Gamma ray bursts: An overview and some recent observations from SROSS satellites

T.M.K. Marar
(ISRO Satellite Centre, Bangalore 560 017)

A brief overview of the nature of gamma ray bursts (GRBs) and some recent results from GRB experiments flown on Indian SROSS satellites are presented.

1 Introduction

Nearly a quarter century after their discovery, gamma ray bursts (GRBs) remain one of the long-standing puzzles in high energy astrophysics. GRBs are transient, non-terrestrial phenomena in which bursts of radiation, predominantly at gamma ray wavelengths, lasting anywhere from a few milliseconds to a few minutes, are observed by gamma ray detectors flown on satellites. Gamma ray detectors onboard US Vela satellites that were launched to monitor violations of the 1963 nuclear tests ban treaty that prohibited nations from conducting nuclear tests in the earth's atmosphere had detected celestial bursts of gamma radiation as early as 1967, but the announcement of this discovery of a new class of astrophysical phenomena had to wait until 1973 when the US military allowed the information to be made public. During the period from 1973 to 1991, over 500 bursts had been recorded by instruments flown on at least 20 satellites. The Burst and Transient Sources Experiment (BATSE) onboard the Compton Gamma Ray Observatory (CGRO), which was launched in 1991, has however been detecting about one burst per day since May 1991. BATSE has thus accumulated data on about 1200 bursts up to February 1995 (Refs 2 and 3).

At energies $> 30$ keV, the flux from the bursts can be as high as $10^{-3}$ erg cm$^{-2}$s$^{-1}$. This is orders of magnitude larger than the emission from the brightest, steady X-ray and gamma ray sources in the sky. The range of energy in bursts extends from a few keV to at least 18 GeV (Ref.4) and the bulk of the emission occurs at energies $> 100$ keV. Counterparts to GRB sources at other wavelength domains of the electromagnetic spectrum like X-ray, optical, IR or radio wavelengths have not so far been identified, except in the case of three Soft Gamma Repeaters, which will be discussed later. Hence distances to GRB sources are completely unknown. This implies that the energies involved in GRBs can range from about $10^{28}$ erg for sources located close to the earth (like, for example, in or near the Oort cloud of comets) to about $10^{41}$ erg for sources located at cosmological distances. Recent reviews on GRBs by Hurley$^5$ and Higdon and Lingenfelter$^6$ and conference proceedings edited by Fishman et al.$^2$ provide abundant information on observations, analysis, interpretations and models of GRBs. Highlights of results from BATSE, motivation for the Indian GRB experiments flown on SROSS satellites, outlines of temporal and spectral features of bursts, classification of bursts and searches for counterparts at other wavelengths and some models of GRBs are briefly presented in the following sections. This is followed by a brief description of the GRB instrument on SROSS satellites and some of the recent observations. For a complete literature survey the reader may see references 2, 5 and 6.

2 Highlights of BATSE results and the role of SROSS-C2 GRB experiment

Until the launch of the Compton Observatory in 1991, many models of GRBs were associated with phenomena on or near galactic neutron stars. There were of course plenty of other models. They ranged from flares on ordinary stars near the solar neighbourhood to wiggles of cosmic strings at cosmological distances. Although most models explained some features of GRBs, none explained all the observations. The map in galactic co-ordinates of sources for which directions were available at that time showed that the GRB sources were distributed isotropically on the sky. It was then expected that if the sources are galactic neutron stars, an improvement in sensitivity for detection of bursts would ultimately result in a picture wherein the sources are distributed predominantly along the plane of the galaxy. BATSE with its high sensitivity for detection of bursts of fluence $> 5 \times 10^{-8}$ erg cm$^{-2}$ was expected to fulfil that dream. The spatial
distribution in galactic co-ordinates of 1000 bursts detected by BATSE is shown in Fig. 1 (Ref. 2). It does not show any clustering of burst sources along the galactic plane, the galactic centre or towards any of the nearby galaxies or clusters of galaxies. In other words, the burst sources are distributed isotropically on the sky. Moreover, as shown in Fig. 2, the log \(N(> S) \sim \log S\) distribution, where \(N(> S)\) is the number of sources with intensity greater than \(S\), does not follow the \(-3/2\) power law that is expected of a uniform distribution of sources out to infinity. In other words, weaker sources are fewer than expected, indicating thereby a boundedness to the region of source confinement. Burst models have necessarily to account for these important results on spatial and intensity distributions. In fact, the above results have triggered a flurry of theoretical modelling activity and there has been a conspicuous swing towards favouring cosmological models for the origin of gamma ray bursts. As the earth is at the centre of the universe in a cosmological model, isotropy is an immediate attribute and the deficiency of weaker bursts can be explained as due to universal expansion and related red shift effects. In summary, results from BATSE have only deepened the mystery of gamma ray bursts.

