Gamma-ray bursts, evolution of massive stars and star formation at high redshifts
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GRB afterglow observations from ARIES Nainital and their importance

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Abstract. Since January 1999, more than 50 gamma ray bursts (GRBs) fields have been observed from Nainital using 1.04m Sampurnanand Telescope. Optical afterglows were detected for 27 GRB fields localized by *Fermi*, *Swift*, *INTEGRAL*, *HETE-II* and *BeppoSAX*. These optical observations along with other multi-wavelength afterglow data were used to understand the degree of collimation, nature of the surrounding environments and progenitors of these energetic cosmic explosions. Newly installed 1.3m telescope at Devasthal and the upcoming 3.6m optical telescope along with the photometric and spectroscopic back-end instruments will further be very helpful in the near future towards understanding the stellar explosions and their host galaxies in more detail.

Keywords : Gamma-ray bursts: afterglows – telescopes : optical

1. Introduction

Gamma-ray bursts (GRBs) are short-lived (10^{-3} to 10^{3} seconds) bursts of gamma-ray photons (~10 keV - 10 GeV) discovered in 1973 by VELA series of mission dedicated to search for terrestrial gamma-rays (Klebesadel et al. 1973). The nature of these sources remained nebulous until the launch of the Burst and Transient Source Experiment (*BATSE*) on board the Compton Gamma-Ray Observatory (*CGRO*) in 1991. The results from *BATSE* established that GRBs do not occur in any particular direction in the sky but show a rather isotropic distribution and have non-thermal spectrum, strongly supporting their cosmological origin (Fishman & Meegan 1995). The classification of GRBs is a function of the observed properties like the duration of the prompt emission, hardness of the observed gamma-ray spectrum etc. indicative of

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diverse progenitors (Piran 1999; Zhang 2011) capable of producing isotropic energies of the order of 10^{50} to 10^{55} ergs.

The ultra-relativistic energy flow during the burst emitted in the form of gamma-rays is converted into radiation. This conversion of energy occurs due to some internal process, such as internal shocks and collisions within the flow (Goodman 1986; Paczynski 1986). However, not all the energy of the relativistic shell can be converted to radiation by internal shocks. The remaining kinetic energy dissipates via external shocks that may produce an “afterglow” seen at different wavelengths (Katz 1994; Meszaros & Ress 1997). Unlike the GRB emission, the afterglow emission is long-lived and can be observed in different frequencies for a much longer duration and provides enormous information about the nature of the progenitors and the underlying physical mechanisms. Optical observations of afterglows are very important to understand about the distance, energetics, environments and nature of host galaxies of GRBs. Synchrotron emission is the leading mechanism to interpret the observed non-thermal spectrum (Sari & Piran 1997; Sari, Piran & Narayan 1998) of the afterglows in a majority of the cases. Synchrotron emission is the emission from relativistic electrons gyrating in random magnetic fields (Rybicki & Lightman 1979). Typical energy of synchrotron photons as well as cooling time depend on the Lorentz factor γ_e of the relativistic electrons and on the strength of the magnetic field. What causes a GRB i.e. the nature of the central engine is still under debate (Gehrels, Ramirez-Ruiz & Fox 2009). Any respectable theoretical model for GRBs should be able to explain not only the observed collimated γ-ray energy of the order of 10^{51} erg but also the underlying emission mechanisms to reproduce the observed time-scales, spectra and their afterglows. Several models have been proposed for the possible progenitors of long (Usov 1992; Woosley 1993; Vietri & Stella 1998; MacFadyen & Woosley 1999) and short-duration GRBs (Eichler et al. 1989; Narayan, Paczynski & Piran 1992). At least, some of the long-duration GRBs are associated with a special type of core-collapse supernovae, the explosions marking the deaths of massive stars (Hjorth & Bloom 2011).

Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India has longitudinal advantage for the observations of time-critical observations like GRBs and other transient events as it lies in the middle of the 180° wide belt between Canary Islands (20°W) and Eastern Australia (160°E) (Pant et al. 1999; Sagar 2000).

The outline of the paper is as follows. In the next Section we discuss some of the key results based on the afterglow data of some of the bursts taken from Nainital. Sections 3 and 4 describe the new upcoming optical facilities at Devasthal, Nainital and their importance in pursuing observations of time-critical events like GRBs.

