RevMexAA (Serie de Conferencias), **48**, 83–88 (2016)

STUDY OF NEW OPTICAL TRANSIENTS USING 3.6M DOT AT DEVASTHAL NAINITAL

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RESUMEN

La localización geográfica del subcontinente indio hace del recientemente inaugurado telescopio de 3,6m una nueva infraestructura para observaciones astronómicas, y especialmente para el estudio de fenómenos críticos, como fuentes esporádicas ópticas. El telescopio conjuntamente con sus instrumentos de primera generación, serán usados de manera eficiente para el estudio de nuevas fuentes astronómicas descubiertas previamente por redes globales de telescopios robóticos. El estudio de nuevas fuentes astronómicas dentro del campo de Astronomía de Dominio Temporal, jugará un importante papel en el futuro junto con las nuevas facilidades multirrango para entender mejor la física subyacente en estos objetos.

ABSTRACT

Longitudinal advantage of Indian sub-continent makes the recently installed 3.6m telescope as a novel facility for astronomical observations, specially, to study time critical events, i.g. transients. This telescope along with the first generation back-end instruments could be efficiently used to study new transients discovered using a global network of robotic survey telescopes. Study of new transients as a part of time domain astronomy will play a key role in near future along with the upcoming multi-wavelength facilities to explore the underlying physics behind these sources.

Key Words: gamma-ray burst: general — instrumentation: photometers — instrumentation: spectrographs — supernovae: general

IV Workshop on Robotic Autonomous Observatories (Torremolinos, Málaga, Spain, September 28- October 2, 2015)
Editors: M. D. Caballero-García, S. B. Pandey, D. Hiriart & A. J. Castro-Tirado

1. INTRODUCTION

The Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India has longitudinal advantage for observations of time-critical events 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). 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). Since 1999, ARIES has contributed significantly towards studies of afterglows of several well-known Gamma-ray Bursts (GRBs) and Supernovae (SNe) using meter-class telescopes like 1.04m Sampurnanand Telescope and 1.3m Devasthal Fast optical telescope and the back-end instruments (Pandey 2006; Sagar & Pandey 2012). A brief description about the newly installed 3.6m Devasthal Optical Telescope along with the back-end instruments is described in following sections aiming towards studying energetic cosmic transients and to discover new ones.

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2. 3.6M DEVASTHAL OPTICAL TELESCOPE

A modern 3.6-m Devasthal Optical Telescope (DOT) has been installed during 2015 and operational since March 2016. 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 Figure 1). The secondary mirror will have a diameter of about 0.9 m. The telescope performance is said to have 80% of the light encircled within 0.45 arcsec diameter in 30-arcmin field over 350-3000 nm wavelength range. The telescope has a Alt-Azimuth mounting with a zenith blind spot of less than 2 degree conical diameter. The science field of view of the DOT is 10 arcmin without corrector and 30 arcmin unvignetted field for axial port and 10 arcmin for side ports. A cylindrical space of minimum 2.5 meter below the focal plane for axial port and approximately 3.0 meter diameter around optical axis is available for the instrument envelope. The telescope will have a pointing accuracy of less than 2 arc sec RMS for any point in the sky with elevation greater than 10 degree and less than 0.1 arcsec

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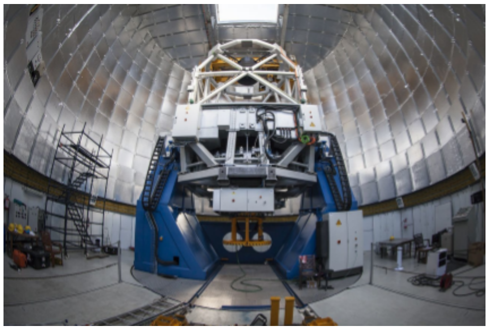

Fig. 1. The 3.6m DOT as installed at Devasthal Nainital by a Belgian company AMOS (fall 2015) inside the dome build indigenous by an Indian firm. This telescope is installed at nearly 11-m height from the ground level to improve seeing.

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 arc sec RMS for about one hour in closed loop (with auto guider). The acquisition and guiding unit is available with the telescope along with the Five axis motion of secondary mirror (see Figure 1).

For the 3.6-m DOT, proposed first generation instruments are (1) 4K×4K CCD optical general purpose imager for deeper photometric observations, (2) ARIES Devasthal Faint Object Spectrograph and Camera (ADFOSC), (3) a high resolution Eachelle spectrograph and (4) a near infrared spectrometer (IRSPEC). 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 25 mag star in V band within an hour of exposure time. The high resolution Eachelle 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 Figure 6). The concept of the high resolution Eachelle spectrograph will be similar to many contemporary high resolution spectrometers such as HERMES (Raskin et al. 201). 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.

