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Gamma Ray Bursts, Swift and REM

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Abstract. Relevant information about the physics of Gamma Ray Bursts (GRBs) is hidden in the first phases of the afterglow, i.e. in the multi-wavelength (X-ray to Radio) emission soon after the explosion. Optical and NIR afterglow are particularly important since they allow to measure the redshift of the source and possibly to discover the host galaxies. We present in these pages the mission Swift, entirely dedicated to GRB science and its ground-based extension to NIR wavelength REM.

Key words. gamma rays: bursts – infrared: general – cosmology – telescopes

1. Introduction

It is worthwhile to briefly introduce how GRB science started. The Vela satellites, while monitoring the sky for artificial nuclear explosions, detected occasional flashes lasting a few seconds. Only later, 1973, Klebesadel, Strong and Olson (Klebesadel et al. 1973) felt enough confident and published the discovery. In the following years and due to the uncertain astrometry, the Gamma ray detectors did not allow enough accuracy to easily pin point the source in the sky, the astronomical community was divided among different believers: 1) those who were convinced of low energy events, distant a few hundred parsecs from us and involving energies of about 10^{37} ergs, 2) those who hypothesized they were in the halo of our galaxy and at distances of the order of a few kpc implying an energy of about 10^{41} ergs and 3) those who sustained an extragalactic origin involving the emission of very large energies and of the order of 10^{51} ergs. The search for optical counterparts has been considered important since the very beginning. Holger Pedersen, to name one among the many, carried on a program from la Silla Observatory in Chile, aimed to detect optically the event and be ready to follow it up with larger telescopes. Due to the loose precision of the available γ-posistions and the apparent ubiquitous character of the events, the project was based in patrolling the largest possible amount of sky any night in search of transients. Luck did not help the la Silla experiment which was one of the best and time consuming effort in the early phases of GRB research.

The big revolution in the field started in 1991 with the BATSE detector on Board of the COMPTON-Gamma Ray Observatory

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(GRO). The observations clearly showed with good statistics that the distribution of the GRBs was isotropic (Megan et al. 1992). It is well known by now that any isotropic distribution of sources is a good indication of their cosmological origin. But that wasn't enough to locate them and to estimate properly their emission energy since we still could not identify the source in the sky with sufficient angular resolution. The real step forward occurred when the Italian-Dutch satellite Beppo-SAX discovered in 1997 the X-ray emission connected with the GRB (Costa et al. 1997a,b). This discovery was made possible because of the large capabilities of the satellite coupled to a well prepared team who took advantage at its best of the facility. It is indeed the satellite Beppo-SAX, coupled to the knowledge gained on the bursts over the years, that told us how to design the next generation satellites such as Swift. We learned that:

1. In order to detect GRBs we must provide a detector sensitive above 100 keV and eventually up to a few MeV.
2. The detector must as well have a fast response since the flux at high energies is characterized by very rapid fluctuations.
3. The high energy detector must have a wide angle. The location of the occurrence of a burst in the sky is random so that we must cover a wide angle to detect them.
4. The astrometry provided by the Gamma detector, albeit a good one, is not good enough for the identification of the object in the sky. Observations at lower energies are needed for precise positioning.
5. The phenomenon must be followed from the very beginning to the later development and at various wavelengths, i.e. from space and from ground.

An Observatory dedicated to GRB observations should take into account all the points listed above. As we will see later on the Swift mission was designed according to the above specifications and in sight of what it is currently known about the physics of GRB phenomenon.

2. Basic information about GRBs.

GRBs are bright, transient events in the γ–ray sky, unpredictable in time and location, with a typical duration of $\sim$seconds. The brightest bursts have γ–ray fluences (flux integrated in time for its duration) of $\sim 10^{-4}$ erg cm^{-2} and most of the energy is released in the 0.1–1 MeV range. Spectra generally display featureless smooth continua. The shape of the spectrum is not yet understood theoretically but it fits the empirical law proposed by **?**, i.e. two power laws connected at a point E^* in the range 100 keV - 400 keV :

$$N(\nu) = \begin{cases} N_o (h\nu)^{\alpha} e^{(\frac{-h\nu}{E_o})} & h\nu < E \\ N_o((\alpha-\beta)E_o)^{(\alpha-\beta)} \times \\ \quad \times (h\nu)^{\beta} e^{(\beta-\alpha)} & h\nu > E \end{cases} \quad (1)$$