In order to converge on the correct model that explains the observations, it is necessary to identify the sources of gamma ray bursts. For this purpose it is necessary to localize the bursts with high angular accuracy. This can be achieved by means of the triangulation technique in which the arrival times of the burst at four or more spacecrafts widely separated in space are compared. If CGRO is involved in the triangulation, detection by two more spacecrafts is sufficient. This is because BATSE on CGRO consists of 8 detectors, forming the faces of an octahedron and hence by comparing the count rates in various detectors, BASTE can determine the arrival directions of strong bursts to an accuracy of 2°-3°. The accuracy of localization varies inversely as the base line distance between pairs of spacecrafts and directly as the timing and synchronization accuracy of clocks used onboard the spacecrafts.

For satellites in near earth space, like the Compton Observatory, nearly 34% of the sky is occulted by the earth at any given time. This is in addition to losses of data due to other reasons. Hence, in order to provide a complete coverage of the sky at
all times, it is necessary to have a few GRB detectors in near earth space. The GRB experiment on SROSS-C2 is expected to fulfill this role in many respects, at least for bursts with fluences greater than $10^{-5}$ erg cm$^{-2}$.

Nearly 25 satellites including Vela, Venera 11, 12, 13 and 14, Helios, Pioneer Venus Orbiter, Solar Max, Prognoz, Ginga, Phobos, Eureka, ISEE-3 (ICE), etc. had carried instruments specifically designed to monitor GRBs. At the present time, USA’s Compton Gamma Ray Observatory and India’s SROSS-C2 satellite in near earth orbits, Russia’s GRANAT in a highly eccentric orbit around the earth, international Ulysses probe in a solar polar orbit and the international WIND spacecraft heading for placement at the first Lagrangian point of the earth-sun system carry instruments that can form the third interplanetary network of GRB monitors. Since Ulysses solar probe is at a distance of about 4 AU from the earth and typical accuracy of recording arrival times of bursts at different satellites is of the order of 1 ms, the sizes of error boxes of events can be as small as one square arc minute. This gives the hope that many GRB sources may be localized accurately in future and the localization may lead to the identification of GRB sources themselves.

3 Time histories and energy spectra

Data collected on GRBs usually consist of intensity variation as a function of time (light curve) and energy spectra along with its evolution with time. Light curves of gamma ray bursts’ with tens of milliseconds time resolution are routinely collected by most GRB instruments. The time histories exhibit a wide variety of shapes and durations. A bimodal distribution of durations with means around 0.3 s and 30 s has been observed. Nearly 15% of the bursts exhibit the lower range of time durations. Typical rise and decay times of bursts range from 0.1 s to 1 s. Flickers with durations of 0.2 ms have also been reported. Figure 3 shows the temporal profile of a burst detected by SROSS-C2 GRB experiment on 26 Nov. 1994. A complex multipeaked structure is evident in this case. This event has been confirmed by GRB triggers onboard Ulysses, CGRO (BATSE), and WIND spacecrafts.

