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Gamma-ray Bursts

https://doi.org/10.1017/S0074180900055935 Published online by Cambridge University Press

GAMMA-RAY BURSTS: OBSERVATIONAL OVERVIEW

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Abstract. Gamma-ray bursts remain one of the greatest mysteries in astrophysics in spite of new and more detailed observations made with the BATSE experiment on the Compton Observatory. The new observation with the greatest impact has been the observed isotropic distribution of bursts along with a deficiency of the weak bursts which would be expected from a homogeneous burst distribution. This is not compatible with any known Galactic population of objects. Other recent important observations include an enormous variety of burst morphologies and gamma-ray burst photons extending to GeV energies. A time dilation effect has also been reported to be observed in gamma-ray bursts.

1. Introduction

Gamma-ray bursts are a phenomenon without precedent in astronomy, having no quiescent counterpart in any other wavelength region, no observations that would provide a direct measure of their distance and no comprehensive model that can explain their origin. Furthermore, the bursts have an extremely wide variety of durations, temporal profiles and spectral variations, which makes modeling them all the more difficult.

It is now over 25 years since the discovery of gamma-ray bursts, and their origin appears as elusive as ever. The field of gamma-ray bursts has undergone a rapid, dramatic, and to many, a surprising change over the past three years as a result of new, more sensitive observations of the gamma-ray sky distribution. The observed isotropy and inhomogeneity of these objects represent a distribution unlike any other known galactic objects. Over a hundred theories of their origin have now been catalogued (Nemiroff 1994).

J. van Paradijs et al., (eds.), Compact Stars in Binaries, 467–476.

https://doi.org/10.1017/S0074180900055935 Published online by Cambridge University Press

These models cover distance scales from the local Oort cloud to cosmological distances. Whatever the distance scale, it will most likely represent a new class of objects, processes and/or emission mechanisms. This paper describes some of the observed properties of gamma-ray bursts, primarily their temporal and spectral characteristics and their distribution. Models based upon bursts at cosmological distances are described in another paper in these proceedings (Piran 1995).

Considerable observational progress has been made in the past few years as more sensitive space-borne detectors have become available. Most of the observations in this paper were made with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory. While many of the observational results are relatively straight-forward, some of the properties and interpretations of ensembles of bursts have become subject to debate. Details of some of the more recent observational results can be found in conference proceedings that have been published in the past three years (Paciesas & Fishman 1992; Friedlander, Gehrels & Macomb 1993; Fishman, Brainerd & Hurley 1994).

2. Time Profiles

Perhaps the most striking features of the time profiles of gamma-ray bursts are their morphological diversity and the large range of burst durations. Coupled with this diversity is the general inability to place many gamma-ray bursts into well-defined classifications. Several attempts have been made in the past to categorize gamma-ray burst morphologies. This difficult task is always hampered by bursts with multiple characteristics, bursts that are too weak to classify, and the rather arbitrary and subjective (non-quantitative) ways that classes are defined. Examples of extreme differences in burst morphologies and durations are shown in a sample page (Fig. 1) from the First BATSE Burst Catalog (Fishman *et al.* 1994).

Weaker bursts have been shown to have the same temporal diversity as the stronger bursts even though the temporal variations are of lower statistical significance (Lestrade 1994). A cursory examination of burst profiles indicates that some are chaotic and spiky with large fluctuations on all timescales, while others show rather simple structures with few peaks. However, some bursts are seen with both characteristics present within the same burst. No periodic structures have been seen from gamma-ray bursts.

The durations of gamma-ray bursts range from about 10 ms to over 1000 s in the energy range in which most bursts are observed (below 1 MeV). Sub-millisecond structure has been detected in at least one burst (Bhat *et al.* 1992). Recent EGRET observations show high-energy (>100 MeV) emission lasting 1.6 hours after the burst trigger (Hurley *et al.* 1994) from a burst