The spectrum contains a very large fraction of high energy γ ray photons and is shows rapid variability indicating that the source is very small, of the order of a few thousands km. In this scenario higher energy (E_1) photons can rather easily collide with lower energy photon (E_2) and produce positron-electrons pairs since we likely have $\sqrt{E_1 E_2} > m_e c^2$. As a consequence the optical depth is expected to be very large, in disagreement with the observed non-thermal spectrum that indicates instead the presence of an optically thin source. However if the source of radiation is moving at relativistic speed, then it is easy to show (see Piran 1999) that the optical depth decreases by a factor $\Gamma^{4+2\alpha}$ where $\Gamma = 1/\sqrt{(1-\nu^2)/c^2}$ and α is the spectral index of the photons. That is the source becomes optically thin if $\Gamma \sim 100$ indicating highly relativistic motions.

GRBs occur in galaxies, this has been demonstrated by imaging. Then the high speed material will at some point, and fairly soon after the burst, impact with the ISM. This fact triggers an external shock, heating of the gas and emission of electromagnetic radiation at softer wavelengths such as X-rays, Optical and Radio. Radio observations of the GRBs are characterized by fluctuations in the flux of about a factor 2. These fluctuation are due, according to Goodman (1997) to the interference of rays traveling through different optical paths in the ISM and the fluctuation stops as soon as the source of the electromagnetic radiation reach a critical radius. Accounting for the time past to reach this radius we find that the source must move very close to the speed of light. The model is therefore of shells of plasma moving with different velocities but close to the velocity of light, fluctuating and generating shocks due to shell collisions.

The observation of the phenomenon requires then a good coverage in energy and high time resolution. Since most of the lower energy instruments have narrow fields of view we need to achieve and accurate position in order to point them. Such an accurate position should also be achieved as soon as possible since the luminosity of these objects fades out very rapidly. In addition the possible presence of flickering in a given band requires fast response and time resolution in all instruments used.

The coverage of the Near Infra-red bands is of paramount importance because a) assuming that the events are correlated with the stellar population, then a large part of these could be hidden by the interstellar dust in the nuclear denser regions of the galaxies, b) if these events are correlated with star bursts and involve mainly the massive young stellar population, then there should be a large percentage of objects at very high redshifts, and c) if neither of this is true then the IR may give important clues on the phenomenon. The NIR observations will give the additional information in the region of the spectrum where the contribution of dust could become visible and estimate the dust status at high redshifts. Indeed it is known that more than 50% of the bursts are not seen at visible wavelengths and it might be that at least a fraction of them are absorbed by intervening matter. The first step is then to properly survey the NIR.

The characteristics of the absorption by dust are well known. Rather than discuss absorption curves in details we may refer to the center of the Milky Way as an example. We receive from this region emission due to the positron-electron annihilation line at 511 keV, some radiation in the continuum light, and emission from the decay of the 26Al at 1.8 Mev: we also receive emission in the X-ray band. However the absorbtion in the V band is of about 30 magnitudes. Much worse in the UV where the absorption increases of about 4 to 12 magnitudes depending on the characteristics of the absorbing grains. Things become more complicated at high redshift. In this case the radiation we receive in the Red and NIR part of the spectrum originates in the UV where the absorption is very high. On the other hand we really do not know the characteristics of the dust at $z > 4-6$ and how abundant it is, how much it has been produced in these young galaxies. In addition at these large distances the flux dims and the atomic absorption becomes very high as illustrated in the Figure 1 and figure 2. Here, following the prescription of Madau (Madau 1996), we plot the absorption expected at z = 6 (left) and z = 4 (right) for absorbers with $NHI > 1.6x10^{17}$ cm^{-2} and $dN/dz \sim 0.27(1+z)^{1.55}$ and normalized at large wavelength. From these figures the need to detect the object as soon as possible, before it decays too much in brightness, and the need to monitor it at NIR wavelength is quite clear.

