*J. Astrophys. Astr.* (2013) **34,** 157–173

# Core-Collapse Supernovae and Gamma-Ray Bursts in TMT Era

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Received 8 May 2013; accepted 25 June 2013

**Abstract.** Study of energetic cosmic explosions as a part of time domain astronomy is one of the key areas that could be pursued with upcoming Giant segmented optical-IR telescopes with a very large photon collecting area applying cutting edge technology. Existing 8–10 m class telescopes have been helpful to improve our knowledge about core-collapse supernovae, gamma-ray bursts and nature of their progenitors and explosion mechanisms. However, many aspects about these energetic cosmic explosions are still not well-understood and require much bigger telescopes and back-end instruments with high precision to address the evolution of massive stars and high-redshift Universe in more detail. In this presentation, possible thrust research areas towards core-collapse supernovae and gamma-ray bursts with the Thirty-Meter Telescope and back-end instruments are presented.

*Key words.* Massive stars—core-collapse—supernovae—gamma-ray bursts—optical—telescopes.

## 1. Introduction

The astronomical community with the aid of ground/space based telescopes has made tremendous progress over the last hundred years or so, in understanding many aspects of our observable Universe. The findings include: discovery of exo-planetary systems, evidence for an accelerating Universe, detailed identification and monitoring of the orbits of the asteroids and comets that may pose great dangers to the inhabitants of the Earth, and many more. Astronomers across the world feel a great need for new generation very large telescopes to probe the Universe much deeper, to unravel its formation and evolution, and to discover the existence of life elsewhere in the Universe. With the current combination of 8–10 m class ground-based telescopes and the Hubble Space Telescope, study about Core-Collapse Supernovae (CCSNe) and Gamma-Ray Bursts (GRBs) have been able to provide a great deal of information about the fate of evolution of massive stars ($>$8–10$M_{\odot}$) and the underlying physical mechanisms (Woosley & Bloom 2006; Langer 2012; Yoon & Langer 2005) and references therein). The unprecedented light gathering power and spatial resolution of the Thirty-Meter Telescope[1] (TMT) and the back-end instruments[2] will allow us to study distant lighthouses like CCSNe and GRBs, which could be studied in more detail probing the high-redshift Universe, dark energy contents and epoch of re-ionization.

### 1.1 *The TMT project*

The TMT project is one of the most innovative among the proposed mega-science projects in the next decade. The project is aimed to build the world's most advanced and capable ground-based optical, near-infrared and mid-infrared observatory. It will integrate the latest innovations in precision control, segmented mirror design and Adaptive Optics (AO). At the heart of the telescope is the segmented mirror, made up of 492 individual segments of 1.45 m. Precisely aligned, these segments will work as a single reflective surface of 30 m diameter. TMT will be located just below the summit of Mauna Kea on Hawaii Island, at an elevation of 4050 meters. The performance of a ground-based telescope is adversely affected by the Earth's atmospheric seeing. The fundamental goal of any AO system is to improve the telescope performance from seeing limited, meaning the image quality is limited by the atmosphere above the telescope, toward diffraction limited, meaning images as sharp as those that could be obtained with the same diameter telescope located in space. Even in seeing limited mode, TMT offers an order of magnitude improvement over existing observatories, mostly due to its light gathering capacity. The AO capability enables TMT to resolve objects by a factor of 3 better than the current 10-m class telescopes and 12 times better than the Hubble Space Telescope. As first generation instruments for TMT, the Wide Field Optical Spectrometer (WFOS) will provide near-ultraviolet and optical (0.3 to 1.0 $\mu$m) imaging and spectroscopy over a more than 40 square arc-minute field-of-view. The concept for the TMT Wide-Field Optical Spectrometer is the Multi-Object Broadband Imaging Echellette (MOBIE) spectrometer. Narrow Field Infrared Adaptive Optics System (NFIRAOS) is the TMT's adaptive optics system for infrared instruments (0.8–2.5 $\mu$m). Two of these science instruments will be delivered for use with the Multi Conjugate Adaptive Optics-Laser Guide Star (MCAO-LGS) system at first light: IRIS-TMT, a near-infrared instrument with parallel imaging and integral-field-spectroscopy support; and IRMS, an imaging, multi-slit near-infrared instrument (Crompton *et al.* 2008; TMT_documents 2007a,b,c). The suite of the above first generation instruments with TMT along with synergy with the E-ELT [3] and JWST[4] would also be very relevant in studying CCSNe and GRBs in great details.

### 1.2 *Indian historical prospects*

India has made several notable contributions towards optical-NIR astronomy during the latter half of the last century and had put in great efforts to set up world class