We have used the following conventions throughout the article: the power-law flux is given as $F(\nu, t) \propto t^{-\alpha}\nu^{-\beta}$, where α is the temporal decay index and β is the spectral slope; we assume a standard cosmology with H_0 = 70 km s^{-1} Mpc^{-1}, Ω_m = 0.3 and Ω_Λ = 0.7; all errors and uncertainties are quoted at the 1σ confidence level.

2. Optical observations of afterglows of GRBs

The general consensus is that the forward shock ploughs into the interstellar media, sweeps up the matter and decelerates. This forward shock deceleration due to the increasing amount of swept-up material produces a slowly fading "afterglow" emission ranging from $X-$ray, UV and optical to radio wavelengths (Sari & Piran 1997). Optical afterglows of long-duration GRBs have generally apparent $R-$band magnitudes between 16 to 22 mag, if detected within a few hours after the burst. Meter-class optical telescopes equipped with CCD detector are therefore capable of contributing significantly to the dense temporal coverage of the afterglows (Sagar 2000). Optical afterglow light-curves and the spectral energy distributions (SEDs) are the two key features required to understand the properties of the GRB afterglows (Sari, Piran & Narayan 1998; Sari, Piran & Halpern 1999). The temporal flux decay indices and the spectral slope of the SEDs are related through various closure relations predicted in terms of various afterglow models for a homogeneous ambient medium (i.e. ISM model) (Sari, Piran & Narayan 1998; Sokolov et al. 2001) and for a pre-existing stellar wind (i.e. WIND model) models (Chevalier & Li 1999). The optical SEDs in combination with observations at other wavelengths like $X-$rays is thus able to constrain not only the values of break frequencies like cooling-break (ν_c) and maximum synchrotron frequencies (ν_m) but also the value of electron energy index p. The constructed SEDs might show a curvature due to extinction in the local burst medium. This deviation from the expected power-law behavior could be used to estimate the extinction in the host galaxy assuming some extinction law (Cardelli et al. 1989; Calzetti et al. 2000; Pei 1992). A good fraction of GRBs have not been detected at optical frequencies up to deep limits, indicating towards a separate class of bursts designated as "dark GRBs". The possible explanations given for these "optically dark" bursts are as follows. (1) Optical afterglows of these GRBs are extinguished by dust (star forming region) in the host galaxy (Reichart & Price 2002), (2) Some optical afterglows are intrinsically very faint (Fynbo et al. 2001; Berger et al. 2002), (3) A few GRBs lie at very high redshift, the Lyman break is red-shifted into optical band (Lamb & Reichart 2000) and/or (4) Some of the GRBs explode in very low-density environments so there are no afterglows produced.

Multi-wavelength optical observations of around ~ 50 afterglows of GRBs were performed using 1.04m telescope at Nainital including GRB 990123 (Castro-Tirado et al. 1999; Galama et al. 1999), GRB 991208 (Castro-Tirado et al. 2001; Sagar et al. 2000a), GRB 000301C (Sagar et al. 2001b), GRB 000926 (Sagar et al. 2001b), GRB 010222 (Sagar et al. 2001a; Bhattacharya 2001), GRB 011211 (Jakobsson 2003), GRB 021004 (Pandey et al. 2003; de Ugarte Postigo et al. 2005; Castro-Tirado et al. 2010), GRB 020405 (Masetti et al. 2003), GRB 021211 (Pandey et al. 2003), GRB 030226 (Pandey et al. 2004), GRB 030329 (Resmi et al. 2005), GRB 0505025A (Resmi et al. 2012), GRB 030328 (Maiorano et al. 2006), GRB 060124 (Misra et al. 2007), GRB 061126 (Gombok et al. 2008) and GRB 071010A (Covino et al. 2008).