3. A hardware answer: The Swift satellite.

The Swift satellite is a multi-wavelength space-borne observatory equipped with three instruments: BAT (Burst Alert

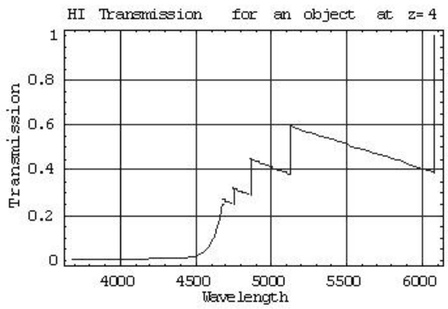

Fig. 1. Transmission of HI for an object at z=4 as a function of wavelength. See text for more details.

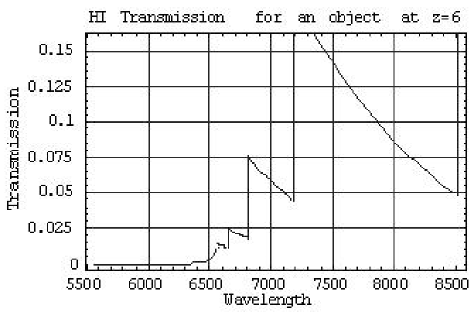

Fig. 2. Transmission of HI for an object at z=6 as a function of wavelength. See text for more details.

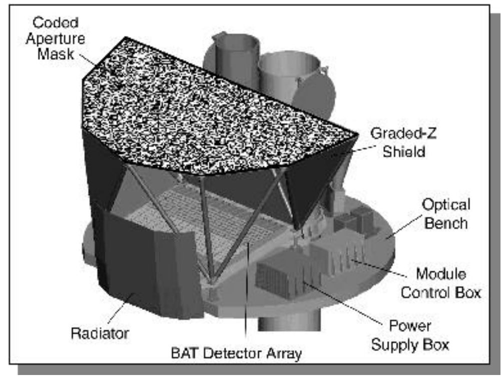

Fig. 3. The Optical Bench of the spacecraft with the three instruments. CRT and UVOT are seen on the top right side of the figure. The tube of the XRT telescope extends below the optical bench.

Telescope), XRT (X - Ray Telescope) and UVOT (UltraViolet Optical Telescope). Swift is a NASA - MIDEX Mission (P.I. Neil Gehrels) realized in collaboration with Italy (Funded by ASI) and UK (funded by PPARC), (Gehrels et al. 1999). A layout of the satellite and its instrumentation is reported in figure 3

The BAT instrument (PI Scott Barthelemy) is mainly sensitive in the 10 - 150 keV band and its Field of View covers about 2 sr of sky. The coded mask, visible on the top of fig. 3, has a detecting area of about 5200 cm^2. The mask is positioned 1 meter above the detector array and produces images by modulating the incident gamma-ray flux. The mask must be kept parallel to and at a constant distance from the detector array in order to get good imaging. The detector operates in a photon counting mode and consists of 256 modules. Each module has 128 elements with a detector size of 4x4x2 mm^3. The response of the detector to a ^{241}Am source is given in figure 4. The 17 arcmin PSF of this instrument allows to estimate the centroid of a burst with an accuracy of about few arcminutes. This is not enough for the accurate pointing of a large telescope or to identify the source, but enough accurate to start a chain of operation that will eventually permit such pointing. The first step is the pointing of the spacecraft to the coordinates of the burst to allow it to be observed by XRT and UVOT. The information of the BAT detection (coordinates and errorbox) is sent on the ground immediately after the detection. With present day GRB statistics and accounting for BAT sensitivity we expect about 150-300 alerts per year distributed over the whole sky.