Typical GRB spectra in the energy range 10 keV-500 keV can be expressed in the form $dN/dE = \text{const} \left(1/E\right) \exp \left(-E/kT\right)$, with $kT$ values ranging from 100 to 500 keV. At higher energies, a power law spectrum with photon number index in the range 1-2.5 has been observed. Bursts with photon energies extending up to GeV energies have also been observed. Figure 4 shows the typical energy spectrum of a burst in the energy range 20 keV-200 MeV measured by BATSE, EGRET and COMPTEL telescopes on CGRO. It also shows that the peak emission occurs at gamma ray wavelengths, whence the name gamma ray bursts. Line features at about 50 keV and 430 keV had been noticed in about 15% of all bursts detected before the advent of CGRO. However they have not been confirmed by the more sensitive spectroscopic detectors of BATSE on CGRO.

4 Classification of bursts and search for counterparts

At least two classes of GRBs have been recognized over the years. These are the classical GRBs and the Soft Gamma Repeaters. Classical bursts have typical durations of tens of seconds and some may last hundreds of seconds. They exhibit hard spectra and often spectral evolution with time.
bursts belong to this class and none is known to repeat. Within the error boxes of classical GRBs, deep searches in the optical band up to V magnitude of about 25 have been conducted for identifying counterparts to the burst sources. Only faint galaxies and some M dwarfs have shown up inside those regions. Their number is consistent with random occurrence within the fields. IR and X-ray searches have also failed to identify any GRB source with a known source in these bands. Results of searches for optical transients in archival plates have been debated in literature, with no consensus on their reality. There is nothing like the simultaneous detection of a GRB in optical, X-ray, IR or radio region. Considerable effort is being expended in this direction at present.

The Soft Gamma Repeaters have nominal durations of 0.1 s and generally last for less than 1 s. They invariably exhibit soft spectra that are independent of time and as the name implies, they 'repeat', although at irregular intervals. There are only three sources belonging to this class, viz. SGR 0526-66, SGR 1806-20 and SGR 1900+14.

SGR 0526-66 is the source that emitted the famous event detected on 5 Mar. 1979 (Ref.5). Sixteen bursts have been detected from this source over the years. The 5 Mar. 1979 event has the distinction of being the brightest event among all GRBs (including classical ones) detected so far. The flux at the initial phase of the event, a spike lasting ~120 ms, was as high as $10^{-3}$ erg cm$^{-2}$s$^{-1}$. The rise time of the spike was less than 0.2 ms, which, from light travel time considerations, would imply an emission region less than 60 km in size, thereby indicating a neutron star as the possible source for the burst. After the initial spike, the event lasted nearly 180 s, exhibiting a modulation of the flux with a periodicity of 8 s. Moreover, the event was detected by at least ten spacecrafts in interplanetary space and therefore triangulation resulted in a precise localization of the event. The error box thus obtained was about 10 arc second × 60 arc second in size and its location is consistent with the N49 supernova remnant (SNR) in the Large Magellanic Cloud. Assuming that there indeed is an association between the burst and the SNR and that the radiation is isotropic, the power radiated during the peak of the burst works out as $\sim 10^{44}$ erg s$^{-1}$, in gamma rays alone. This may be compared to the luminosity of our entire galaxy, which is about $10^{43}$ erg s$^{-1}$ only and that too mostly in visible light. More recently, a faint X-ray source consistent in position with the GRB error box has been detected with the ROSAT satellite.

SGR 1806-20 has produced over 100 bursts, irregularly spaced in time, between 1979 and 1985 (Ref.10) and six bursts in 1993 (Ref.11). Kulkarni and Frail discovered that its position coincides with the radio nebula G10.0-0.3. A steady X-ray counterpart was detected at the position of the peak of the radio nebula and simultaneous X-ray and gamma ray bursts have also been recorded by the Japanese ASCA satellite and CGRO respectively. Hence the associations of SGR 0526-66 and SGR 1806-20 with SNRs appear to be rather secure.

SGR 1900+14 has produced 6 bursts during 1979-93 and is also probably associated with the galactic SNR G 42.4+0.6, although its location lies just outside the remnant. Vasisht et al. have suggested that SGR 1900+14 is a neutron star that was born with high speed and has now overtaken the
expanding shell of G 42.8 + 0.6. In summary, the association of SGRs with neutron stars in SNRs appears strong. Models that explain the energetics involved, modes of emission, repetition cycles, etc. have yet to be worked out.