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[1] www.tmt.org/documents

[2] http://www.tmt.org/observatory/instruments

[3] http://www.eso.org/public/teles-instr/e-elt.html

[4] http://www.jwst.nasa.gov/

observing facilities, which culminated in the indigenous building of the 2.3 m Vainu Bappu Telescope (VBT) in 1987. The most recent astronomy facilities which have been set up in the country are IIA's 2.0 m Himalayan Chandra Telescope (2003) at Hanle, Ladakh and the 2.0 m IUCAA Girawali telescope (2006) at Girawali, near Pune. There are two upcoming 4.0 m class optical-NIR astronomical facilities led by ARIES, Nainital: the 3.6 m optical-NIR facility (Devasthal Optical Telescope) which is expected to be commissioned in 2013, and the proposed 4.0 m International Liquid Mirror Telescope, both being set-up at Devasthal (Sagar *et al.* 2012). India will soon launch a dedicated astronomy satellite, ASTROSAT, with multi-wavelength capabilities in the UV and X-ray wavelengths. Indian astronomers have also contributed towards studying stellar explosions and early Universe apart from other areas of observational astronomy. Using the observational capabilities in the country during the last two decades, Indian astronomers have been able to study many SNe (e.g. Ashok *et al.* 1987; Pandey *et al.* 2003a, b; Sahu *et al.* 2006; Roy *et al.* 2011; Kumar *et al.* 2013) and afterglows of GRBs (e.g. Sagar *et al.* 1999; Bhattacharya 2003; Pandey *et al.* 2003a, b, 2004; Resmi *et al.* 2013) in detail.

### 1.3 *India-TMT*

India's participation in international projects was envisaged in the Astronomy and Astrophysics 'Decadal Vision Document 2004' sponsored by the Indian Academy of Sciences and the Astronomical Society of India. In this context, international consortia for mega telescope projects approached astronomy institutes in the country for India's participation. The Indian astronomy community after due diligence and thorough deliberations, arrived at the conclusion that TMT presents the best options for India and participation in the project at a 10% level would be optimal.

The Department of Science and Technology (DST) reviewed the proposal submitted by Indian astronomers and approved the observer status for India in the TMT project in June 2010. Since then, India has been participating in all the policy decisions and development activities of the project. The Aryabhatta Research Institute for Observational Sciences (ARIES), Nainital; the Indian Institute of Astrophysics (IIA), Bangalore; and the Inter-University Center for Astronomy and Astrophysics (IUCAA), Pune are the three main institutes spearheading the efforts. Options for other Indian Institutes and Universities are open to join the ongoing efforts by India-TMT. The activities of India-TMT[5] will be coordinated by the India TMT Coordination Center (ITCC), jointly funded by the Department of Science and Technology and Department of Atomic Energy, Government of India.

## 2. Core collapse supernovae

It is commonly recognized that CCSNe represents the final stages of the life of massive stars ($M > 8$–$10 M_{\odot}$) (Heger *et al.* 2003; Anderson & James 2009). Generally, the fate of massive stars is governed by its mass, metallicity, rotation and magnetic field (Fryer 1999; Woosley & Janka 2005). Massive stars show a wide variety in these

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[5] tmt.iiap.res.in

fundamental parameters, causing diverse observational properties among various types of CCSNe. The presence of dominant H lines in the spectra of Type II SNe strongly suggests that their progenitors belong to massive stars which are still surrounded by significantly thick hydrogen envelope before the explosion (Filippenko 1997). For a Salpeter IMF with an upper cut-off at $100M_\odot$, half of all Type II SNe are produced by stars with masses between 8 and $13M_\odot$. This means that more than half of the stars producing SNe are poor sources of ionizing photons and of UV continuum photons, and that the bulk of the UV radiation, both in the Balmer and in the Lyman continuum is produced by much more massive stars. So, both the H-alpha flux and the UV flux are measurements of the very upper part of the IMF (about $>40M_\odot$), representing stars with masses larger than $8M_\odot$ and are least understood. The analysis of archival images of HST have been able to detect some of the type II SNe progenitors as red and yellow super-giants (Yoon *et al.* 2012; Van dyk *et al.* 2012). On the contrary, H and He deficient features are commonly observed in the spectra of Type Ib/c SNe and are supposed to have luminous Wolf-Rayet stars as the possible progenitors. However, search for Type Ib/c SNe progenitors in the archival deep images has thus far been unsuccessful. The rate of core-collapse SNe (II, Ib/c) is a direct measurement of the death of stars more massive than $8M_\odot$, although it is still a matter of debate whether stars with mass above $40M_\odot$ produce a 'normal' SNe-II and Ib/c, or rather collapse forming a black hole with no explosion, i.e. a 'collapsar' (e.g. Heger & Woosley 2002). These explosions and their possible progenitors are rather poorly understood research problems in astrophysics and a subject of great scientific interests (Taubenberger *et al.* 2009; Modjaz *et al.* 2011; Crowther 2013).

At low ($z < 0.1$), intermediate ($0.1 < z < 1.0$) and high ($z > 1.0$) redshifts many SN search programs such as CRST, PTF, KAIT, CfA, ESSANCE, SDSS, HST-GOODS are going on whereas many more are proposed in the coming years e.g. SKYMAPPER, PANSTARRS, LSST, WFIRST, JWST. So far, the fraction of total number of discovered CCSNe (∼76%) is found to be much more in comparison to the number of type Ia SNe (∼24%). Out of the total number of discovered CCSNe, Type-II events are much more than Type Ib/c SNe (Lennarz *et al.* 2012). Statistically, the number of Type Ib/c SNe in the local Universe have been very less (only 4% of the total population) in comparison to number density of Type-II SNe and their possible progenitors are WR stars. No conclusive results have been found for the brightness distribution of CCNSe with their redshifts (Habergham *et al.* 2012).