The spacecraft alignment procedure takes about 10 seconds after which XRT and the UVOT begin operation. XRT (PI David Burrows) consists of the spare mirror module (110 cm^2 effective area) made by Italy for the JET-X - SXG collaboration and by the focal plane instrumentation made in the UK. The Field of View

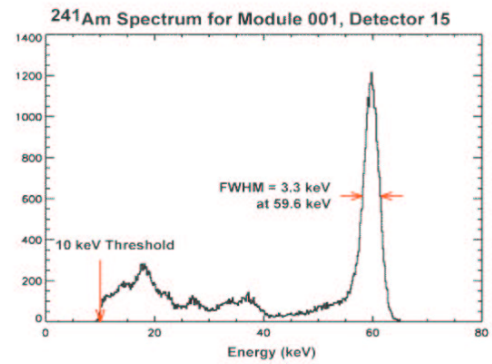

Fig. 4. Response of the BAT detector to a ^{241}Am source.

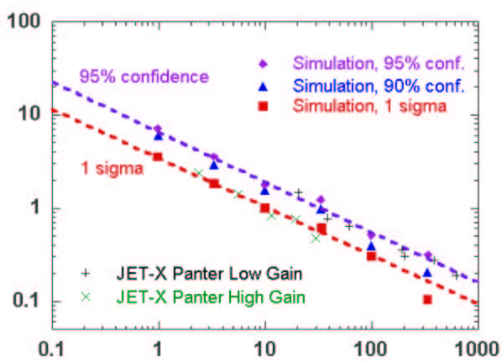

Fig. 5. Error circle radius as a function of the intensity of the source in the XRT telescope.

of the telescope is of about 23.6 x 23.6 arcmin^2 with a scale of 2.36 pixels per arcsec and a PSF of 15 arcsec Half Peak Energy Diameter at 1.5 keV. XRT allows an accurate positioning of the source as it can be seen in figure 5 where we plot the error circle radius as a function of the intensity of the source in millicrab units.

The detector used in XRT is the EPIC CCD developed for XMM with 600x600 pixels. This detector provides three different operative modes: Photon counting, integrated imaging and high timing. The instrument sensitivity allows to reach a flux of 2×10^{-14} erg cm^{-2} s^{-1} in 104 seconds, a huge gain compared to the Beppo-SAX satellite (hereinafter BS). Also the time factor helps Swift with respect to BS. The X-ray afterglow, for instance in the case of GRB 970228, decreases as $\sim t^{-1.3}$. In the 8 hr needed on the average by BS to point the source, its brightness would decrease by a factor of about 10000. Swift will instead point the source in 30-70 seconds.

Furthermore Swift will be able to detect and observe not only fainter bursts but also short lasting bursts. The astrometry given by XRT has a few arcsecs accuracy allowing large telescopes to point already the transient with XRT coordinates, at least for those bursts that are not too faint. Indeed it is at this point that all the Ground facilities are activated. Nevertheless together with the XRT, the UVOT telescope (PI Keith Mason) begins integrating and gathering information at different wavelengths and particularly in the UV at about 2200 $\mathring{A}$. The Optical part of the UVOT pass-band can also be covered from the ground by the many small and large telescope alerted by BAT or XRT. It is however important for the science goals, i.e the definition of the statistical properties and the understanding of the physics of the source and of the afterglows, to gather simultaneous multi-wavelength observations independently on weather condition and/or telescope time assignment.

Finally we emphasize that a fundamental role in the telemetry of the whole Swift Mission will be played by the ASI Ground Station of Malindi that will be the primary station of the project.

4. The REM (Rapid Eye Mount) Telescope.

Since UVOT is blind to wavelength longer than 650 nm, it does not allow us to observe the afterglows at NIR wavelength and to retrieve all the information contained therein (see section 2). This fact itself prompts for the realization of an extension of UVOT toward longer wavelength. Such an extension, figured already in (Chincarini & Lazzati 2001), has been designed and procured in the last two year by a team of Italian institutes under the auspices of MURST (COFIN 2000), CNAA and ASI.

REM (PI Filippo M. Zerbi) is a fast slewing robotic telescope with a 60 cm primary mirror (Zerbi et al 2001). The main characteristic of the telescope design is the fast response and the capability to point the target from any position of the sky in 60 seconds or cover 60 degrees (the field of view of the BAT) in 5 seconds. The principal instrument with which REM is equipped is a NIR (0.9-2.3 microns) fully cryogenic camera with a 10x10 arcmin^2 field of view covered by a 512x512 HgCdTe chip (HAWAII) working at 77 Kelvin. The scale of about 1.2 as/px is well suited with the Airy disk dimension (in the Ks band) for a 60 cm telescope and the Field of View allows to point REM on the BAT coordinates with a sufficient level of confidence. Such a pointing, due to the telescope velocity, will be achieved more or less at the same time of the re-pointing of the spacecraft also accounting for the communication time between Swift and REM.

