Part 2

The Data Base of High Energy Astrophysics

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The Gamma-Ray Astronomy Database: 1990-2002

K. Hurley

University of California, Space Sciences Laboratory, Berkeley, CA 94720-7450, USA

Abstract.

I review five missions (SIGMA/GRANAT, the Compton Gamma-Ray Observatory, BeppoSAX, the Interplanetary Network, and the High Energy Transient Explorer) which have contributed to a golden age of discovery in gamma-ray astronomy. The data from many of these missions and experiments have been archived and are available to the public to analyze.

1. Introduction

Experimental gamma-ray astronomy is 44 years old. In that time, gamma-radiation has been detected from the Earth, its auroral zones and its atmosphere, the surfaces of the Moon, Eros, and Mars, the Sun, neutron stars and black holes in the Galaxy, the disk of the Galaxy, and active galactic nuclei and gamma-ray burst sources at cosmological distances. Because gamma-ray astronomy is a relatively young discipline, much of its data has been archived in various databases, many of which are accessible to the public.

In this paper, I will review the major missions which have contributed to this database. The start date, 1990, corresponds to the beginning of a "golden age" of gamma-ray astronomy. We are still living in this age, and it should continue for years to come. The end date is the present date, 2002; future missions are discussed elsewhere in these proceedings.

2. The Early History of Gamma-ray Astronomy

In the 1950's, there were several predictions of gamma-ray emission from various cosmic objects (Hayakawa 1952, Burbidge et al. 1957, Morrison, 1958). Although some predictions proved to be optimistic, the first experiments did indeed measure cosmic gamma-radiation.

Some of these early measurements were the detection of solar gamma-rays (Peterson and winkler, 1958), the discovery of 100 keV - 3 MeV diffuse cosmic gamma-radiation (Metzger et al., 1964), the detection of >50 MeV gamma-rays (source unknown, Kraushaar, 1965), and the detection of gamma-radiation from the Crab (Haymes et al., 1968). In 1972, NASA launched the SAS-2 spacecraft, which ultimately detected ≈600 cosmic gamma-rays from ≈5 sources in the >35 MeV energy range. 1973 saw both the announcement of the discovery

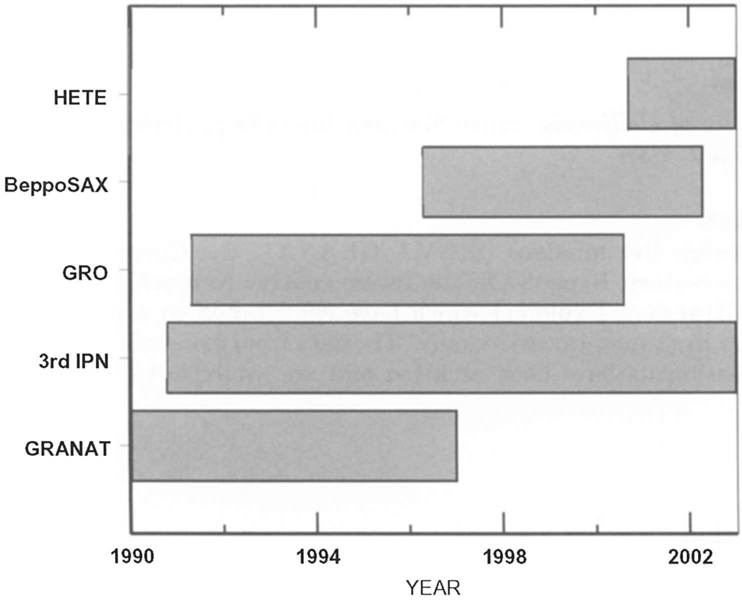

Figure 1. Timelines of the missions considered here.

of cosmic gamma-ray bursts (Klebesadel et al. 1973) and the first detection of solar gamma-ray line radiation (Chupp et al. 1973). The European Space Agency launched the COS-B satellite in 1975, which eventually discovered ≈25 70-500 MeV sources. Electron-positron annihilation radiation was detected by Leventhal, MacCallum, and Stang (1978) with a balloon-borne Ge spectrometer, and 1.8 MeV ^{26}Al line emission was announced by Mahoney et al. (1984) based on HEAO-C results. Finally, in 1990, Leising and Share (1990) found ^{56}Co line emission from SN1987A.

Thus by 1990, it was clear that there *was* such a thing as gamma-ray astronomy. However, few of these early experiments had any imaging capability, and this often led to confusing or contradictory results.