The TMT along with the back-end instruments is optimized both in OA and seeing-limited modes for the rapid response i.e. 10 minutes, which is extremely important for studies of time critical observations like SNe and GRBs. For example, IRIS-TMT spectra of a point source in one hour exposure time with $S/N \sim 10$ will be able to look at J ∼ 24.1 mag, H ∼ 23.7 mag and K ∼ 22.9 mag. Whereas seeing limited imaging of $S/N \sim 100$ will be able to see sources up to J ∼ 27.3 mag, H ∼ 26.2 mag and K ∼ 25.5 mag in a similar exposure time.

### 2.1 *CCSNe of Type II by TMT*

SNe IIn (3% of type-II populations) are the brightest SN type in the far-UV and have long-lived emission lines, making them potential candidates to study in great detail at high redshifts. The average far-UV flux of Type IIn SNe at $z \sim 2$ corresponds to $m\_v \sim 28$ mag, that enabled photometric detections in deep surveys. Moreover, the bright long-lived spectral features seen in case of Type-IIn SNe, remain above the threshold of 8–10 m class telescope for years after the explosion, enabling WFOS-TMT kind of instrument to obtain rest-frame far-UV emission-line detections, spectral properties and inferred kinematics of $z > 2$ Type IIn SNe and host galaxies. The rest-frame far-UV light would be red-shifted to optical wavelengths for $2 < z < 6$ SNe and enables photometric detection in existing, and future, deep ($m\_v \sim 27$–$28$ mag) multi-epoch, wide-field optical surveys using 4–8 m-class facilities. The ejecta of SNe IIn interact with cold circumstellar material expelled during previous evolutionary episodes and create extremely bright and long-lived emission lines. Current 8–10 m class telescopes do not have spectral sensitivity to detect Ly-alpha emission from $z > 3$ SNe of Type II. The strength and duration of the prominent emission lines permit spectroscopic detection of $2 < z < 6$ using IRMS and WFOS-TMT for ~3–15 years after outburst (Cooke *et al.* 2009; Whalen *et al.* 2013a). Early time spectroscopy of Type IIn SNe during photospheric and shock-breakout phases using TMT is very important to understand the environments and the nature of the possible progenitors (Schawinski *et al.* 2008; Bufano *et al.* 2009). Late time spectral evolution of Type IIn SNe with TMT will be important to understand the geometry of the inner ejecta using evolution of line profiles and chemical enrichment of ISM and IGM.

On the other hand, CCSNe Type IIp are quite common in nearby Universe and their atmosphere are dominated by H lines. Observational constraints on the possible progenitors of Type IIp SNe (Smartt 2009) using the pre-explosion images further make these locations as promising targets for TMT to put limits on the masses and types of the progenitors. It is also possible to probe Type IIp SNe at $z > 1$ to study possible shock-breakout phase probing the underlying mechanisms of the possible progenitors of Type IIp SNe using TMT capabilities (Tominaga *et al.* 2011). Existing 8–10 m class telescopes required 2–3 hours of exposure time to get a good $S/N$ nebular phase spectra ($z < 0.3$) with Fe-II lines showing correlation with I-band luminosity, not seen in case of other Type II SNe. So, with the TMT capabilities, high-$z$ SNe of Type IIp could be studied to be used as standard candles (Poznanski *et al.* 2010).

### 2.2 *CCSNe of Type Ib/c by TMT*

Hydrogen-stripped Type Ib/c SNe (see Fig. 1) are another potential targets for TMT to be studied in more details. The upcoming SN survey programs like LSST, WFIRST, JWST are expected to produce a sizeable number of high-$z$ Type Ib/c SNe. Massive Wolf-Rayet stars ($>25$–$30 M_\odot$) are supposed to be the potential progenitors for these SNe (Crowther 2007), so far not identified in pre-discovery images taken by HST and ground-based 8–10 m class telescopes (Maund *et al.* 2005; Crockett *et al.* 2007, 2008). Another plausible way to produce Type Ib/c SNe is a lower mass helium-star in a binary channel with mass-loss mechanism (Podsiadlowski *et al.* 1992; Nomoto *et al.* 1995). Majority of Type Ib/c SNe are found in star forming galaxies. Taking advantage of TMT OA and IFU capabilities, stellar population studies (Murphy *et al.* 2011; Anderson *et al.* 2012; Eldridge *et al.* 2013)

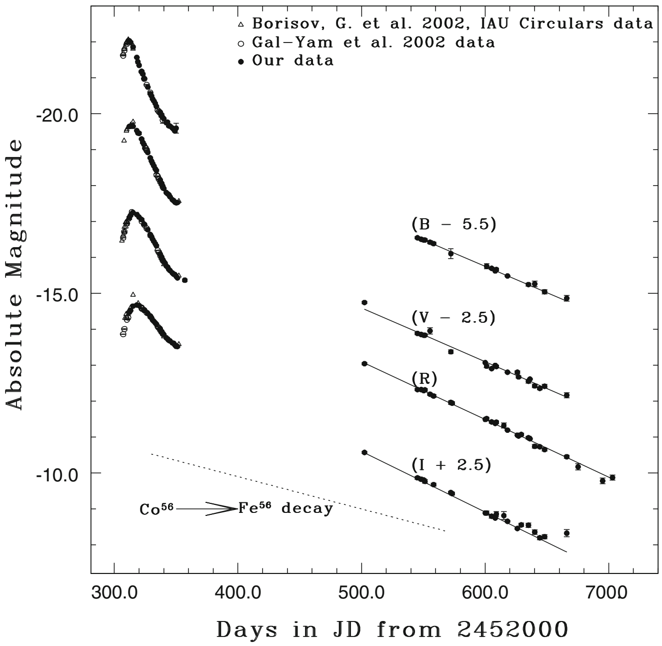

**Figure 1.** BVRI light-curves of broad-lined Type Ic SN 2002ap discovered in M74 at $z \sim 0.002$, showing the typical decay nature of H-stripped CCSNe (Pandey 2006). SN 2002ap is more energetic than typical SNe of Type Ib/c and exhibit close resemblance with SN 1998bw profile at later epochs.

close to the explosion site would tell more about the possible progenitors of Type Ib/c SNe.

