History of gamma-ray telescopes and astronomy

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Abstract Gamma-ray astronomy is devoted to study nuclear and elementary particle astrophysics and astronomical objects under extreme conditions of gravitational and electromagnetic forces, and temperature. Because signals from gamma rays below 1 TeV cannot be recorded on ground, observations from space are required. The photoelectric effect is dominant <100 keV, Compton scattering between 100 keV and 10 MeV, and electron–positron pair production at energies above 10 MeV. The sun and some gamma ray burst sources are the strongest gamma ray sources in the sky. For other sources, directionality is obtained by shielding / masks at low energies, by using the directional properties of the Compton effect, or of pair production at high energies. The power of angular resolution is low (fractions of a degree, depending on energy), but the gamma sky is not crowded and sometimes identification of sources is possible by time variation. The gamma ray astronomy time line lists Explorer XI in 1961, and the first discovery of gamma rays from the galactic plane with its successor OSO-3 in 1968. The first solar flare gamma ray lines were seen with OSO-7 in 1972. In the 1980's, the Solar Maximum Mission observed a multitude of solar gamma ray phenomena for 9 years. Quite unexpectedly, gamma ray bursts were detected by the Vela-satellites in 1967. It was 30 years later, that the extragalactic nature of the gamma ray burst phenomenon was finally established by the Beppo–Sax satellite. Better telescopes were becoming available, by using spark chambers to record pair production at photon energies >30 MeV, and later by Compton telescopes

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for the 1–10 MeV range. In 1972, SAS-2 began to observe the Milky Way in high energy gamma rays, but, unfortunately, for a very brief observation time only due to a failure of tape recorders. COS-B from 1975 until 1982 with its wire spark chamber, and energy measurement by a total absorption counter, produced the first sky map, recording galactic continuum emission, mainly from interactions of cosmic rays with interstellar matter, and point sources (pulsars and unidentified objects). An integrated attempt at observing the gamma ray sky was launched with the Compton Observatory in 1991 which stayed in orbit for 9 years. This large shuttle-launched satellite carried a wire spark chamber “Energetic Gamma Ray Experiment Telescope” EGRET for energies >30 MeV which included a large Cesium Iodide crystal spectrometer, a “Compton Telescope” COMPTEL for the energy range 1–30 MeV, the gamma ray “Burst and Transient Source Experiment” BATSE, and the “Oriented Scintillation-Spectrometer Experiment” OSSE. The results from the “Compton Observatory” were further enlarged by the SIGMA mission, launched in 1989 with the aim to closely observe the galactic center in gamma rays, and INTEGRAL, launched in 2002. From these missions and their results, the major features of gamma ray astronomy are:

- Diffuse emission, i.e. interactions of cosmic rays with matter, and matter–antimatter annihilation; it is found, “...that a matter–antimatter symmetric universe is empirically excluded...”

- Nuclear lines, i.e. solar gamma rays, or lines from radioactive decay (nucleosynthesis), like the 1.809 MeV line of radioactive ^{26}Al ;

- Localized sources, i.e. pulsars, active galactic nuclei, gamma ray burst sources (compact relativistic sources), and unidentified sources.

Keywords Gamma ray · Telescope · Astronomy

Gamma-rays originate in nuclear decay processes, nuclear interactions and interactions in strong electromagnetic fields. Therefore, Gamma-ray astronomy’s aim is to investigate the nuclear and the high-energy universe. Originally, the nuclear universe had been presenting itself through the discovery of cosmic rays early in the twentieth century and the studies of their origin and propagation. After the discovery of the π -meson in 1947, and the $\pi^0 \rightarrow 2\gamma$ decay, it was clear that γ -rays (as seen, for example, by extensive air showers) could be produced by charged cosmic rays. High-energy nuclear interactions and cascade showers were observed in nuclear emulsions [1]. Therefore, possible sources of cosmic rays, like supernovae and their remnants, and places of cosmic ray confinement, like the galactic plane were expected to become visible in gamma-ray astronomy [2]. In addition, sites of nucleosynthesis [3] and the possible existence of antimatter were expected to reveal themselves if the sky was investigated in the light of gamma-rays. Cosmic rays, nuclear physics and elementary particle physics are the ancestors of gamma-ray astronomy.

Cosmic gamma-rays are absorbed quickly in the upper atmosphere, and their signal is drowned in the local background produced by the interaction

of cosmic rays with local matter. Thus, gamma-ray astronomy requires observations from space.