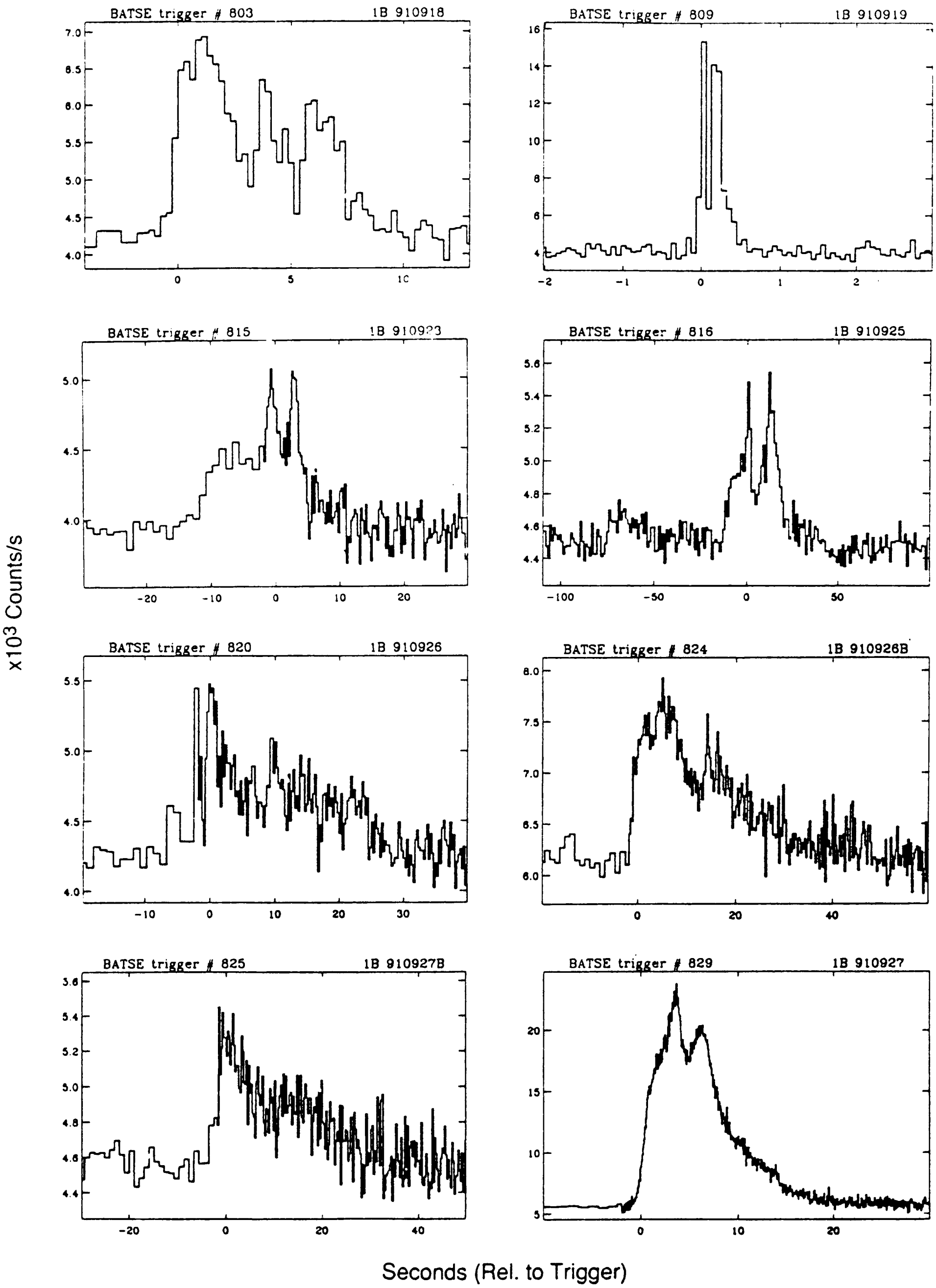

Figure 1. **A sample of eight gamma-ray bursts from the first BATSE Catalog (Fishman *et al.* 1994), showing the extreme range of burst time profiles and durations.**

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that occurred on 17 February 1994. At the lower photon energies, characteristic of that observable with the BATSE and Ulysses detectors, this gamma-ray burst lasted only 180 s. During this initial time, EGRET observed about a dozen high-energy photons, with energies as high as 4 GeV. EGRET high energy photons are seen coming from the burst direction as late as 1.6 hours after the initial outburst. Fig. 2 (from Hurley *et al.* 1994) shows the composite time profiles of this burst, as seen with the EGRET, BATSE, and Ulysses experiments.