Using WFOS-TMT capabilities, late time optical spectroscopy of type Ib/c SNe could tell about kinematical, chemical information about the shocked ejecta and its interaction with the circumstellar material (Chevalier & Fransson 2006). Late time optical spectroscopy could also help in probing the mass loss history and evolutionary status of the progenitor stars (Leibundgut *et al.* 1991; Fesen *et al.* 1999). Time series optical spectroscopy of Type Ib/c SNe in nebular phases could also tell about the evolution of line widths and ratios of various line strengths, distinguishing the late time underlying physical mechanisms and ejecta structure. Recent observations of light echoes in supernova remnants have opened yet another method to determine the progenitors of supernovae. For example, light echoes from SN 1993J have been detected at the level of 22.3 mag/arcsec$^2$ square by HST 'V' band (F555W) observations. Telescopes like TMT will be able to detect light echoes to V $\sim$ 28.5 mag/arcsec$^2$ in galaxies well beyond the Virgo cluster. With this capability one can determine the nature of SN types of all recorded explosions whose types (i.e. whether thermonuclear or core-collapse) are not known, in the past hundred years or so or of the SN remnants in the local group of galaxies by faint object spectroscopy of the echoes of light given out originally by the SN when it exploded (Milisavljevic *et al.* 2012).

### 2.3 *Pair instability SNe*

Pair Instability SuperNovae (PISN) are thought to arise from extremely massive progenitors, possibly population-III stars above 100 solar mass (Rakavy & Shaviv 1967; Barkat *et al.* 1967). Massive stars, with an initial mass range $140 < M < 260 M_\odot$ die in a thermonuclear runaway triggered by pair production instability (Kasen *et al.* 2011; Joggerst & Whalen 2011). Although PISN are rarely observed in the present, it is thought that they were very numerous in the distant past, among primordial, supermassive, low-metallicity rotating stars (Chatzopoulos & Wheeler 2012), releasing huge energy of the order of $10^{53}$ ergs and may synthesize considerable amount of $^{56}$Ni (up to $50 M_\odot$). The PISN are characterized by peak magnitudes that are brighter than that of Type II SNe and comparable, or brighter than type Ia, and fall in the category of super-luminous SNe of Type I and Type II observed in nearby Universe (Quimby *et al.* 2013). Hydrogen lines are present in these SNe, arising from the outer envelope and have a long decay time (∼1 year) due to large initial radii and large mass of material involved in the explosion. Very massive stars that can retain most of their mass against mass loss are those that have metallicity close to zero, and are hence expected at high redshifts. At redshift $z \sim 2$, the PISN/SN ratio is expected to be 4–10 times higher than the observed local rate, for sub-solar metallicity stars (Langer & Norman 2006; Langer *et al.* 2007). Study of PISN using IRIS-TMT will also help in understanding the history of chemical enrichment, the nature of metal free stars at $z \sim 6$ and the evolution of gaseous matter in the Universe (Scannapieco *et al.* 2005; Whalen *et al.* 2013b,c).

### 2.4 *Environment and progenitors of CCSNe*

Host galaxies of CCSNe provide very useful information about the environments of these explosions, indirect clues about nature of their progenitors and evolution of high mass stars. With the help of ground-based 8–10 m class telescopes and HST imaging capabilities with differential alignments of 10–130 mas, progenitors of some of the Type-II SNe have been identified, though limited to 10–120 Mpc only (Smartt *et al.* 2009; Modjaz *et al.* 2011). There are evidences, though not conclusive, for a correlation of masses of the progenitors with the types of CCSNe (Crowther 2013). However, estimates of host metallicities do not show any such conclusive difference for various types of CCSNe (Boissier and Prantzos 2009; Modjaz *et al.* 2011; Kelly & Krishner 2012). Locations of Type Ib/c SNe seems to be more centrally concentrated than Type II SNe in their host galaxies (Anderson & James 2009; Arcavi *et al.* 2010).

With the help of AO capabilities of TMT and first generation instruments like WFOS and IRIS-IFU, metallicities and star formation rate of the immediate environments of the host galaxies could be studied on the scales of kpc (Modjaz *et al.* 2008; Sahu *et al.* 2009; Anderson *et al.* 2010; Modjaz *et al.* 2011; Neill *et al.* 2011), providing more conclusive results about ages and metallicity of the stellar population. TMT-IRIS and WFOS could be used to obtain rest-frame far-UV emission-line detections, spectral properties and inferred kinematics of a large number of $z > 2$ galaxies hosting CCSNe of Type II and Ib/c, useful to understand the density, evolution and dynamics of such events and the process of galaxy formation. There are evidences that some of the SNe Type IIn are PISN events (Langer 2012; Whalen *et al.*

2013a), providing a clue to understand the evolution of pop-III stars using follow-up observations of a larger sample of $z > 2$ Type IIn SNe by LSST and other upcoming surveys.