It is important to remember that nuclear physicists were used to construct and calibrate their own equipment and to translate their data into results of experimental observation. Working with one's hands has been an important ingredient in the process of “grasping” the meaning of the new discoveries. Therefore, the history of gamma-ray astronomy is the history of gamma-ray telescopes, constructed by the scientists themselves, flown on space missions. Some of these are very large observatories, others are more specialized experiments (Fig. 1).

It is a coincidence, though not completely fortuitous, that both, space observations and the study of high energy and elementary particle physics with large accelerators like CERN, became available in the late 1950s. At that time, elementary particle physics using cosmic rays came to an end, although most of the elementary particles had then been discovered using cosmic rays [4]. The cosmic ray community split up. Some went to the large accelerator laboratories, others into astrophysics, and gamma-ray astronomy became one of their new fields of interest.

The beginnings of gamma-ray astronomy were difficult. Philip Morrisons's paper [5] in 1958, in which he made an estimate of gamma-rays source strengths, raised hopes that balloon observations might permit gamma-ray

Fig. 1 Gamma-ray astronomy timeline

Fig. 2 Explorer XI

observations. But this was in vain. In reality, gamma-ray sources were so weak that observations with large equipment for extended periods from space were required. Explorer XI in 1962 [6], and its successor OSO-3 in 1968 [7] were the first successful gamma-ray astronomy experiments, indicating the prominence, in gamma-rays, of the galactic plane (Fig. 2).

The experiment on board of Explorer XI was the prototype of a gamma-ray telescope, consisting of an anticoincidence vessel, a converter of gamma-rays into electrons (by pair production, the Compton- or the photoeffect), de-

Fig. 3 Galactic plane observed by OSO 3

tecting them by a directional Cerenkov counter. Later instrumental improvements replaced the converter by a spark chamber, or by a Compton telescope, or by coded masks, in order to improve the directionality of the telescope (Fig. 3).

1 The galactic plane

The earliest signal of an astrophysical object in gamma-rays was the galactic plane, observed by OSO 3. From then on, one had a clear understanding of the sensitivities required. As a consequence, instruments in the energy range above 30 to 50 MeV were developed, where electrons and electron-positron-pairs were recorded and the gamma-ray direction determined from their visualisation in spark chambers. Their energies were determined either with scintillation calorimeters, or by multiple scattering measurements [8]. Gamma-rays resulting from the π^0 -decay have a mean energy of 70 MeV. SAS 2 (NASA) [9] was launched in 1972, COS – B (ESRO/ESA) in 1975. SAS 2, unfortunately, had a very short life only, but COS-B [10] observed the sky for 7 years. It was here in Noordwijk in 1970 that ESRO/ESA was finally convinced

Fig. 4 The COS-B payload and the first COS-B gamma-ray

Fig. 5 Imaging with pair telescopes > 100 MeV. In the COS-B map, the Cygnus Region, Inner Galaxy, Vela Pulsar and Crab and Geminga Sources beyond the “galactic hole” between 210° and 250° galactic longitude are visible. In the EGRET map, extragalactic sources are added, like 3C279, PKS 0524 + 134, the LMC, PKS 0208-512, or 3C454.3

to commit itself to a single aim gamma-ray astronomy satellite, COS-B [11] (Fig. 4).

COS-B is an example of translating technology into science: Its spark chamber was very long lived due to metal-ceramic technology, thus providing a large time integral, so that the first detailed map of the galaxy in gamma-rays could be recorded (Fig. 5).

Beyond the diffuse emission from the galactic plane expected from the interaction of cosmic rays with interstellar matter, the Crab and Vela pulsars were discovered in gamma-rays and the periodicity of their light curves observed.

Fig. 6 The Compton Gamma-ray Observatory. The four instruments are: Oriented Scintillation-Spectrometer Experiment OSSE [14], Burst and Transient Source Experiment BATSE [15], Compton Telescope COMPTEL [16], and Energetic Gamma-ray Experiment Telescope EGRET [17]

A first extragalactic source, 3 C 273 was seen by COS-B, although most of its observation time was directed towards the galactic plane.