A bimodality is seen in the logarithmic distribution of gamma-ray burst durations, with broad, unresolved peaks at about 0.3 s and 20 s and a minimum at around 2 s. The shorter bursts are also seen to have harder spectra, as measured by a hardness ratio (Kouveliotou *et al.* 1994a). Another general property of the gamma-ray burst time profiles is that they tend to have shorter rise-times and fall-times (sharper spikes) at higher energies. Most bursts also show an asymmetry, with shorter leading edges than trailing edges. This has been quantified by Link, Epstein & Priedhorsky (1993) and by Nemiroff *et al.* (1994). Other analyses have used a variety of temporal parameters and constructs to quantify and characterize gamma-ray burst temporal properties.

A recent analysis of time profiles by Norris *et al.* (1994) shows a systematic widening or stretching of gamma-ray burst time profiles as bursts become weaker. This analysis was performed by artificially weakening the stronger gamma-ray bursts and introducing the appropriate background so that all bursts could be analyzed in a consistent manner. The quantitative analysis of the time profiles was made through the use of wavelets. The observed stretching of the profiles of bursts is consistent with that expected from the effects of time-dilation from bursts at cosmological distances. However, the time dilation observation and its interpretation are still somewhat controversial.

3. Spectral Characteristics

A distinctive feature of gamma-ray bursts is their high-energy emission: almost all of the observed power is above 50 keV. Some bursts show emission as low as 1 keV, but this power is less than 1 or 2 percent of the total power. Most bursts show rather simple continuum spectra which appear similar in shape when integrated over the entire burst and when sampled on various time scales within a burst. Fig. 3 shows a typical burst spectrum from 0.1 to 10 MeV, with the peak power at $\sim$600 keV (Share *et al.* 1994).

Spectral shapes which have been fit to burst spectra include broken power laws (Schaefer *et al.* 1992), log-normal distributions (Pendleton *et al.* 1994), and exponential spectra with power-law high energy tails (Band

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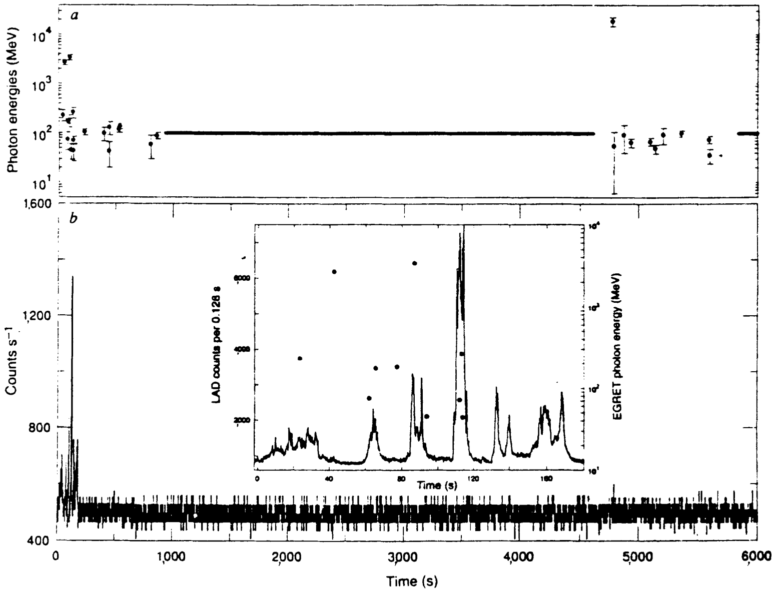

Figure 2. The extremely long high photon energy gamma-ray burst of 17 February 1994, as seen with the EGRET, BATSE and Ulysses experiments. Only the EGRET experiment shows photons above 100 MeV, up to 1.6 hours after the initial outburst (from Hurley *et al.* 1994).