5 Some models of classical GRBs

As mentioned in the introduction, many models have been proposed for explaining the nature of GRB sources. They can generally be grouped into two classes: galactic and extragalactic (or even cosmological).

Before the launch of the Compton Observatory, galactic neutron stars were the favourite objects. One of the early models proposed the fall (accretion) of a comet or an asteroid onto (by) a neutron star and the subsequent explosion. Neutron star quakes and thermonuclear flashes on accreting neutron stars were some of the other models. In order to retain galactic neutron star models for GRB sources and to explain the recent BATSE results on isotropy of spatial distribution and inhomogeneity of intensity distribution, it is however necessary to distribute the galactic neutron stars in an extended halo to the galaxy of at least 100 kpc radius.

A leading model among the cosmological class proposes neutron star-neutron star mergers or neutron star-black hole mergers in distant galaxies as the sources of GRBs. This model relies on the statistics of detection of several binary pulsars in our galaxy and their expected ultimate merger scenarios. Even a hundredth of the binding energy released in such mergers is sufficient to explain the energetics required from such far away systems. As mentioned earlier, after the launch of CGRO, there has been a swing among some astronomers towards favouring cosmological models. It must be reemphasized that none of the models can at present explain all the observational data and the most difficult problem has been to explain why all the energy appears to come in gamma rays alone.

6 The GRB experiment on SROSS satellites

We have already pointed out the need for more than one GRB detector in near earth space for achieving a complete coverage of the sky at all times. The GRB experiment on SROSS satellites is expected to partially fulfill this need and therefore complement BATSE on CGRO. It is also expected to join the interplanetary network of GRB detectors used for localization of GRB sources and thereby lead to their ultimate identification.

The SROSS-C and SROSS-C2 satellites carrying the GRB experiment were launched on 20 May 1992 and 4 May 1994 respectively. The scientific objectives of the experiment included the following: (a) monitor GRBs in the energy range 20 keV-3 MeV; (b) monitor intensity variations with high time resolution (2 ms); (c) search for periodicities in the incident radiation; (d) determine the evolution of the energy spectra with time; and (e) search for cyclotron absorption features in the 20-100 keV energy range and look for possible red shifted annihilation radiation line in the 400-500 keV range.

The GRB experiment flown on SROSS-C2 satellite consists of a 76 mm diameter, 12.5 mm thick CsI(Na) scintillation crystal with an associated microprocessor-based processing electronics. The crystal is optically coupled to a 76 mm diameter photomultiplier tube (PMT) which is powered by an onboard high voltage package. The charge output of the PMT is fed to a charge sensitive preamplifier which is followed by a linear amplifier and shaper. The amplitude of the output signal is proportional to the incident gamma ray energy. This output signal is fed to both counting circuitry and a pulse height analyzer to derive information about the intensity and energy of the incident gamma rays.

The processing electronics, which is based on a CDP 1802 microprocessor, is programmed to accept the signal from the detector and enable it for further processing and storage based on the mode in which the experiment is operated. The different modes have different recording capabilities with respect to the counting rate (intensity measurement) and pulse height analysis (spectral measurement).

The detection of a gamma ray burst is based on the 0.1-1 MeV counting rate exceeding a preset threshold value. Based on initial background measurement, the threshold is set through command to well over 6 sigma times the equatorial radiation background level. We have onboard two thresholds for comparing the count rate at every 256 ms and at every second. The two thresholds will not always have a ratio of 1:4. This is done in order to take into account statistical variation for different integration times and also to detect bursts of differing rise times. Whenever the incident count rate in the energy band 0.1-1 MeV from the detector exceeds either of the preset thresholds, an event trigger is detected, processed and stored.

Temporal data for the ensuing 204 s is stored with varying time resolutions of 2 ms from the time of burst \( T_o \) to \( T_o + 1 s \), 16 ms from \( T_o + 1 s \) to \( T_o + 8 s \) and 256 ms from \( T_o + 8 s \) to \( T_o + 204 s \). In addition a circulating memory stores 2 ms data for a duration of 1 s prior to burst and 256 ms data for a duration of 65 s prior to burst.