## 3. Gamma-ray bursts

GRBs are short-lived ($10^{-3}$ to $10^{3}$ seconds) extremely bright (isotropic equivalent $\gamma$-ray energy $\sim 10^{50}$–$10^{55}$ erg) cosmological (redshift $z \sim 0.01$ to 8.3) $\gamma$-ray sources, emitting photons of energy ∼10 keV–90 GeV. They appear at random locations in the sky and have non-thermal spectrum (Piran 1999; Gehrels *et al.* 2009). Long-duration GRBs are now believed to be relativistic analogues of CCSNe explosions and are among the most energetic stellar-scale events known so far (Woosley & Bloom 2006; Tout *et al.* 2011). The gamma-rays are not effected by dust absorption and optical extinction, hence could be seen at very high redshifts (Lamb & Reichart 2000). More than a decade or so, we have been able to understand GRBs and their properties using all possible ground and space-based observing facilities, however, many more questions about these enigmatic explosions are yet to be answered (Zhang 2007). GRBs are the only astrophysical sources known to be found in low-metallicity environments and tools to probe the progenitors at high redshifts. Capabilities of TMT along with the first generation instruments specially the AO system with IRMS will be very helpful in exploring high-redshift Universe using GRBs.

### 3.1 *Afterglow light curves at late phases*

Followed by the prompt emission, ultra-relativistically ejected material interact with the surrounding medium through shocks and may produce afterglows, visible in all bands from $X$-ray to radio wavelengths. Afterglows being longer-lasting than GRB prompt emission, provide a multi-band platform to study these energetic cosmic explosions in detail. The afterglow light curves generally show a power-law behavior. In general the flux $f_\nu$ from the afterglow follows a power law decay with time, a combination of several characteristic properties of the ejecta, represented as $f(\nu, t) \propto \nu^{\beta} t^{-\alpha}$ where $t$ is the time since the burst and $\alpha$ is the temporal flux decay index, $\nu$ is the frequency of observations and $\beta$ is the spectral index (Sari *et al.* 1998; Wijers & Galama 1999; Pandey *et al.* 2004). In the case of most of the afterglows, generally the optical-IR emission is very faint (V ∼ 23 mag, 1–2 day after the burst) and only 8–10 m class telescopes could monitor the emission to observe the characteristic jet break time and other possible light curve features at late epochs (Sari *et al.* 1999; Castro-Tirado *et al.* 1999; Mészáros 2002). Scaling similar bursts at $z \sim 1$ to $z \sim 6$–10, the expected jet-break time and other light curve features (see Fig. 2) would shift at later epochs and the afterglow emission would also shift towards IR bands due to Ly-$\alpha$ absorption, making the observations difficult even for existing 8–10 m class telescopes. TMT imaging capabilities will be able to detect a good number of afterglows up to $z \sim 6$–10 with the help of the upcoming next generation GRB missions like EXIST.

One third of GRBs, termed as ‘dark GRBs’, do not show any optical-IR emissions to very deep limits at very early epochs observed with 8–10 m class telescopes. The afterglow observations of these bursts at X-ray and mm-wavelengths indicate

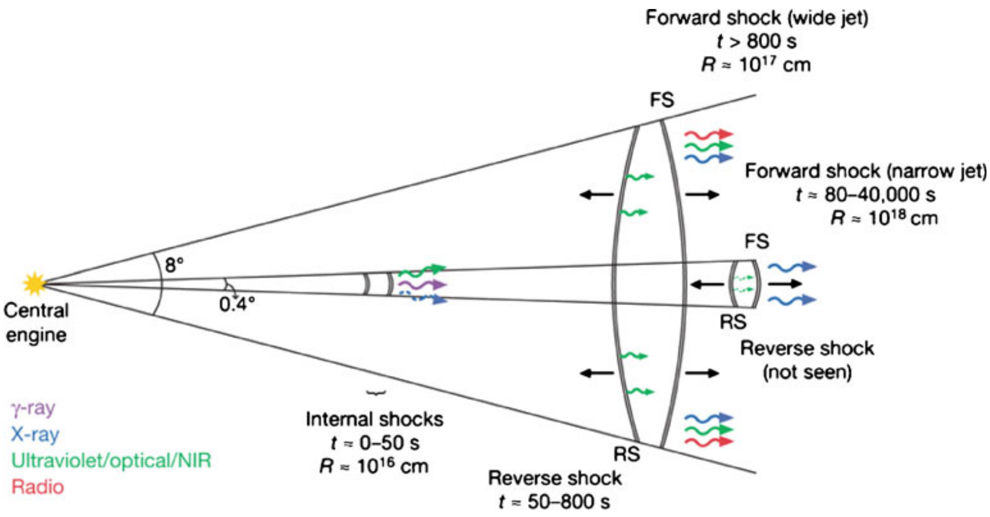

**Figure 2.** Schematic of the proposed two-component jet model of the afterglow of the 'naked-eye' GRB 080319B. The inner narrow-jet gives rise to the high energy emission whereas wider-jet is supposed to produce forward shock emission (Racusin *et al.* 2008). GRB 080319B ($z \sim 0.94$) was very bright at optical frequencies and could have been observed even at redshift $z \sim 16$ with the existing IR facilities hours after the burst.

that these bursts could either be extinguished by heavy dust of the host galaxies or exploded in very low-density environments (Reichart & Price 2002). It is also proposed that these bursts lie at very high redshifts (Lamb & Reichart 2000) or these bursts are intrinsically very faint (Fynbo *et al.* 2001; Berger *et al.* 2002; Melandri *et al.* 2012b; van der Horst 2009; Jakobasson *et al.* 2004). Deep imaging capabilities of WFOS/IRIS-TMT with AO will be very useful in answering these questions about 'dark GRBs'.