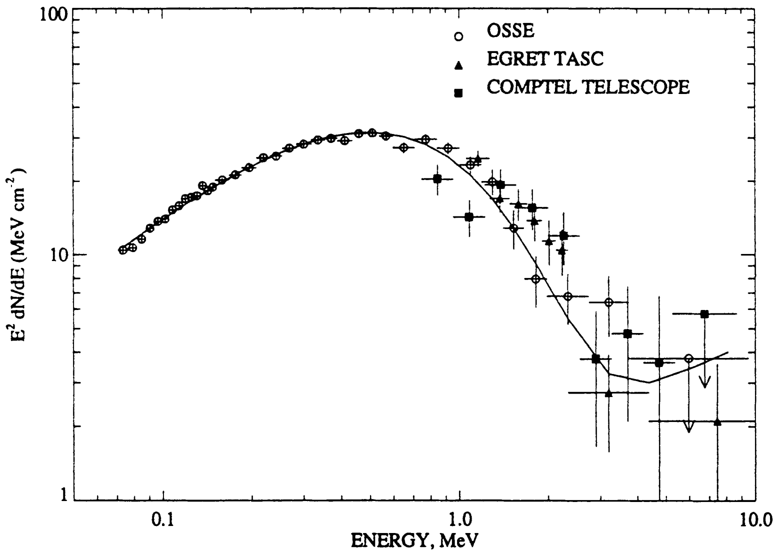

Figure 3. The high-energy spectrum of GRB 910601, as measured by three of the experiments on the Compton Observatory (Share *et al.* 1994), integrated over a large portion of the burst. A characteristic broad spectral shape, with peak power at about 0.6 MeV is seen. (The spectral up-turn at high energies is not real.)

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et al. 1993). Although the spectral shapes of many bursts are similar, the energy at which peak power is emitted changes greatly from burst to burst and it is seen to change rapidly within a burst. Some significant changes on time scales as short as tens of milliseconds have been observed (cf., Ford *et al.* 1995). Earlier observations with the gamma-ray spectrometer on the Solar Maximum Mission showed that in many bursts, the high energy emission follows the same power law to over 80 MeV (Share *et al.* 1992). The EGRET observation of the long-duration burst (Fig. 2) shows a single photon from the burst direction with an energy of about 20 GeV, occurring late in the burst. Within most (but not all) bursts, there is a hard-to-soft spectral evolution, resulting in the lower energies peaking earlier (Pendleton *et al.* 1994; Ford *et al.* 1995).

A search for unambiguous gamma-ray line features with BATSE/GRO has thus far been unable to confirm the earlier reports of spectral line features from gamma-ray bursts (Palmer *et al.* 1994). Several recent papers from the proceedings of the last Huntsville Gamma-ray Burst Workshop (Fishman, Brainerd & Hurley 1994) have also discussed the preliminary BATSE line search analyses and their results.

4. Burst Counterparts

There is no doubt that a great advance in our understanding of gamma-ray bursts can be attained through successful correlated observations of gamma-ray bursts at other wavelengths. This fact was demonstrated recently by the combined gamma-ray, X-ray, optical and radio observations of Soft Gamma-ray Repeaters (SGR's) (Kouveliotou *et al.* 1994b; Murakami *et al.* 1994; Kulkarni *et al.* 1994). Within the past four years, there have been major, renewed efforts to find a counterpart to a gamma-ray burst in other wavelength regions as evidenced by either simultaneous emission or afterglow emission. Some of the world's most powerful ground-based facilities are involved with these attempts for correlated burst observations. A sensitive, wide-field transient optical camera has been operating for over three years at Kitt Peak (Vanderspek *et al.* 1994). Space-borne correlated observations of well-located gamma-ray bursts have also been attempted in the UV, EUV, and X-ray regions. Comprehensive studies of archival plates also have been made. There have been several suggestions for counterparts although the results are inconclusive and problematic. In view of the importance of the implied results, further observational evidence is needed before these results are accepted. A recent review of the present status of correlated gamma-ray burst observations is given by Schaefer (1994).

A new near-realtime BATSE burst location system called BACODINE (BAtse COordinates DIstribution NEtwork) (Barthelmy *et al.* 1994) is now operational. This system, when linked to a rapid slewing optical telescope, opens the exciting possibility of obtaining optical images of burst regions while the burst is in progress. Although the present BATSE location accuracies are coarse (~4 deg.), plans are being made for new, powerful wide-field CCD camera systems dedicated for such burst counterpart searches.

