumably due to synchrotron emission of accelerated electrons. This behaviour (compact 'erupting' γ-ray source + radio jets moving at relativistic velocities) has also been observed in a few other sites in our Galaxy. These objects form the family of 'micro-quasars' (by analogy with the much more powerful and distant QUASARS) and represent ideal laboratories for the study of gravitational and relativistic astrophysics.

Diffuse γ-ray emission in the galaxy

Some of the 'products' of stellar activity may pervade the interstellar medium and give rise to diffuse γ-ray emission. This is the case of cosmic rays (energetic particles, accelerated by supernova explosions), long-lived radionuclei (decaying away from their production sites) and positrons.

Diffuse γ-ray emission from the Galaxy was first detected in 1968 by OSO-7 and galactic maps were provided by COS-B and CGRO. The emission correlates, in general, with features of the galaxy known from observations in other wavelengths: the molecular 'ring' at a galactocentric distance of 10 000–15 000 light-years, the spiral arms or a few molecular clouds, i.e. sites of rich gaseous content and active star formation. The analysis of the local γ-ray spectrum shows that at low energies (1–30 MeV) it results mainly from bremsstrahlung radiation of cosmic ray electrons; at higher energies, the emission of π^0s dominates. The LARGE MAGELLANIC CLOUD is the only other normal galaxy where γ-ray emission of this type has been detected.

During its million-year lifetime, radioactive ^{26}Al from more than 10 000 Wolf–Rayet stars and supernova explosions has been accumulated in the Galaxy's disk. Its characteristic 1.8 MeV line has been detected by HEAO-3 in 1984 and mapped by CGRO as diffuse emission along the galactic plane (figure 3). The HEAO-3 detection revealed that stars continue to enrich the Galaxy with their nucleosynthesis products. The galactic ^{26}Al map reveals, better than any other tracer, where the sites of current nucleosynthesis lie in the Milky Way.

Balloon-borne spectrometers detected in the 1970s the electron–positron annihilation line (at 0.511 MeV) from the Galactic center direction. For some time it was

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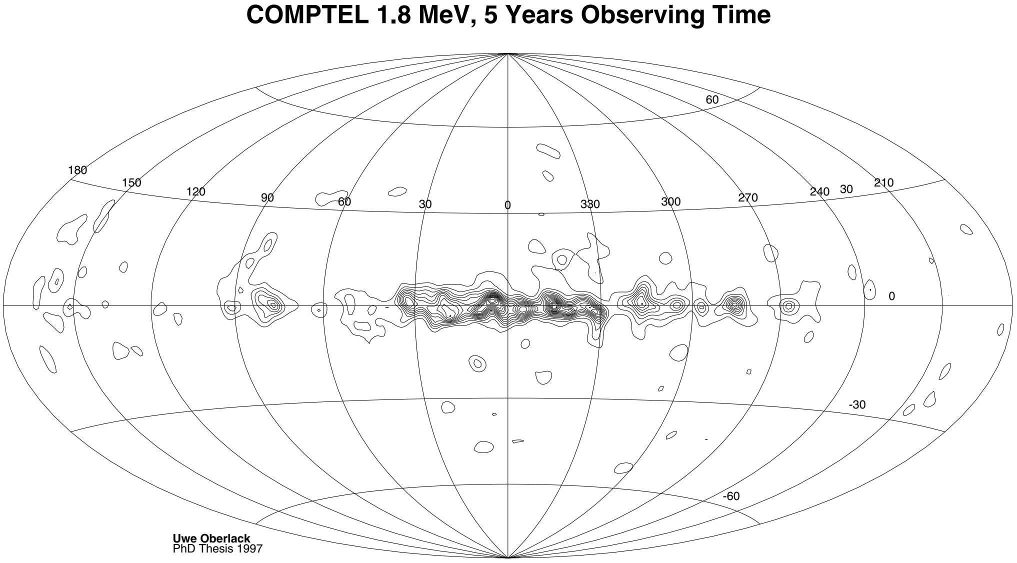

Figure 3. Map of the Galaxy in 1.8 MeV (^{26}Al line). Data from COMPTEL on CGRO.

thought that this emission was variable, but this variability was presumably due to the different properties of the instruments used. CGRO established the existence of diffuse (and steady) 0.511 MeV emission in the Milky Way, with $\sim$80% coming from the galactic bulge and the remaining $\sim$20% from the disk. Positrons produced by the β^+ decay of radionuclides, such as ^{26}Al, ^{56}Co and ^{44}Sc, are (most probably) at the origin of this galactic emission.