### 3.2 *Time-resolved spectroscopy of afterglows*

Spectroscopy of afterglows of GRBs have many more useful implications than just measuring the distances. Early time afterglow spectra provide information about the absorption features due to fine structure transitions and resonance enabling accurate measurements about the dust content, chemical composition and complex gas kinematics of host and other intervening galaxies in the line of sight (Savaglio 2006; Prochaska *et al.* 2009). Present 8–10 m class telescopes need a lot of time to get spectra of GRB afterglows, for example, Subaru-FOCAS required ∼4 hours for GRB 050904 ($z = 6.295$), VLT-FORS2/ISAAC required ∼1.0 hour for GRB 090423 ($z = 8.3$) to get spectra just for the redshift determination (Tanvir *et al.* 2009). Gravitational collapse of rapidly evolving massive stars are supposed to produce long-duration GRBs, useful to probe young star forming regions to quite far away distances (Tanvir *et al.* 2009). In fact, spectroscopy of optical-IR afterglows are proxies to probe the interstellar medium and intergalactic gas at cosmological distances in detail (Vreeswijk *et al.* 2007, 2013; Délia *et al.* 2009; Ledoux *et al.* 2009). Time resolved spectroscopy of optical-IR afterglows could also be used to understand the collisional excitation of fine structure lines, dust destruction effects due to UV/X-ray afterglows, measuring ISM densities and abundances (Vreeswijk *et al.* 2007). Taking advantage of rapid response modes along with the suite of back-end spectroscopic facilities (wavelength range = 0.31–0.62 $\mu$m and 2–2.4 $\mu$m; R = 1000–50000 and 0.05 mas astrometry), TMT would be able to address many of these aspects in detail which is not possible to understand with help of current 8–10 m class telescopes. High resolution spectroscopy of GRBs with TMT-HRMS (at 0.34–1.0 $\mu$m, SN/100, $m_{\rm AB} \sim 20$) would be able to provide information about components effecting ISM up to kpc scales. Currently, the distances of absorbing gas from GRBs and study of fine structure lines have been done just in a handful of cases using VLT-MISTICI and X-SHOOTER instruments (Délia *et al.* 2007, 2009, 2011; Ledoux *et al.* 2009; Piranomonte *et al.* 2008; Vreeswijk *et al.* 2007, 2013).

### 3.3 *Observational cosmology and GRBs*

GRBs at high-$z$ could be used as proxies to high-$z$ quasars to investigate the epoch of re-ionization. As the end products of massive stars, GRBs briefly outshine any other source in the Universe and can be easily observed at cosmological distances. The recent discovery of a GRB at a redshift of $z \sim 8.3$ (Tanvir *et al.* 2009; Salvaterra *et al.* 2009), around similar redshifts of the most distant spectroscopically confirmed galaxies and quasars, establishes that massive stars were being produced and dying at these epochs. This recent detection of the distant GRBs using 4–10 m class telescopes clearly indicates that it is possible to detect and study many GRBs at $z > 10$ using the TMT and back-end instruments. GRBs being associated with individual stars, serve as signposts of star formation at the early epochs and can also provide a measure of the neutral fraction of IGM at the location of the burst. The observations of several GRBs at high-$z$ would provide multiple lines-of-sight through the IGM and thus allow us to trace the process of re-ionization from its early stages.

The above properties suggest that GRBs could be good candidates to probe the cosmological models of the Universe with a much longer arm than Type Ia SNe (Soderberg *et al.* 2006, 2010). However, the huge dispersion (four orders of magnitude) of the isotropic GRB energy $E_{\rm iso}$ makes them everything but standard candles barring the clustering of energy around $E_{\rm jet} \sim 10^{51}$ erg corrected for their jet opening angle (Frail *et al.* 2001) with a considerable scatter. The recent discovery of a very tight correlation between the collimation corrected energy $E_{\rm jet}$ and the GRB spectral peak energy $E_{\rm peak}$ are used as standard candles to constrain the cosmological parameters (Ghirlanda *et al.* 2004). The prospects for the use of GRBs as standard candles clearly depend on the increase of the number of detected GRBs which satisfy the $E_{\rm peak} - E_{\rm jet}$ correlation for a much longer redshift span. This will offer the unprecedented opportunity to investigate the nature of dark energy beyond what can be reached by study of Type Ia SNe. Cosmology with GRBs through the $E_{\rm peak} - E_{\rm jet}$ correlation requires a set of observables, which are derived both from the GRB high energy emission (i.e. the prompt gamma-ray emission phase) and from the afterglow observations in the optical and IR band. In particular, the afterglow spectroscopic observation should provide the GRB redshift, while the long term (days to weeks) photometric monitoring of the afterglow emission allows measurement of the jet-break time. The latter allows us to estimate the GRB opening angle $\theta_{\rm jet}$ and, therefore, to derive the collimation corrected energy $E_{\rm jet}$. TMT imaging capabilities at IR bands would be quite helpful constraining jet-break time in conjunction with facilities at other wavelength for very high redshift GRBs.