3. The Missions of the Golden Age

For the purposes of this paper, I will define gamma-rays to be photons with energies between approximately 20 keV and 30 GeV, detected with space-based instrumentation, and gamma-ray sources to be either steady or transient, diffuse or point-like, excluding the Sun and the planets. The timelines of the missions which have operated since 1990 are shown in figure 1, and figure 2 shows the progress in gamma-ray astronomy, using the number of sources detected by various missions as a metric, since 1972. Figure 3 shows the energy coverage of

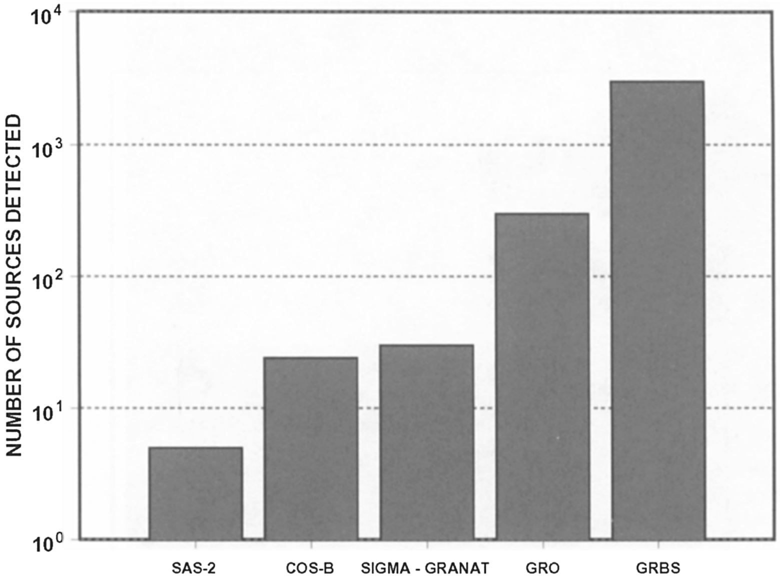

Figure 2. Number of sources detected by various mission. SAS-2 operated during 1972, COS-B from 1975 to 1982, SIGMA-GRANAT from 1989 to 1998, and GRO from 1991-2000. The number of gamma-ray bursts (GRBS) shown were detected by various missions between 1973 and the present.

some missions. From this figure, it is evident that not all gamma-ray astronomy missions have confined their coverage strictly to the gamma-ray energy range. In fact, multi-wavelength coverage has proved to be crucial to the understanding of most gamma-ray sources.

3.1. SIGMA/GRANAT

The SIGMA telescope aboard the GRANAT spacecraft was the first space-based gamma-ray imaging telescope. It employed a coded mask and scintillator to achieve $\approx 10'$ resolution over an $\approx 5 \times 5^{\circ}$ field of view. One of SIGMA's major achievements was to produce the first gamma-ray images of the Galactic center region. It eventually dedicated >3000 h of observations of this area, detecting 15 sources. These observations demonstrated that this region contained variable sources which had not been resolved by previous, non-imaging experiments. One of those sources, 1E1740-2942, was shown to be a Galactic microquasar (Mirabel & Rodriguez 1998). Although jet sources such as SS 433 were known prior to the launch of GRANAT, it was the powerful multi-wavelength combination of gamma-ray imaging with SIGMA and radio imaging with the VLA which made the discovery of microquasars possible.

In the following subsections, I will briefly review the missions since 1990, selecting in each case a few of what I consider to be their major achievements.