The capabilities of the REM telescope have been recently enhanced via the merge with the Team coordinated by Eliana Palazzi who designed and procured ROSS (REM Optical Slitless Spectrograph), an imaging and slitless spectrograph working at optical wavelength (0.45-0.9 microns). ROSS will sample the spectrum with 30 points (2 pixels bins) on a 1024 x 1024 peltier-cooled Marconi CCD. A 3D sketch of the REM/ROSS assembly is shown in figure 6.

Although the telescope has two Nasmyth focal stations only one will be used for both instruments since there is the need to operate them simultaneously. A dicroic splits the beam sending the visible light at 90 degrees where the ROSS instrument is mounted while the NIR wavelength are transmitted to the Infrared arm.

Both instruments have been designed with efficiency in mind. As a consequence in spite of the rather small primary mirror REM achieves considerable results. The efficiency of both the Visible and the NIR arm are represented in figure 7.

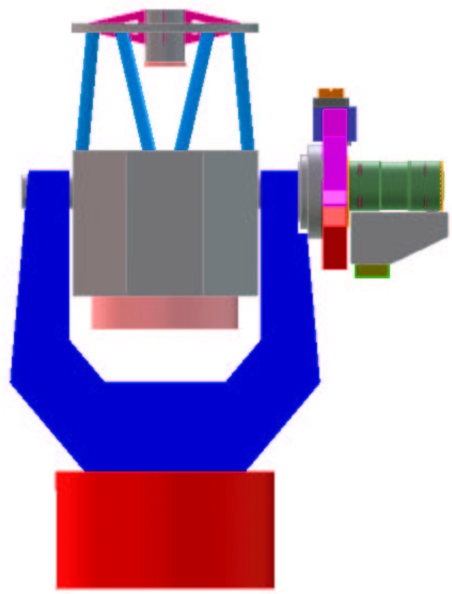

Fig. 6. 3D sketch of the REM/ROSS assembly

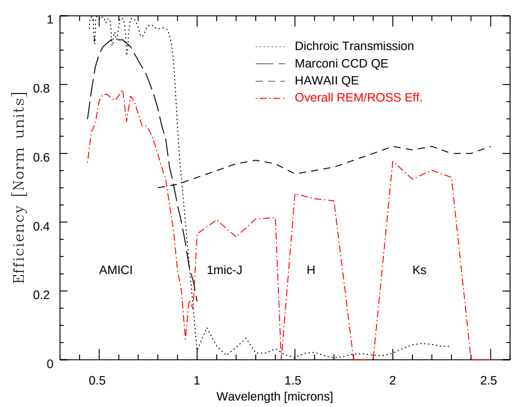

Fig. 7. Overall efficiency of the REM-IR and ROSS assembly

We have only one example of prompt optical/IR emission during the first minutes of the afterglow: GRB 990123. This GRB (see fig. 8) has been detected by the robotic telescope ROTSE 22 seconds after the γ–ray trigger at $m \sim 11.7$, reach-

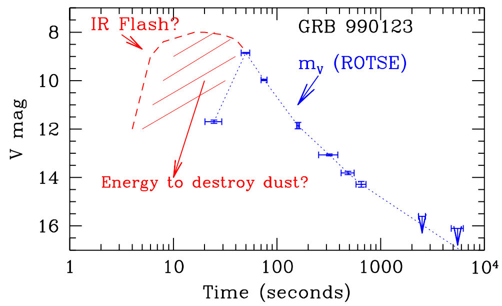

Fig. 8. Light curve of the prompt afterglow of GRB 990123

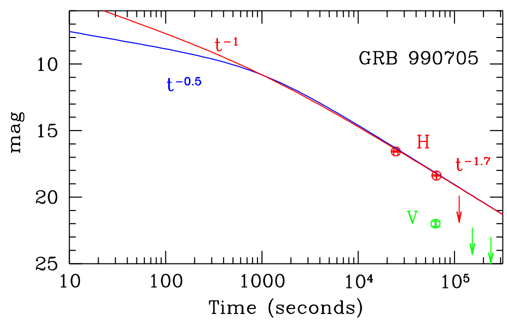

Fig. 9. Extrapolation at earlier times of the light curve of GRB 990705

ing $m \sim 8.9$ 47 seconds after the trigger (Akerlof & McKay 1999), well within the REM limits.