A joint BATSE-COMPTEL capability also exists that is able to provide more accurate (~1 deg) locations within several hours for those gamma-ray bursts which also happen to be within the COMPTEL field-of-view. This capability has been demonstrated for the intense gamma-ray burst of 31 January 1993, when an extraordinary effort involving over 30 instruments observed the burst region within hours and days of its occurrence (Schaefer *et al.* 1994).

5. Repetition and Burst Distributions

There have been reports of burst repetition in the BATSE data but the evidence is not statistically compelling and additional data have not supported these claims of burst repetition. Recent papers by the BATSE team have detailed the observational and statistical arguments concerning burst repetition (Meegan *et al.* 1995; Hartmann *et al.* 1995) and an analysis of time-dependent repetition has also been made, with negative results (Brainerd *et al.* 1995). Typical upper limits of classical gamma-ray burst repeaters on time scales of years are ~20 percent. From BATSE data alone, the coarse error locations cannot provide greater constraints on burst repetition.

The isotropy of the BATSE gamma-ray burst distribution, coupled with its inhomogeneity (as measured by the deficiency of weak gamma-ray bursts) continues to be the most surprising recent observation of gamma-ray bursts, and the one that has eliminated most of the usual Galactic distribution models (Meegan *et al.* 1992; Briggs *et al.* 1995). Fig. 4 shows the distribution of 921 BATSE gamma-ray bursts, plotted in Galactic coordinates. The BATSE sky exposure used in the derivation of this map is uniform to within ±20% (Fishman *et al.* 1994). When corrected for sky exposure, no significant dipole exists with respect to the Galactic center and there is no significant quadrupole moment with respect to the Galactic plane. The inhomogeneity for the measurable bursts in this distribution, as measured by $V/V_{\rm max}$ (cf., Schmidt 1968), is $V/V_{\rm max} = 0.32 \pm 0.01$. A value of 0.5 for $V/V_{\rm max}$ is expected for a homogeneous distribution. Recently, the BATSE intensity distribution has been combined with the PVO intensity distribution to yield a combined data set over almost four decades in intensity (Fenimore *et al.* 1993). The composite intensity distribution matches well in the overlap region, showing a smooth transition to the $-3/2$ power law expected at the higher intensities.

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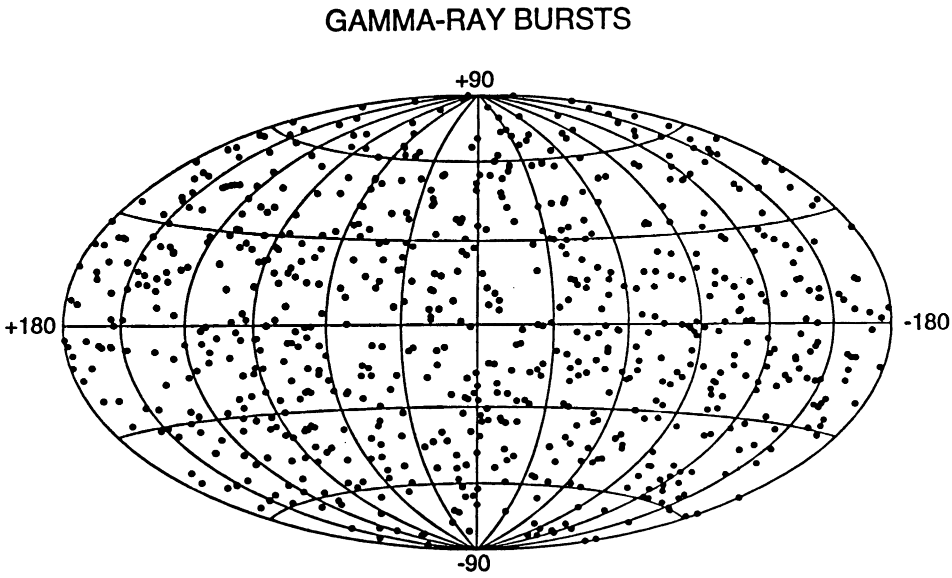

Figure 4. The sky distribution of 921 gamma-ray bursts observed with BATSE on the Compton Gamma-Ray Observatory. The isotropy of the bursts is apparent.