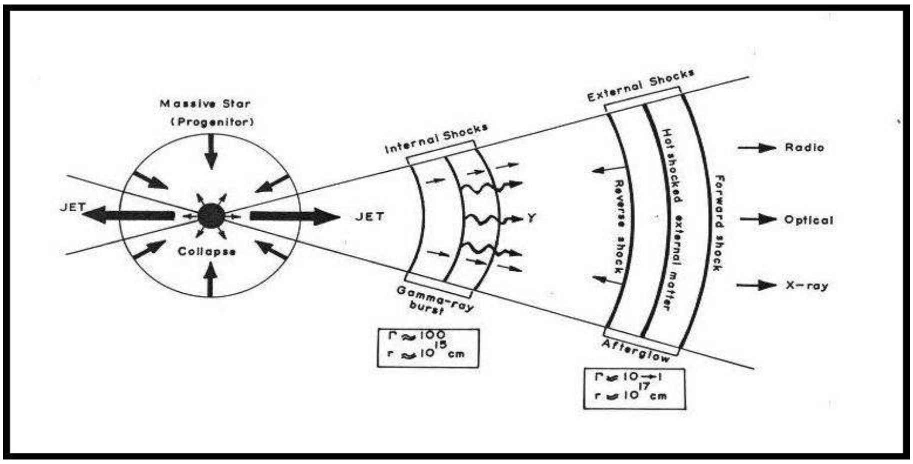

Figure 1. Schematic diagram of fireball model showing GRBs from internal shocks and afterglows from external shocks from a relativistic jet emerging due to a massive star collapse. Similar jets could also arise from other progenitor models.

2.1 GRB 010222

Multi-wavelength optical, radio and millimeter observations of the afterglow of GRB 010222 along with other published data were used to understand the properties of this burst (Sagar et al. 2001a). The GRB 010222 afterglow is rather unusual and exhibits a relatively flatter temporal power-law decay indices accompanied with a flat electron energy index p (Bhattacharya et al. 2001) seen only in a couple of cases. In Fig. 2, the broken power-law model fit shows an achromatic break in the optical data. The fitted light-curve parameters along with the spectral slopes derived from SED at various epochs indicate for a very low value of cooling break frequency ν_c at early epochs. Such a low value of the cooling frequency, so early in the evolution (at t < 0.5 day) is certainly unusual, and indicates the presence of a very strong post-shock magnetic field (Sagar et al. 2001a).

2.2 GRB 021004

GRB 021004 is a well sampled case with superimposed variability in the observed multi-band optical afterglow light-curves. The flux decay nature of the optical afterglow shows very uncommon rapid flux variations, especially during early times (t < 2 days), superimpose on an underlying broken power-law decay (Pandey et al. 2003). The residuals, after subtracting the best fit broken power-law from the light-curves, are plotted in the bottom panel of Fig. 3. The variations appear to be achromatic and are clearly visible, thanks to the dense temporal coverage of the photometric observations. An estimate of the duration of variations by Gaussian fitting yields FWHM

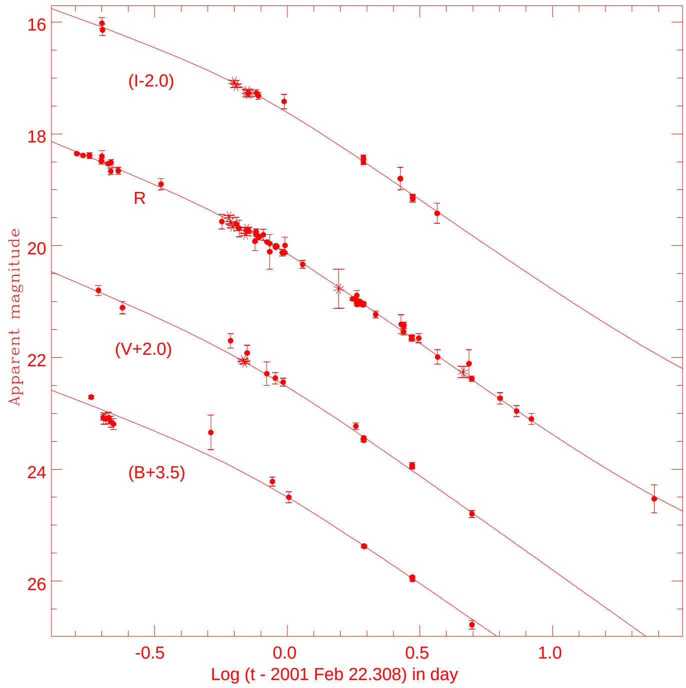

Figure 2. Light curves of GRB 010222 afterglow in optical B, V, R and I photometric passbands. The observations taken from 1.04m Telescope at Nainital have been indicated as asterisk. Suitable offsets have been applied to avoid overlapping in data points of different passbands. Flux decay cannot be fitted by a single power-law. Solid lines represent the non-linear least square fit for jet model.