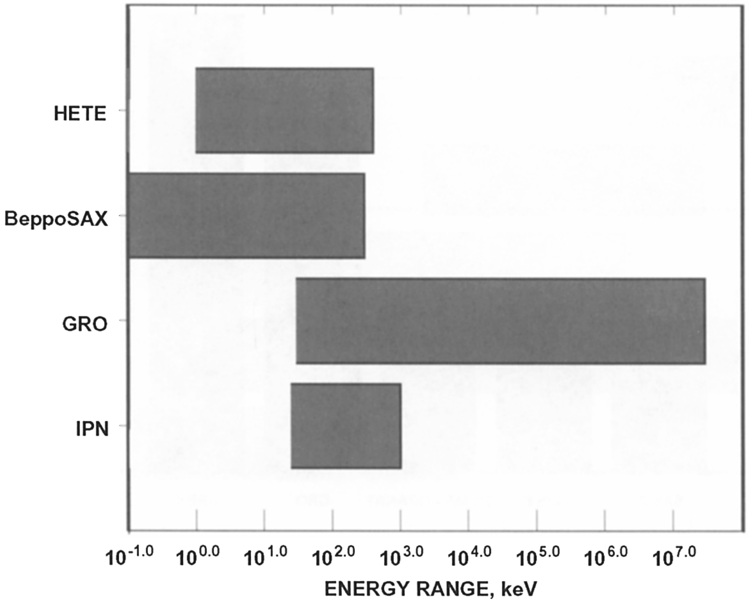

Figure 3. Energy ranges of the missions discussed in this paper. Some extend well beyond the traditional gamma-ray range. Multi-wavelength coverage is in fact essential for understanding gamma-ray sources.

Another SIGMA contribution was the observation of variable line emission from Galactic point sources. Earlier evidence for such emission was difficult to confirm, in part because of the lack of imaging experiments. SIGMA detected broad, time-variable lines from Nova Muscae (Gilfanov et al. 1991) and the microquasar 1E1740-2942 (Cordier et al. 1993). One observation of the 1E source proved to be controversial (Jung et al. 1995), and the exact interpretation of the other two is uncertain (they could be redshifted electron-positron annihilation lines or nuclear lines), so the final demonstration of the existence of such features may have to be done with missions such as INTEGRAL.

SIGMA's legacy was the demonstration that the gamma-ray sky is dynamic, with variability on all timescales, and crowded. Imaging is a necessity to understand gamma-ray observations. Today, this point seems obvious, but SIGMA was the first to actually accomplish this.

3.2. The Compton Gamma-ray Observatory (GRO)

GRO was one of NASA's four great observatories. It covered an unprecedented 6 decades in gamma-ray energies, from 30 keV to 30 GeV, with a unique combination of four instruments, BATSE, OSSE, COMPTEL, and EGRET. Of the

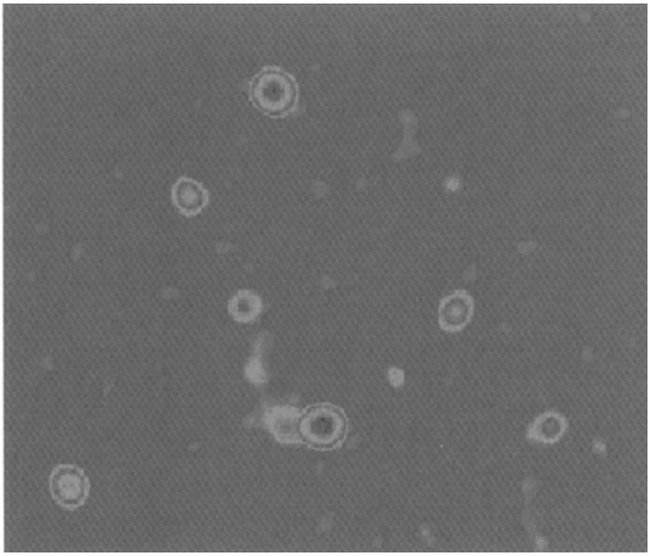

Figure 4. SIGMA image of the galactic center region, with numerous previously unresolved point sources. This image is from www-dapnia.cea.fr/Sap/Activites/Science/Compact/CentreGalactique/index.html.

four, only COMPTEL and EGRET were imagers, but source positions could be obtained by other means to roughly degree accuracies by the others.

One of the great innovations of GRO was the ability of BATSE to transmit the coarse positions of gamma-ray bursts (GRBs) to the ground in near-real-time. This made it possible to develop rapidly slewing ground-based telescopes to search for optical emission simultaneous with bursts. This resulted in the first, and so far the only, detection of such emission. The Rapid Optical Transient Search Experiment observed the error box of GRB990123, and found a transient source which reached 9th magnitude before fading (Akerlof et al. 1999). This has been interpreted as being caused by an reverse shock in the fireball model (Sari & Piran 1999).

A second surprising result, again due to BATSE, was to demonstrate that the GRB population was *both* isotropic and homogeneous (Meegan et al. 1992). Prior to BATSE, isotropy appeared likely, but the statistics were too poor to prove it with sufficient accuracy, while inhomogeneity (as measured by the number-intensity relation) could not be convincingly demonstrated because of the lack of sensitivity of earlier experiments. These two properties gave the first reliable evidence that GRBs were cosmological, although it was to be several more years before their cosmological origin could be proved beyond a doubt.