### 3.4 *Supernova connection of GRBs*

Some of the broad-lined Tpye Ib/c SNe are characterized by very high kinetic energies (Iwamoto *et al.* 1998; Nomoto *et al.* 2004; Mazzali *et al.* 2008), have been observed to be associated both temporally and specially with long duration GRBs. Apart from spectroscopically confirmed such associations, several late time red-bumps have also been identified in the late time afterglow light-curves of long duration GRBs, which have close resemblance with SN 1998bw profile (see Fig. 3; Cano *et al.* 2011). The GRBs associated Type Ib/c SNe couple bulk of their energy to relativistic ejecta whereas ordinary SNe Ib/c couple less than a per cent of their total energy to the fast material. Type Ib/c SNe related with GRBs have higher ejected mass in comparison to those not associated with GRBs (Mazzali *et al.* 2005, 2006; Taubenberger *et al.* 2006; Valenti *et al.* 2008). Nature of the progenitors of SNe of Type Ib/c is still not understood and that how do they differ from those associated with GRBs. However, the link to GRBs is a strong hint that GRBs associated to

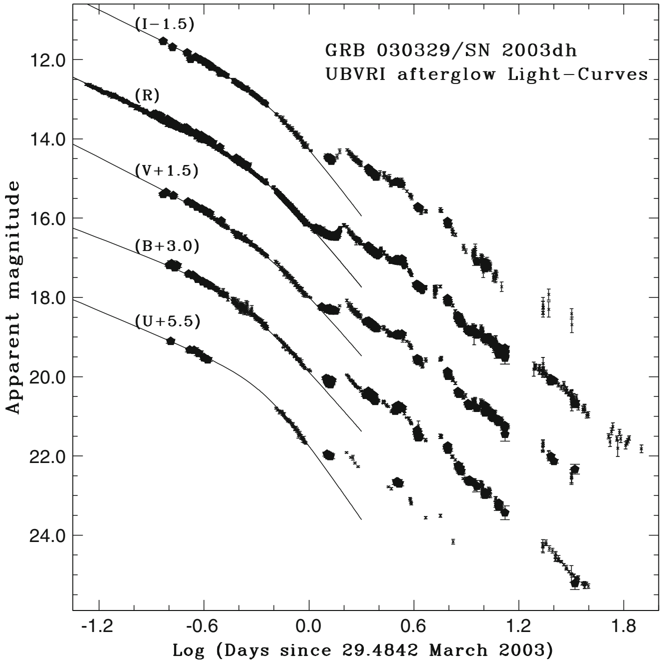

**Figure 3.** Light-curves of GRB 030329/SN 2003dh showing the deviation from the modeled light-curve of afterglows (Pandey 2006). The light-curve at late epochs are flattened due to contribution of the underlying SN 2003dh along with other light curve features. The time-resolved observations of such events could tell a lot about the explosion mechanism and underlying physical conditions.

Type Ib/c SNe could be significantly aspherical. If a jet is produced by a collapsing star (McFadyen & Woosley 1999), then only it can emerge and generate a GRB. A jet-like explosion is required for GRBs from energetics considerations, indicating asphericity in the explosion mechanism. Ordinary Type Ib/c SNe are clearly distinguishable from the ones associated with the GRBs in terms of the relativistic ejecta produced by the central engine. There are some cases of low redshift Type Ib/c SNe with broad lines typical of hypernovae but not always associated with large luminosities typical of hypernovae (Mazzali *et al.* 2005; Valenti *et al.* 2008; Sahu *et al.* 2009; Drout *et al.* 2011). In the local Universe, it has been seen that the rate of energetic broad-lined Ic SNe is similar to the rate of long-duration GRBs, which might indicate that most (or all) energetic Ic SNe produce GRBs (Podsiadlowski *et al.* 2004). However, the observed rate of production of WR stars (initial masses of $> 40 M_\odot$) in galaxies are much higher than the rate of broad-lined SNe of Type Ic, indicating that not all WR stars produce broad-lined Type Ib/c SNe. Associations of Type Ib/c SNe have mostly been seen with low-luminosity nearby long duration GRBs (Hjorth & Bloom 2011; Melandri *et al.* 2012a; Sanders *et al.* 2012). Whether cosmological GRBs at higher redshifts are associated with SNe are quite challenging due to contamination by the afterglow and the host galaxy and is an open question to be addressed with TMT and other such facilities in near future.