values of 11.5 and 21 hours for the bumps between t = 0.25 to 1 day, and t = 1.1 to 2.1 day respectively. The peculiar nature of the GRB 021004 afterglow LCs was explained in terms of variation in energy of the blast wave with time (Nakar, Piran & Granot 2003) i.e. the patchy shell model. Heyl & Perna (2003) have tried both the variable energy and the variable density models to compare with the observed afterglow data and got a better fit for a variable density model with constant shock energy. The location of the cooling frequency ν_c above the optical band, in the model by (Pandey et al. 2003; de Ugarte Postigo et al. 2005; Castro-Tirado et al. 2010) also supports the variable density profile as an explanation for the observed variability in the optical LCs of GRB 021004.

2.3 GRB 030329/SN 2003dh

We monitored the afterglow of GRB 030329/SN 2003dh in *UBVRI* photometric passbands for a period of 3 hours to 34 days after the burst (Resmi et al. 2005; Pandey

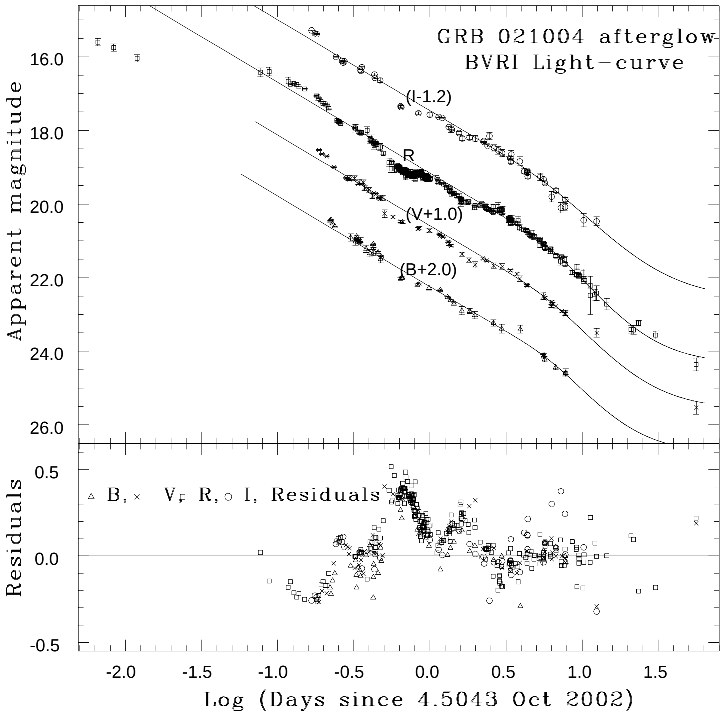

Figure 3. *BVRI* afterglow LCs of GRB 021004 afterglow published in (Pandey et al. 2003). Solid line represents the modeled broken power-law nature of the afterglow LCs and the possible contribution from the host galaxy. Marked vertical offsets have been applied to avoid overlapping of the data points of different pass-bands. For comparison, *R* magnitude of a nearby comparison star is also plotted in the upper panel. The *BVRI* band residuals i.e. observed minus fitted power-law (in magnitudes) are displayed in the lower panel. The residuals show random and erratic behaviors of the afterglow LCs.

2005). The complex nature of the GRB 030329/SN 2003dh afterglow LCs is due to the underlying bright SN 2003dh (Stanek et al. 2003). The well observed re-brightening around 1.5 day after the burst is explained as an effect of wide-angle jet being dominant, as modeled by (Berger et al. 2003), with a "two component jet model". The observed step-wise sharp features cannot be explained in terms of variable external density medium (Wang & Loeb 2000; Nakar, Piran & Granot 2003). In the present case (see Fig. 4, left panel) all the fluctuations exhibit the same amplitude after the jet break when all the jet structure is visible, whereas decrease in amplitude of successive fluctuations is expected in a patchy shell model (Granot, Nakar & Piran 2003). If no break frequency is passing through the observed frequencies then the observed colors should not evolve, and power- law decay with the same slope should be resumed after the re-brightening, giving rise to step wise profile. This prediction of the refreshed shock model appears to match the observed step wise profile in the case of GRB 030329/SN 2003dh (Granot, Nakar & Piran 2003).