The existence of a diffuse ^{26}Al was not in doubt before the launch of GRO; it had been detected by HEAO-C (Mahoney et al. 1984) and confirmed by SMM (Share et al.1985). What was uncertain was its actual distribution. COMPTEL succeeded in mapping this emission for the first time (Diehl et al. 1994; figure

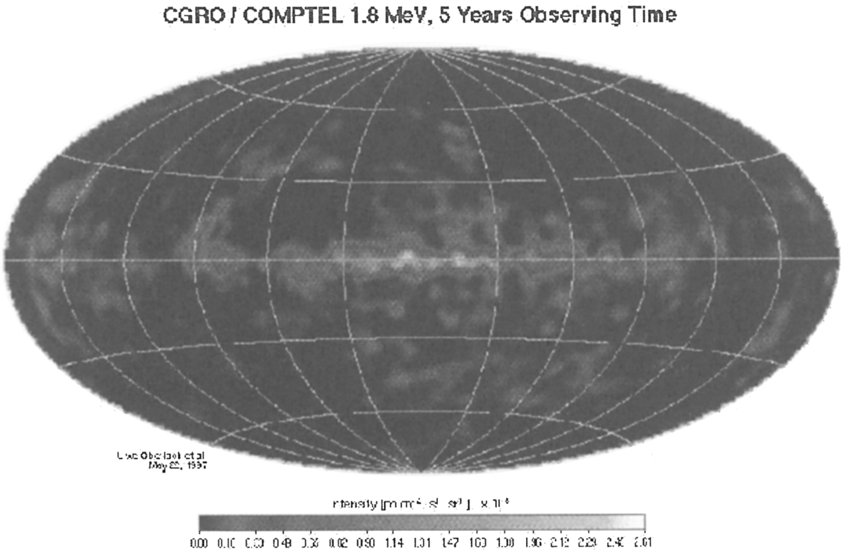

Figure 5. Galactic coordinate map of the ^{26}Al line from COMPTEL. From cossc.gsfc.nasa.gov/comptel/index.html

5). From this map, more detailed models of its origin could be constructed. One current working hypothesis is that the line originates from core-collapse supernovae and Wolf-Rayet stars.

EGRET produced the first all-sky survey at energies $>$ 100 MeV (figure 6). From it, the diffuse emission from the Galactic disk was mapped (Hunter et al. 1997), blazars were discovered (Mukherjee et al. 1997), and 20 GeV emission was measured from a GRB, the highest energy to date (Hurley et al. 1994). The EGRET source catalog includes 270 objects, including pulsars and AGNs, but 170 remain unidentified.

It would be difficult to overstate the impact of GRO. Prior to this mission, only people with gamma-ray experiments could be gamma-ray astronomers, and accordingly, there were few of them. GRO made it possible for any astronomer to do gamma-ray astronomy, either as a guest investigator, or simply by using the archived data (GRO data were archived between 3 and 12 months after the observations). Today it is clear that high energy emission is an important, sometimes dominant, feature of many astrophysical objects. Thanks to GRO, gamma-ray astronomy has entered the mainstream.

3.3. BeppoSAX

This Italian-Dutch mission had five instruments, covering the 0.1 - 300 keV energy range. Only one, the Phoswich Detection System (Frontera et al. 1991), was actually a gamma-ray detector, but the mission's multi-wavelength coverage proved to be a unique and valuable feature.

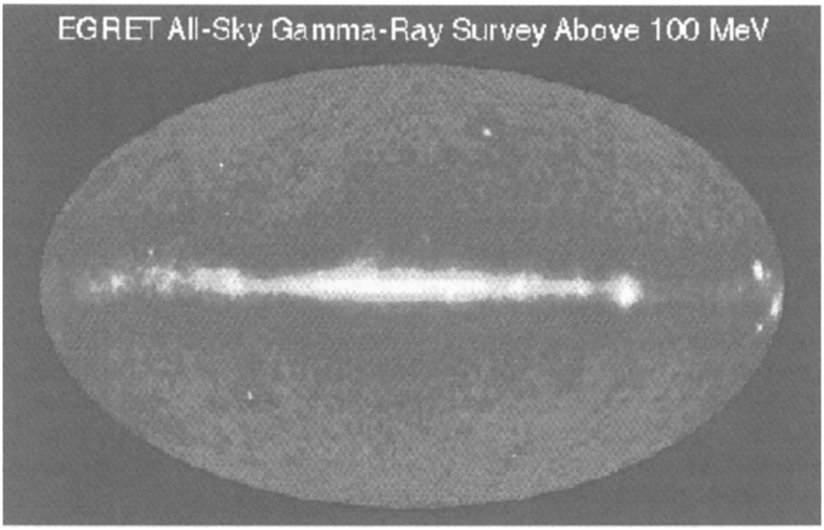

Figure 6. Galactic coordinate map of the sky in gamma-rays with energies > 100 MeV. The diffuse emission from the Galactic disk can be seen, as well as point sources at high Galactic latitudes. From cossc.gsfc.nasa.gov/egret/index.html