In addition spectra consisting of 107 channels over
the energy range $20\text{-}1024$ keV is stored every $0.512$ s from $2$ s prior to burst to $15$ s after the burst detection. Towards the end of processing, from $T_0 + 188$ s to $T_0 + 205$ s, two spectra, each integrated for $8$ s are collected in order to give information about the background spectrum soon after the event.

Immediately after processing one event trigger, the instrument starts the burst search again. Onboard memory consists of two banks, each capable of storing $7$ triggers. After one bank is filled, the data is readout and the instrument is reinitialized with the second memory bank. This enables us to again readout the earlier data in the first memory bank in case of any link errors, without sacrificing the duty cycle of the burst search process. Data can however be readout during any visible pass even if the particular memory bank in which it is recorded is not completely full (i.e., if less than $7$ bursts are stored). This enhanced memory feature was designed in order to improve the duty cycle of the experiment in SROSS-C2 as compared to that of SROSS-C where only one burst data could be stored between two consecutive readouts. Further details of the instrumentation are available in Marar et al.\textsuperscript{23} Figure 5 shows a photograph of the GRB payload and Fig.6 shows it mounted on SROSS-C2 satellite.

7 Observations from SROSS satellites

The experiment flown on SROSS-C worked very satisfactorily during the entire mission life of $55$ days of the satellite. It recorded $3$ GRB candidate events, which were however not confirmed by their detection by GRB detectors onboard other satellites in the interplanetary space. Details of the instrumentation and results from the experiment can be obtained from Marar et al.\textsuperscript{24} and Kasturirangan et al.\textsuperscript{25}

The GRB experiments on SROSS-C2 satellite has been operating in the burst search mode satisfactorily during the past $10$ months and is likely to provide useful GRB data for the next $5$ years. Table 1 gives a list of GRB candidate events detected up to $28$ Feb. 1995. Their time histories in the energy range $100\text{-}1024$ keV are given in Fig.7.
Fig. 7—Mosaics of SROSS-C2 candidate GRB events detected between 19 July 1994 and 11 Feb. 1995. Note that the ordinate axis of 11 Feb. 1995 event is in counts/8 ms, this event being the shortest (~112 ms) detected so far.
The sensitivity of the GRB instrument onboard SROSS-C2 is such that we can expect about 18 celestial events per year. The present rate of detection of genuine events (i.e. 11 events in 8 months of operation after the spacecraft was placed in its final orbit on 10 July 1994) is consistent with that estimate. The minimum fluence detected so far (\( \sim 3 \times 10^{-6} \text{ erg cm}^{-2} \)) is also consistent with the sensitivity estimate. In summary, the GRB experiment on SROSS-C2 is working very satisfactorily and we hope that during the expected mission life of 5 years it will contribute significantly to the international efforts of tracking down the sources of gamma ray bursts.

### 8 Conclusions

The nature of Soft Gamma Repeaters is better understood after the discovery of their associations with SNRs. The mystery surrounding the nature of classical GRBs is still persisting. Its resolution will demand measurement of spectra with better energy resolution, say for example, using cooled germanium spectrometers, and localization of events with better accuracy, say, within several arc seconds using spacecrafts with longer base lines, followed by deep searches to identify the counterparts of GRB sources at other wavelength regions of the electromagnetic spectrum. A simultaneous detection of a GRB in optical or radio band may also lead to the identification of the source.

The performance of the GRB experiment on the Indian SROSS-C2 satellite has been very satisfactory so far. A majority of the shortlisted candidate events have been confirmed as genuine GRBs. With good luck, it is hoped that this experiment may also share the moment of satisfaction and glory of solving the GRB puzzle in the not-too-distant future.

### Acknowledgements

The author thanks Dr S Seetha for reading the manuscript and suggesting several improvements. He is also thankful to his colleagues in the Technical Physics Division for their sincere efforts in making the GRB payload work flawlessly in space.

### References