In the late 1960s, NASA planned a number of High Energy Astrophysical Observatories (HEAO) which were to be free-flying very large satellites to be launched from the shuttle. At that time, Carl Fichtel and I agreed to collaborate and propose a very large Gamma-ray Experiment, which later (1978) became the proposal of C.E. Fichtel, R. Hofstadter and me of the Energetic Gamma-ray Experiment Telescope EGRET for HEAO. HEAO had a very complicated and involved history, but in the end it led to the Compton Gamma-ray Observatory (GRO) with EGRET part of its payload, launched in 1991. It is the status of gamma-ray astronomy after COS-B and before EGRET, which is well documented in C.E. Fichtel and J.I. Trombka's book [12], while the status in 2001 is well recorded in Schönfelder's compilation [13] (Fig. 6).

In the energy range from about 30 MeV to several GeV, impressive pictures of the gamma-ray sky have been produced by COS-B, EGRET, adding extragalactic observations, and, very recently the Fermi gamma-ray space telescope (Fig. 7).

The diffuse emission from the plane of the galaxy, resulting from interactions of cosmic rays with interstellar matter is conspicuous. Also, the Large Magellanic Cloud is visible in gamma-rays, probably by the same process. In a way, the gamma-ray observations wrap up what we know of cosmic rays from the most recent observations of their composition and spectra: they are interstellar matter, accelerated by the turbulent motion of plasma and magnetic fields; they reside within the galaxy (galaxies), their intensity in intergalactic space is low.

Fig. 7 Fermi gamma-ray space telescope 2008: 4 days exposure. Display of the enormous power of this most recent instrument (http://science.nasa.gov/headlines/y2008/26aug_firstlight.htm)

2 Localized sources

Embedded in the galactic plane, but also extending beyond the galaxy, gamma-ray point sources are visible. The Crab and Vela pulsars, spin-down neutron stars, are one class (Fig. 8). Other sources, known from x-ray astronomy, are accreting binaries. A sub-class of accreting binaries are superluminal jet sources—accreting, rapidly spinning black holes. And finally, supernovae and their remnants also are visible in gamma-rays.

A particular feature of gamma-ray point sources is their variability. Variability is a great help in the identification of gamma-ray point sources with astronomical objects which are known from other spectral regions. A complete understanding of the astrophysics involved requires these identifications, which are sometimes very difficult and uncertain [18].

Fig. 8 High energy pulsar light curves

3 The sun

In the 1960s, interest in the sun as a gamma-ray source was large as part of the general interest in solar physics and the physics of the interplanetary medium, which received strong support from the aim to land a man on the moon, because the astronauts had to be protected from the impact of solar flares.

Solar flares were predicted to emit gamma-ray lines at 0.511 MeV due to positron annihilation, at 2.2 MeV due to neutron capture, at 4.4 and 6.1 MeV from the de-excitation of carbon and oxygen nuclei. Peterson and Winckler [19] discovered high-energy bremsstrahlung gamma-rays in a balloon experiment, and Chupp et al. [20] discovered nuclear lines in two large flares by the OSO-7 satellite. The sun can be the brightest source of gamma-rays in the sky, making it unnecessary to apply special pointing equipment.

4 Gamma-ray bursts

When the Vela-satellites in 1967 discovered the gamma-ray burst phenomenon, this was completely unexpected. The Vela satellites were operated in order to detect nuclear explosions and to enforce the nuclear test ban treaty. However, it soon became clear that the gamma-ray burst phenomenon observed had nothing to do with nuclear explosions on earth. The gamma-ray bursts are by far the brightest objects in the gamma-ray sky. The Burst and Transient Source Experiment BATSE (<http://www.batse.msfc.nasa.gov/batse/>) on board the Compton Gamma-ray Observatory detected more than 2,000 bursts until 1998, with an isotropic distribution. BATSE consisted of a number of flat scintillation counter discs, pointing in different directions. Because a gamma-ray burst is so luminous, the relative amplitude of the gamma-ray signal recorded in the various scintillators allows

Fig. 9 Gamma-ray lines from solar flares. The lines from the de-excitation of nuclei are indicated, positron-electron annihilation results in the 511 keV, and neutron capture in the 2.2 MeV line. RHESSI stands for Ramaty High-Energy Solar Spectrometer Imager [21]

Fig. 10 BATSE catalogue of 2,704 gamma-ray bursts. The colour code of the data points refers to the fluence (i.e. integral energy flux) recorded: from red (10^{-4} erg/cm 2) to dark blue (10^{-7} erg/cm 2)

the direction of arrival of the gamma-rays to be derived to within about one degree.