Before the launch of BeppoSAX, GRB energy spectra were thought to contain too few photons below 10 keV to be interesting, and in particular, too few to image. However, BeppoSAX was indeed able to obtain 2-30 keV images of bursts with its Wide Field Camera and slew the spacecraft to carry out deeper observations with the narrow field instruments in the 0.1 - 10 keV range. These rapid, precise localizations of bursts at X-ray wavelengths (e.g. Costa et al. 1997) led to the discovery of optical (van Paradijs et al. 1997) and radio (Frail et al. 1997) counterparts, which in turn ultimately demonstrated beyond any doubt that bursts were at cosmological distances, ending a 25 year old mystery. Review talks on GRBs, and the role of BeppoSAX in studying them, have been given at this symposium.

If nothing else, the BeppoSAX mission showed how important it is to attempt observations at different frequencies and on different timescales when exploring a field like gamma-ray astronomy, where a complete census of sources and their characteristics has not been carried out.

3.4. The Third Interplanetary Network (IPN)

Interplanetary networks are collections of up to about half a dozen widely separated spacecraft equipped with GRB detectors. The 3rd IPN started operations in 1990 with the launch of the Ulysses spacecraft. Today, it also contains Mars Odyssey, Wind, the High Energy Transient Explorer, and the Ramaty High Energy Solar Spectroscopic Imager; INTEGRAL is presently being added to it. The various IPN detectors cover the 25 keV - 1 MeV energy range. The network locates gamma-ray burst sources by comparing burst arrival times at the spacecraft, and has localized about 1000 bursts to date. The best achievable accuracy is of the order of an arcminute. The network as a whole is isotropic, with a duty cycle close to 100%; however, due to the limitations imposed on experiments aboard interplanetary spacecraft, is generally sensitive only to the stronger bursts.

One of its major achievements has been a decade of continuous monitoring of the soft gamma repeaters (SGRs). These sources are thought to be magnetars, that is, neutron stars with magnetic fields whose strengths are of the order of 10^{14} G. This monitoring has resulted in the discovery of a new candidate SGR (Cline et al. 2000), as well as the observation of a giant flare from SGR1900+14 (Hurley et al. 1999). This is only the second such event observed from an SGR since 1979, and it provides additional evidence for the magnetar model.

The IPN also detected and localized GRB000131 (Andersen et al. 2000). Optical follow-up observations of this event reveled that it is at a redshift of 4.5, making it the highest redshift GRB observed to date.

Finally, a surprising result is the observation of strong outbursts from Cygnus X-1 (Golenetskii et al. 2002). These outbursts display fluxes which are about one order of magnitude larger than any previously known state of this source.

3.5. The High Energy Transient Explorer (HETE)

HETE is the first mission dedicated entirely to the study of GRBs. It was launched in 2000, and is still operating. The spacecraft has 3 instruments, covering the energy range $\approx 1 - 400$ keV. HETE is the first mission to provide both rapid *and* precise localizations of bursts. Prior to HETE, burst localizations could be obtained rapidly (in near real-time, in fact), but they were coarse (several degree accuracy), or precisely (e.g., with the IPN or BeppoSAX), but they were delayed by hours to a day or more. More details about the mission have been presented at this symposium.

Since HETE is still operating, it is too early to discuss its legacy. However, HETE's major achievements to date include rapid, precise localizations of two classes of bursts which we know almost nothing about, namely x-ray rich GRBs, and short-duration, hard-spectrum GRBs (for which no counterparts have been identified).

3.6. Conclusions

The data from many of the missions and experiments discussed above have been archived in the High Energy Astrophysics Science Archive Research Center, or HEASARC (heasarc.gsfc.nasa.gov). In many cases, the data are still being analyzed and significant discoveries are being made. This means that *you* can be a gamma-ray astronomer, for a day, a month, or longer, while the golden age lasts.

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