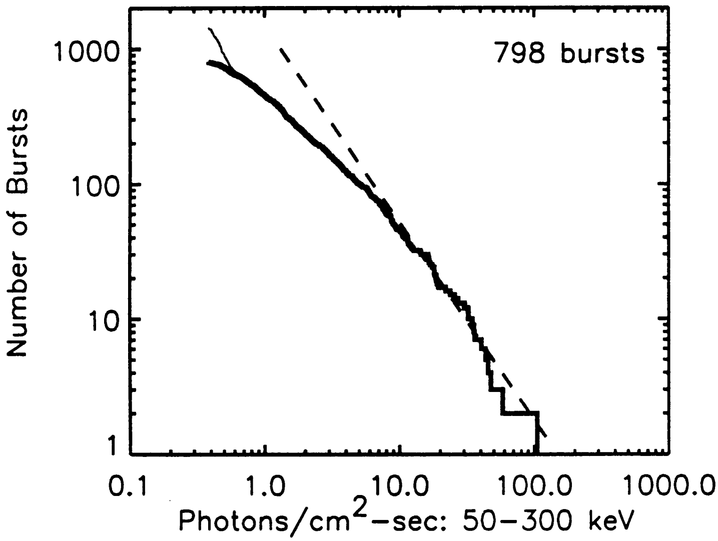

Figure 5. The intensity distribution (peak flux measured on a 256 ms time scale) of gamma-ray bursts, measured with BATSE (from Pendleton *et al.* 1994). There is a clear deviation from a homogeneous distribution (dashed line).

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6. Future Observations

Two US spacecraft containing gamma-ray burst instruments are scheduled to begin operation soon: TRGS/WIND in 1994 and HETE in 1995. The TRGS (Transient Gamma-Ray Spectrometer) is an experiment on the US WIND spacecraft (Owens *et al.* 1991). The detector is a high-resolution, passively cooled germanium detector that operates between 20 keV and 8 MeV. It has a nearly hemispherical field-of-view and a typical energy resolution of about 2 keV.

The HETE (High Energy Transient Explorer) satellite is a small satellite mission dedicated to the study of gamma-ray bursts (Ricker *et al.* 1992). The prime objective is the precise localization and rapid follow-up observation of gamma-ray burst locations by on-board UV detectors and observatories on the ground. HETE consists of an array of wide-field scintillation detectors which can operate from 6 keV to greater than 1 MeV with good energy resolution, a set of two coded-mask X-ray proportional counters, and an array of sensitive UV CCD detectors. Burst localization to 0.1 degree can be achieved with the X-ray detectors and to 3 arcsec with the CCD, if there is concurrent, detectable UV emission. Data can be distributed in near real-time to a large number of primary and secondary receiving sites for rapid follow-up observations.

There has not been a successful interplanetary probe launched with a gamma-ray burst detector since Ulysses in 1990 (Hurley 1992). The Russian Mars-96 spacecraft will carry several burst detectors. It will become an important component of the Interplanetary Network (IPN) of gamma-ray burst detectors.

7. Summary

The gamma-ray burst enigma appears to be as difficult now as when it was described over 20 years ago (Ruderman 1975). A wealth of new data on time profiles, spectral characteristics and burst distributions has thus far failed to provide conclusive evidence on the distance scale, central object(s) or emission mechanism(s) for the classical gamma-ray bursts. The isotropy and inhomogeneity of the bursts only shows that we are at the center of the apparent burst distribution. Many feel that the identification of a burst with an object in another wavelength region may be the key to understanding these objects. The recent EGRET-Compton Observatory discovery of delayed GeV emission from a burst is yet another severe constraint for many burst models. The field continues to be exciting and frustrating.

Acknowledgements. This paper is based upon lectures given by the author at the Les Houches School of Theoretical Physics/ NATO Advanced

Studies Institute "The Gamma Ray Sky with Compton GRO and SIGMA," January 1994.

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