In 1997, the Italian–Dutch satellite BeppoSax was able to identify several burst sources because X-ray and optical observations of the transient source al-

Fig. 11 Principle of the Compton telescope technique

lowed identification and observation of red shifts of 0.835 and 3.42, respectively [22]. Gamma-ray luminosities of 7×10^{51} erg and 3×10^{53} erg were derived, assuming isotropic emission. In 1999, Akerlof et al. [23] detected bright optical emission from a burst and derived a luminosity of 3.4×10^{54} erg assuming isotropic emission. For comparison, the rest mass energy of the sun is 1.6×10^{54} erg and therefore, very massive objects must be involved to produce these enormous energies.

5 Low-energy (1–30 MeV) gamma-rays

Another instrument on board of GRO was the Compton Telescope COMPTEL, observing the sky in the range from 1–30 MeV [11, 14].

The development of the Compton scattering technique in the 1960s at the Max Planck Institute in Garching followed the construction of a neutron telescope, in which two successive elastic recoil collisions of an incoming neutron with hydrogen nuclei were recorded in thin spark chambers. This successful experimental approach led to the development of a Compton Telescope, recording first, the recoil electron in a first Compton collision and secondly, the total remaining energy of the scattered photon. As shown in Fig. 9, this technique allows the gamma-ray's direction to be determined to lie on an “event circle”. It would be an improvement if it were possible to determine the azimuthal angle of the recoil electron. For the time being, a statistical

Fig. 12 Imaging with Comptel

analysis makes it possible to construct sky maps, and to observe localized sources (Figs. 10, 11, and 12).

The sky map of low-energy (1–30 MeV) gamma-rays [24] shows similar features to that at higher energies. The sky map of ^{26}Al [25] is taken as an example of the topic of nucleosynthesis and gamma-ray astronomy. Because its radioactive decay time is 1.04×10^6 years ^{26}Al accumulates in the interstellar medium from many different sources. Gamma-ray lines from radioactive decay can be well studied with the SPI instrument aboard INTEGRAL. This is a coded mask telescope with a solid state Germanium detector [26] (<http://www.mpe-garching.mpg.de/gamma/instruments/integral/spi/www/>) (Fig. 13).

Extragalactic gamma-ray sources have been studied by the SIGMA mission (covering the hard X-ray/low energy gamma-ray region) and GRO with its instruments OSSE, COMPTEL, and EGRET. They consist of active galactic nuclei (AGN), pulsars, supernovae and supernova remnants and unidentified objects, likely to involve massive objects. Variability is one of the characteristics of gamma-ray sources (Fig. 14).

Fig. 13 ^{26}Al gamma-ray line as seen by INTEGRAL-SPI [27]

Fig. 14 Catalogue of gamma-ray sources. A compilation of the 3. EGRET Catalogue [28] and the 1. Comptel Catalogue [29]

In the study of individual sources, gamma-ray astronomy connects to astronomy at other energies (wavelengths). As mentioned before, gamma-ray sources in the TEV region have not been considered here. They will be the topic of the presentation by H. Völk.

However, there is particular interest in the nature of the gamma-ray background. At intermediate energies, careful analysis has led to the conclusion, that the gamma-ray background is produced by unresolved point sources. This leads to one result, rather exclusive to gamma-ray astronomy, and perhaps more fundamental than the other—albeit exciting—results: from their study of the 1 to 10 MeV gamma-ray background radiation, A.G. Cohen, A. de Rújula, and S.L. Glashow [30] “conclude that a matter–antimatter symmetric universe is empirically excluded.”

6 Conclusions

If one asks what the particular contribution of gamma-ray astronomy is to our knowledge of the universe, then the following summary could be made:

- Gamma-rays are produced by cosmic ray interactions, also due to large-scale acceleration processes, using mechanical energy of the clouds of the interstellar medium; they reside inside the galaxies: the acceleration process is slow, using the mechanical energy of magnetized clouds;
- Other forms of acceleration processes also produce gamma-rays, be it directly or through interactions of the accelerated particles, like in solar flares, or massive accreting or objects. These sources are highly variable and belong to the most luminous objects in the sky: strong acceleration processes using the rotational energy of spinning or accreting massive and/or magnetized objects.

- Gamma-ray lines indicate the sites and the nature of processes of nucleosynthesis.
- A completely different aspect of high significance is given by the absence of nucleon-antinucleon annihilation gamma-rays, which should be seen in the 1 to 10 MeV region, red-shifted from the π^0 -decay. The diffuse gamma-ray flux from COMPTEL, lies several orders of magnitude below the annihilation flux expected for a universe, in which matter–antimatter symmetry is achieved by dividing it into regions populated exclusively by matter or antimatter.

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