### 3.5 *Host galaxies of GRBs*

GRBs being far away, lack direct identification of their progenitor stars. The evidence of what gives rise to GRBs therefore remains circumstantial. One important input to this body of evidence comes from the study of their host galaxies, and wherever possible, that of the immediate stellar neighborhood of the GRB. The GRB sample goes out to high redshift: the measured GRB redshifts at present have a median value of $z \sim 2.7$. The host galaxies of GRBs that have been detected to date have their redshifts in the range 0.01–8.3. Clearly, a large fraction of the high redshift GRB host population remains to be discovered. The majority of the known hosts have magnitudes in the range R $\sim$ 22–27 mag and K $\sim$ 20–25 mag, close to the limit of studies possible with the present-day 8–10 m class telescopes (Savaglio *et al.* 2009). The TMT and the proposed back-end instruments will have an excellent opportunity to address questions exploring nature of GRB hosts. In addition to increasing the sample size at the high redshift end, TMT will enable detailed spectroscopic studies of the host galaxies. At present multi-band photometry of GRB hosts is being used to fit synthetic spectral models, from which the mass, metallicity, age and star formation rates are being deduced. The derived values suffer from very large uncertainties, making it difficult to reach definite conclusions about the nature of these galaxies and their population. TMT with the combination of OA and IFU will enable to study these objects spectroscopically, enhancing the reliability of model fitting and parameter extraction manifold. The present viewpoint that GRBs originate in sub-solar luminosity, actively star-forming galaxies with low metallicity can be seriously tested only by such detailed spectroscopic study about these host galaxies. Extending this study with TMT to a larger sample, especially at high redshifts would be able to tell more about the correlation of GRBs with low-metallicity progenitors. Morphological classification of GRB hosts, carried out mainly using the HST (Fruchter *et al.*

2006; Wainwright *et al.* 2007) so far, seems to suggest a preponderance of irregulars among them. The enhanced angular resolution of the TMTs compared to the present-day ground-based telescopes can be put to use in conducting such morphological classification of a larger sample of GRB hosts and their mass function. Multi-band imaging with TMT could be used to understand the morphology of long and short duration host galaxies more in detail. This kind of study may also throw some light on whether the GRB production rate is influenced by galaxy mergers and the nature of galaxies hosting ‘dark GRB’.

## 4. Polarimetric studies of CCSNe and GRBs

It is now established that afterglows of GRBs arise from synchrotron emission in a relativistically shocked ejecta, collimated outflow and emission is intrinsically polarized (Lazzati 2006; Wang & Wheeler 2008). Evolution in the polarization as a function of viewing geometry as well as degree of orientation of the magnetic field (Medvedev & Loeb 1999) is expected in collimated outflows of GRBs. Models show that the maximum degree of polarization occurs around the time of geometric break called ‘jet-break’ (Rossi *et al.* 2004; Lazzati *et al.* 2003). For GRB afterglows, optical imaging polarimetry have been successfully done in case of a handful of GRBs and a polarization up to 9% have been observed (Bersier *et al.* 2003; Wiersema *et al.* 2012a; Steele *et al.* 2009; Mundell *et al.* 2007). For the observed afterglows in optical-NIR, lack of strong variability in the position angle of linear polarization indicate that magnetic field of the jet to be ordered rather than a random one. Even with the help of existing 8–10 m class telescopes like Keck and VLT, spectropolarimetric observations of GRB afterglows have been covered sparsely with no concluding results (Wiersema *et al.* 2012b). Some of the Type Ib/c SNe associated with GRBs have also shown polarization indicating towards asymmetry of the ejecta (photosphere/chemical inhomogeneity) for early photospheric phase of SNe (Kawabata *et al*. 2002, 2003; Tanaka *et al.* 2012a, b). So far, spectropolarimetry of core-collapse SNe have only been possible using 8–10 m class telescopes with rather low-resolutions (Hoffman *et al.* 2008) not providing any conclusive results about the structure of magnetic fields, rotational distortion of the progenitor stars and effect of interaction between circumstellar material and the ejected matter.

Bigger observing facilities like TMT will be able to collect many more photons, enabling to measure the polarization more accurately. However, the present design of the TMT with a three-mirror system is expected to produce considerable instrumental polarization due to tertiary mirror at Nasmyth focus (Tinbergen 2007) at optical-IR frequencies. To reduce the instrumental polarization some ideas have been suggested, like, putting a polarization modulator or an additional optical component in the optical path to cancel out the instrumental polarization. However, it is not easy to implement these possible solutions as the instrument will be rotating with the telescopes. To compensate the rotation of the telescope polarization, the possible ways are to put a achromatic half-wave plate or to bend the optical path using Fresnel Romb before the focal plane. It is highly required to optimize the design of TMT or other upcoming extremely large optical-IR telescopes to reduce the instrumental polarization to make best use of the collected photons from various faint celestial objects. Early phase spectropolarimetry of afterglows of GRBs and CCSNe will be able to tell us more about the explosion geometry, chemical structure, velocity and composition of the SN ejecta.

## 5. Conclusions

The TMT and the back-end instruments are capable to address some of the unanswered questions about CCSNe and GRBs and their implications to understand the evolution of massive stars and star formation at high redshifts. Time resolved optical-IR spectroscopy of PISN and CCSNe of Type II at $z > 2$ will be able to understand the shock-break out phase and interaction of ejecta with the circum-stellar matter in more details. Photometric identification of CCSNe at $z \sim 2$–6 will be helpful to know about evolution of massive stars at high-$z$. Time-resolved observations of afterglows of GRBs would be quite helpful not only in understanding progenitors at high-$z$ and population of massive stars but also to probe the ISM and IGM in detail. Possible polarimetric observations using TMT would be able to tell about the geometry of the ejecta and structure of the magnetic field in these energetic cosmic explosions.

## Acknowledgements

The author is thankful to organizers of TMT Science and Instrumentation Workshop, 10–12 December 2012, Pune, India, for inviting him to deliver the talk on SNe and GRBs. The author acknowledges the TMT documentation at www.tmt.org/documents/ while preparing this manuscript. The author is also thankful to Professors Ram Sagar, D. Bhattacharya and G. C. Anupama for discussions on SNe and GRBs.

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