The photometrically calibrated observations of this afterglow (Resmi et al. 2005; Pandey 2005) were used to study temporal evolution of the observed colors (see Fig. 4, right panel). The colors do not evolve significantly till $t \sim 6$ days after the burst. The derived color values are typical for GRB afterglows, similar to those compiled by (Simon et al. 2001) for a set of optical afterglows in the redshift range $z = 0.36 - 3.5$. In the color values at $t > 6$ days after the burst, a clear trend is seen: the $(B - R)_o$ colors grows redder and the $(V - I)_o$ colors grows bluer, converging towards colors typical for a supernova, for which the emission peaks around V band. The trend in the observed colors at $t > 6$ days confirms the contribution from the underlying supernova SN 2003dh, discovered spectroscopically by Stanek et al. (2003).

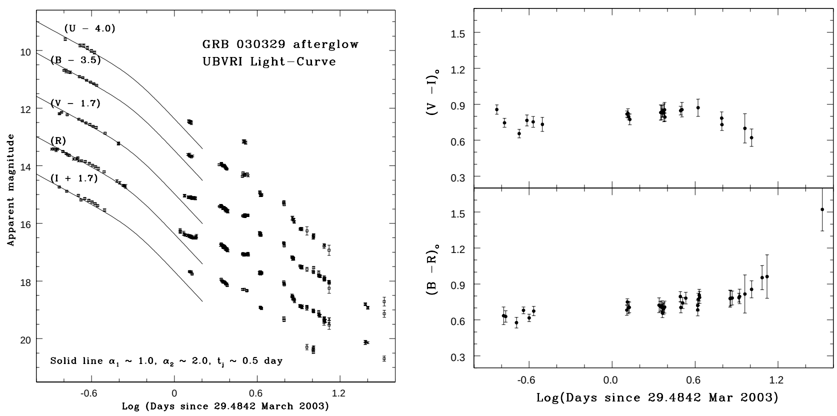

Figure 4. *UBVRI* afterglow light curve of GRB 030329/SN 2003dh (Left panel). The solid line is a fitted broken power-law model (Beuermann et al. 1999) over-plotted on observed *UBVRI* points. Offsets have been used to avoid overlap of different bands. Solid pentagons represent our observations while triangles represent data taken from (Lipkin et al. 2004). In the right panel, observed colors (B - R) and (V - I) of GRB 030329/SN 2003dh afterglow are plotted against time. The colors show no significant evolution till 6 day after the burst but after 6 days it shows SN 2003dh contribution.

3. Optical facilities at Devasthal

Devasthal, the new observing station of ARIES Nainital (a mountain peak 60km away from Nainital, an altitude of ~ 2450 m above msl, longitude 79.7E and latitude 29.4N) has advantages like dark skies, sub-arcsec seeing conditions, low extinctions and at the same time the site is easily accessible (Pant et al. 1999; Sagar 2000; Stalin et al.

2000). Such characteristics of an astronomical site are well-suited to establish modern optical telescopes to optimize scientific outputs.

3.1 1.3m Optical Telescope

The 1.3m telescope recently installed at Devasthal has been fabricated by DFM Engineering Inc. USA. The design of this telescope is Ritchey-Chretien Cassegrain along with a field-flattener. The effective focal length of this system is f/4 giving rise to a field of view up to 66 arcmin. The mirrors of the telescope are made of Corning's TSG material and are polished to optical wavelength accuracies coated with Aluminum to obtain high reflectivity at visible wavelengths. The telescope is controlled using dedicated softwares and has remote operating capability (see Fig. 5).