γ-ray bursts

Cosmic γ-ray bursts (GRBs), discovered in the late 1960s by the Vela satellites, are flashes of high-energy radiation which appear at random times from random directions, briefly dominating the γ-ray sky (from a few milliseconds to a few seconds) and then fading away. For more than a quarter of a century their nature remained a mystery: their non-thermal γ-ray emission presented no regularities at all, they did not seem to radiate in other wavelengths and it was impossible to evaluate their distances or to associate any known object with them.

The situation improved considerably in the 1990s. The BATSE instrument aboard CGRO detected about 1 burst per day for several years and established that their distribution in the sky is isotropic (figure 4). Such a distribution is naturally obtained from sources located at cosmological distances (several 10^8–10^9 light-years); in that case, their observed frequency implies about one burst per galaxy per million years, i.e. they represent events much rarer than supernovae. The Italian–Dutch x-ray satellite BeppoSAX allowed for an accurate location of GRBs, and in several cases relatively long-lived emission ('afterglow') at x-ray, optical and radio wavelengths was detected. In at least one case the afterglow optical spectra showed redshifted absorption lines due to the presence of remote intervening gas clouds, supporting the idea that the GRB is at a cosmological distance.

To be detectable at large distances, GRBs must radiate huge amounts of energy, about 10^{53} erg on average. Collisions involving neutron stars and/or black holes may produce such energies, mainly in the form of neutrinos, but the exact mechanism of the energy conversion to γ-rays is not elucidated yet. 'Fireball' models, involving material expanding at relativistic energies, seem the most promising at present.

Active galactic nuclei and blazars

The first detection of an extragalactic γ-ray source, the BRIGHT QUASAR 3C 273, was reported in 1978 by a team working with the COS-B satellite. Several other objects were subsequently detected in the low-energy γ-ray band ($<$1 MeV) and identified with the highly variable, moderately distant (redshift $z < 0.05$) ACTIVE GALACTIC NUCLEI (AGNs). In the 1990s, the EGRET instrument aboard CGRO detected high-energy γ-ray emission ($>$100 MeV) from several dozens of powerful and distant ($z > 2$) sources, a class of AGNs now known as BLAZARS; these objects radiate in their 'active' phase more energy in high-energy γ-rays (10^{45} erg s^{-1} on average) than in all other wavelengths.

The short time-scale of variability of AGNs (a few days to weeks for blazars), combined with their high γ-luminosities, suggests that accretion onto a massive black hole ($(10^6$–$10^9)M_\odot$) is the most probable power source. This idea could explain, in a unified framework, both the low-energy γ-emission of AGNs and the high-energy γ-emission of blazars. In the former case, the γ-rays are emitted from the hot inner regions of the accretion disk surrounding the black hole (as is the case with accreting stellar mass black holes in our Galaxy); in