The typical early magnitudes of the afterglow can also be estimated by extrapolating back in time the light curves of known afterglows, as shown in Fig. 9. It will be possible to follow with REM the NIR afterglow during the first 2–4 hours even with an exposure time of 5 seconds. By increasing the exposure time (after the initial phases) to 10 minutes, afterglows can be followed up to 12 hours, after which larger telescopes will have to take over.

ROSS is capable of reaching V = 20 with a S/N = 5 in 30 seconds and get a spectrum of a point like source of V = 14 with a S/N = 10 in 1 second. The numbers above are like to allow us to observe all the GRBs detected by Swift, and other satellites, soon after the alert. At the same time the limit magnitudes of REM-IR, listed in table 1, state that a similar efficient follow up should be achieved as well at Infrared wavelengths.

The key scientific points that REM/ROSS can address concerns High z bursts. The simultaneous detection in the IR and a *non detection* in the optical can flag the presence of a highly absorbed burst *or* a high–z object. By the use of color-color techniques one can discriminate between the two possibilities and select good candidates high-z objects automatically, in real time and drive large telescopes (as VLT) to point at the target while it is still bright enough for large dispersion spectroscopic observations. This is probably the only way to obtain high quality spectra for large redshift (even $z > 10$) objects, to study the distribution of Lyα clouds in redshifts, their metallicity etc. Moreover, in the majority of cases, GRBs are associated with galaxies. The detection of a very high redshift GRB would hence mark the likely location of a very high redshift galaxy providing relevant information for cosmology.

In the case of highly absorbed bursts the optical flux is instead absorbed by intervening matter (dust), either in the close vicinity of the burst (if exploded in a dense star forming region whose dust has not been completely destroyed by the burst emission itself), or by dust distributed along the line of sight, even at large distances from the burst site. In this case the infrared light is much less absorbed, and therefore an infrared transient can be detected even if the optical is not. Combining IR and optical datasets, it will be possible to estimate the amount of absorption if, at it seems to be the case, the intrinsic spectrum is a power law.

Moreover such a comparison can yield a possible explanation for the lack of dust absorption in the spectra of bursts, thought to be associated with star–forming regions, in the case that dust grains are sublimated by the prompt optical/UV emission. In this case, an IR flash should be observed to

Table 1. limiting magnitudes as a function of the S/N (10 or 5) and of the passband, for the different integration times foreseen in the REM target operation.

Tint.	*Z* $S/N = 10$	*Z* $S/N = 5$	*J* $S/N = 10$	*J* $S/N = 5$	*H* $S/N = 10$	*H* $S/N = 5$	*K* $S/N = 10$	*K* $S/N = 5$
5*sec*	17.0	17.7	15.7	16.5	14.5	15.3	13.2	14.0
30*sec*	19.9	20.7	16.6	17.4	15.5	16.2	14.2	14.9
600*sec*	24.5	25.3	17.6	18.3	16.7	17.4	15.5	16.3

start before the optical one, as the IR radiation can penetrate unabsorbed in the cloud while the higher energy photons progressively clean out the dust. The observed IR fluence before the detection of the optical flash would greatly constrain the amount of dust in the cloud.

In addition any possible optimization of the trigger sources will leave some time in which REM can not observe any GRB afterglow due to latitude/longitude constraint. We estimate such *Idle Time* to be of the order of 40% of REM observing time. During the idle time REM will be used for multifrequency monitoring of variable object. Three *Key programs* have been identified by REM science team as particularly suitable for REM: a) monitoring of Blazars, b) monitoring of flare stars and c) observation of IR counterparts of galactic BH candidates.

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