Three CCD cameras are currently available with the telescope as first generation back-end instruments for obtaining images of the celestial sky. The cameras are (1) 2048×2048 pixels, 13.5 micron pixel size conventional back-illuminated, deep thermo-electrically cooled (-80 C) CCD, (2) 512×512 pixels, 16 micron pixel size electron multiplying frame transfer back-illuminated deep thermo-electrically cooled (-90 C) CCD, (3) 3326x2504 pixels, 5.4 micron, front illuminated thermo-electrically cooled (-30 C) conventional CCD. The first two cameras use high quantum efficiency E2V chip assembled by ANDOR with low read noise electronics. The third camera is from SBIG using Kodak chip. The images obtained with the telescope show best FWHM at nearly 1 arcsec. The sky brightness is measured as 21.2 mag/arcsec^2 in the V band on moonless night, comparable to those for other major national and international optical observing sites. The telescope is equipped with a motorized filter changer, design and developed at the institute. Currently, broad-band ($BVRI$), (u, g, r, i, z) and narrow-band interference filters for O[III], S[II], and H-alpha line observations are available. The telescope is currently being used for photometric observations of star clusters, galaxies, and monitoring extrasolar planets, transients such as GRB afterglows and supernovae (Sagar et al. 2011).

3.2 3.6m Optical Telescope

At Devasthal a modern 3.6-m optical telescope (DOT) will be installed by the end of 2012. The fundamental telescope optics parameters are a primary mirror of diameter 3.6-m, f/2 primary, f/9 effective focal ratio, Ritchey-Chretien configuration with back focal distance of 2-m (see Fig. 6). The secondary mirror will have a diameter of about 0.9 m. The telescope performance is said to have 80% of its encircled energy within 0.45 arcsec diameter over 350-3000 nm wavelength range. The telescope will have a alt-azimuth mounting with a zenith blind spot of less than 2 degree conical diameter. The science field of view of DOT is 10 arcmin without corrector and 30 arcmin unvignetted field for axial port and 10 arcmin for side ports. A cylindrical

Figure 5. A view of 1.3m optical telescope, installed at Devasthal.

space of minimum 2.5 meter below the focal plane for axial port and approximately 3.0 meter diameter around optical axis will be available for the instrument envelope. The telescope will have a pointing accuracy of less than 2 arcsec rms for any point in the sky with elevation greater than 10 degree and less than 0.1 arcsec rms for 10 arcmin off-set. The tracking accuracy of DOT will be smaller than 0.1 arcsec rms for less than one minute in open loop and smaller than 0.1 arcsec rms for about one hour in closed loop (with auto guider). The acquisition and guiding unit will be available with the telescope along with the five axis motion of secondary mirror.

For this telescope, the first generation proposed focal plane instruments are (1) ARIES Devasthal Faint Object Spectrograph and Camera (ADFOSC), (2) a high resolution Echelle spectrograph, (3) a near infrared spectrometer (IRSPEC), and (4) an optical imager dedicated for photometric observations. The ADFOSC is a focal reducer instrument and shall work both in imaging and spectroscopic modes. The instrument will have imaging capabilities with one pixel resolution of less than 0.3 arcsecond in the whole unvignetting field of view (10×10 arcmin) of the telescope and low-medium resolution spectroscopy with spectral resolution (250-5000) covering the wavelength range from 350 nm to 1000 nm. It is expected that we can image a V$\sim$25 mag star within one hour of exposure time (see Fig. 6). The high resolution Echelle spectrograph, capable of giving continuous spectral coverage (350 nm to 1000 nm) in a single exposure with a signal-to-noise ratio of 100 per 4 km/s bin for an integration time of one hour for a star of 14 magnitude at V band (see Fig. 6). The concept of the high resolution Echelle spectrograph will be similar to many contemporary high resolution spectrometers such as HERMES.

A general purpose near-infrared imaging camera with limited spectroscopic capability is proposed by TIFR Mumbai for observations in the near-infrared bands between 1 to 2.5 micron. It will use a 1024×1024 Hawaii HgCdTe detector array manufactured by Rockwell International USA and will have flexible optics and drive electronics that will permit a variety of observing configurations. The array will have a pixel size of 40 microns, read-noise of about 30 e/pixel, dark current of less than 0.2 e/sec/pixel and a gain of 10 e/adu. The primary aim of this instrument would be to obtain broad and narrow band imaging of the fields as large as 4×4 arcmin and also to use it as a long-slit spectrometer with moderate resolving power ($\lambda/\Delta\lambda \sim 400$) when attached to the telescope. The proposed IRSPEC when coupled with the 3.6 m telescope is expected to reach the 5σ detection of 22.5 mag in J, 21.5 mag in H and 21.0 mag in K with one hour integration. The optical imager will have a back-illuminated, blue-enhanced 4K×4K CCD camera and 2 filter wheels having Bessel $UBVRI$ and SDSS set of broad-band filters.