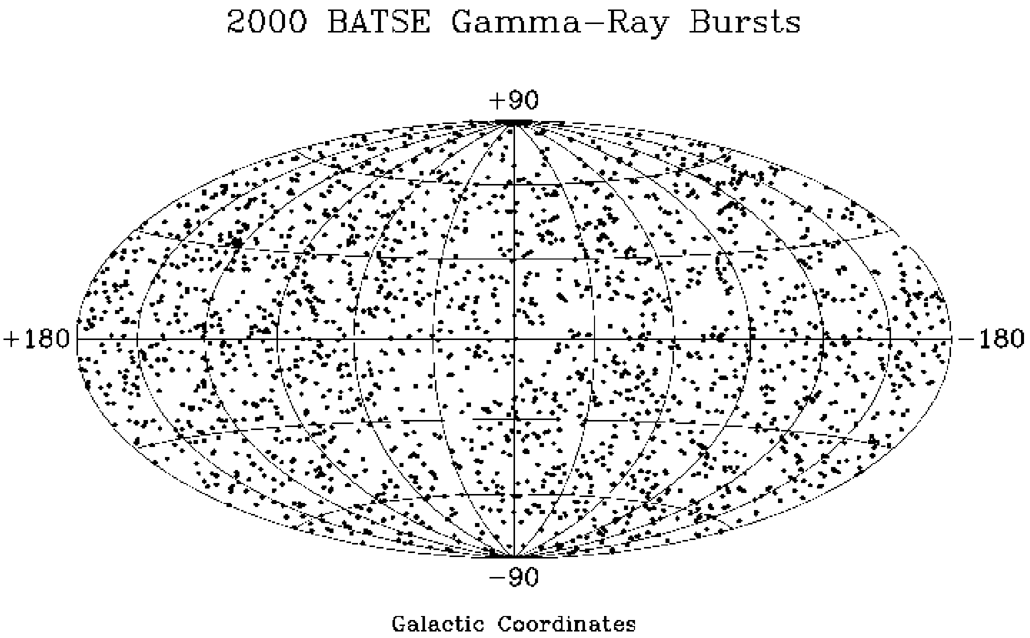

Figure 4. Isotropic distribution of GRBs in the sky.

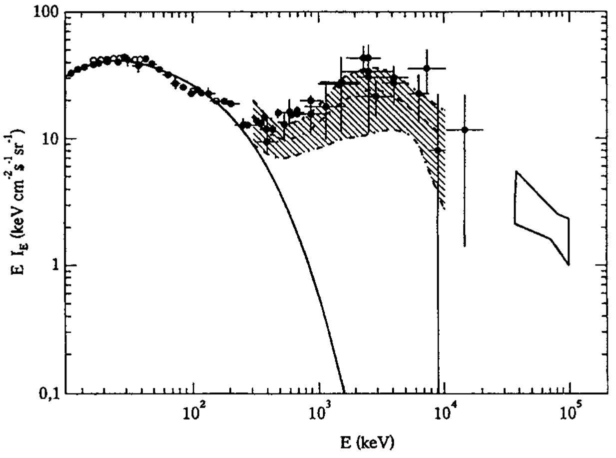

Figure 5. Diffuse extragalactic γ-ray background. Data compiled by Paul and Laurent (1998).

the latter case γ-rays are emitted by relativistic particles moving in diametrically opposite highly collimated jets (the intensity of the emission being enhanced along the direction of motion). This unified scheme seems able to explain not only the γ-ray properties of AGNs and blazars, but also their observed features in other wavelengths.

Diffuse extragalactic background

Since the early days of γ-ray astronomy, observations established the presence of a uniform, diffuse, isotropic γ-ray emission in the sky, most probably of extragalactic origin (figure 5). The most natural explanation for this diffuse γ-ray background involves the contribution of numerous extragalactic high-energy sources, unresolved by current instruments. In the low-energy range ($<$300 keV), the observed γ-ray background spectrum can be explained by the collective emission of Seyfert galaxies (a class of AGNs), while in the high-energy range ($\sim$100 MeV) it is the collective emission of blazars that prevails; indeed, in both cases, the observed spectra of resolved individual sources compare favourably with the observed diffuse spectrum. Finally, the CGRO found no excess diffuse emission in the intermediate range of $\sim$1 MeV, contrary to all previous reports (obtained by instruments with underestimated and difficult to assess instrumental 'noise'). Despite that, this intermediate spectral region is not satisfactorily explained by the combination of Seyferts and blazars and another source seems to be required; the superposition of redshifted nuclear γ-ray lines from remote SNIa (mostly from the decay of ^{56}Co) seems the most promising candidate.

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