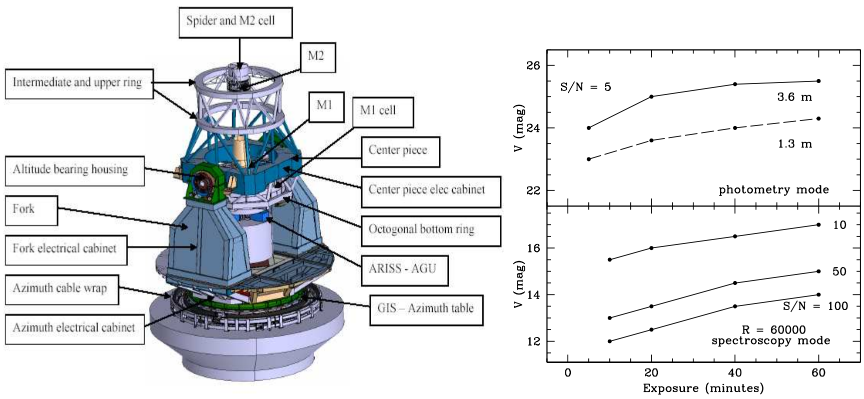

Figure 6. Top : Major sub-assemblies of the telescope with height ~14 m and weight ~120 ton; Bottom : The simulated sensitivities of detections for 3.6-m and 1.3-m optical telescopes.

4. Discussions and results

Follow-up observations of optical afterglows of GRBs from Nainital have provided a good sample of well-calibrated photometric data for more than a decade taking advantage of the geographical location of India, crucial for time critical observations. Optical afterglow observations from Nainital along with other multi-wavelength observations have been helpful to understand the nature of forward shock emission and constraining the output energetics. The observed superimposed variability in the optical light-curves have been able to indicate towards the nature of ambient media and hence towards the nature of the progenitors. The spectral energy distributions of the afterglows using optical observations have helped towards our understanding about the intrinsic extinction towards the burst direction which in turn indicate towards the possible progenitors. Some of the non-detections of the afterglows at optical frequencies also indicate towards the exciting nature of these energetic sources. Some of the *Swift* GRBs exhibit a chromatic break in the multi-band data, indicating towards the possible energy injection episodes at later epochs. The multi-band modeling of some of the afterglows have been able to estimate the values of physical parameters, important to constrain the nature of the outflow and the progenitor models. The Supernova connections with long duration GRBs have also been detected photometrically in case of couple of nearby events.

GRBs, the energetic cosmic explosions and their correlation with SNe has now become quite a mature research area, addressing some of the very important unanswered questions in the field of astronomy including the evolution of very massive stars and the observational cosmology. The correlation of GRBs with SNe has now been established clearly in many cases and indicates the underlying physical mechanisms and the possible progenitors of these stellar explosions. GRBs have been observed up-to a redshift of $z = 8.2$ (Tanvir et al. 2009; Salvaterra et al. 2009) probing the star formation at very high redshifts. The *Fermi*-LAT has now detected more than a dozen of GRBs having delayed GeV excess emission, indicating a close connection to the low-energy afterglow emission (Pandey et al. 2010; Ghiselini et al. 2010). As a bi-product during GRB search missions, many other gamma-ray transients were also discovered with high energy properties similar to GRBs but multi-wavelength follow-up observations of such events specially at optical-NIR frequencies indicate different physical circumstances. For example, SWIFT1644+57 indicate towards an outburst from a massive black-hole fed by a tidally disrupted star (Bloom et al. 2011; Levan et al. 2011) and SWIFTJ195509+261406 apparently a galactic transient candidate soft gamma-ray repeater (Castro-Tirado et al. 2008).

The newly installed 1.3m telescope and the upcoming 3.6m telescope along with the first generation focal plane instruments are very useful to carry out photometric and spectroscopic observations of the transients like GRBs and Supernovae in more detail. The proposed optical imager along with the 3.6m telescope will also be very useful towards studying the host galaxies of GRBs and late time evolution of SNe in more detail.

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