As a part of this presentation, the first light instrument called 4K×4K CCD Imager is described in more detail.

2.1. *4K×4K CCD Imager*

The 4K×4K CCD imager is designed and developed in-house to be mounted at the main/axial port of the 3.6m telescope as one of the first-light instruments. The beam of the telescope is f/9 is used without any focal reducer and will have a plate-scale of 6.4 arcsec/mm. We plan to use the f/9 beam directly to utilize the central unvignated $\sim$ 10×10 arcmin of the science field using appropriate filters (see Figure 3 and 4). The automated filter-wheel designed and developed in-house will carry set of Bessel $UBVRI$ and SDSS $ugriz$ filters with 90mm diameter each. For deeper exposures, it is also planned to interface the camera/filter electronics with the Telescope control system making use of the in-built auto-guiding facilities. For the given plate scale of 6.4 arcsec/mm, a 15 micron 4KX4K CCD camera ia-long with ARCHON controller (purchaged from STA USA, http://www.sta-inc.net) along with a 125mm Bonn shutter is able to image $\sim$ 6.5×6.5 arcmin of the sky, though images would be over-sampled (0.1 arcsec/pixel 15 micron). This sky coverage is good enough for our scientific requirements. For a 15 micron pixel CDD, the sky covered per pixel will be $\sim$ 0.1 arcsec/pixel, we will use on-chip binned mode to increase the sky covered per pixel. Binning the pixels will further improve the signal to noise and the read out would be faster for a given sets of read-out noise and gain values (see Figure 2). The details about the charecterization of the camera and calibration results will be published soon in Pandey et al. (2017).

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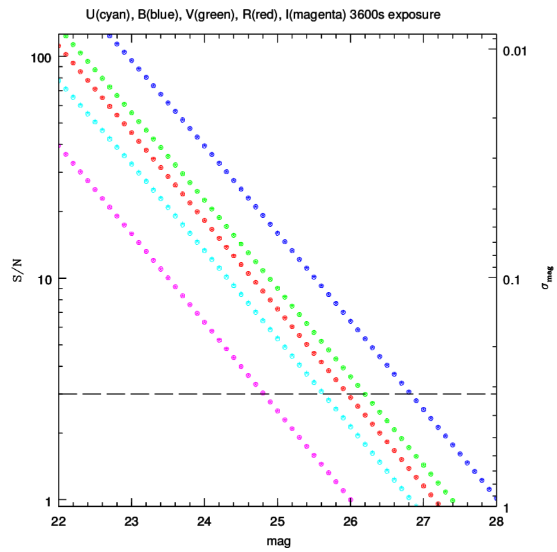

Fig. 2. A simulated plot of magnitude (X-axis) vs. signal-to-noise ratio (Y-axis, left) and corresponding error in the magnitude determinations (Y-axis, right) based on the throughput calculations (Mayya 1991) of the 3.6m telescope with the proposed 15 micron 4K×4K CCD camera for set of Bessel $UBVRI$ filters, for assumed equivalent exposure time of 1 hour each, seeing value of 1.5 arc-sec. and for other standard values of the observing site and the CCD chip (STA 15-micron).

3. STUDY OF TRANSIENTS WITH THE 3.6M DOT

Due to longitudinal advantage, Indian optical telescopes have contributed significantly towards study of time critical energetic transients like GRBs and SNe during last more than two decades using well-calibrated photometric data through meter-class telescopes. During last decade, multi-wavelength studies about verity of transients have evolved this field considerably and have added value towards understanding the physics and nature of these sources. At present, the transient community is more interested towards understanding nature of rather fainter sources happening on a time scales of minutes to hours as highlighted in Figure 5 below.

In the light of above, we plan to study following transients with the help of 3.6m DOT and the first generation back-end instruments.

3.1. *SGRBs and "Kilonovae"*

Ever since their clear categorization (Kouveliotou et al. 1993; Castro-Tirado et al. 2005) , short-duration Gamma Ray Bursts (SGRBs) have been identified as energetic cosmic transient sources of great scientific potentials (Berger 2014). Since their discovery in 2005, more than 70 afterglows of SGRBs have been detected at various wavelengths exhibiting diverse properties (Gehrels et al. 2009). The prompt emission properties of SGRBs like harder spectra, higher E_{peak} relatively lower energy spectral slope, nearly zero spectral lag, T_{90} duration < 2 sec etc. distinguishes them from long-duration GRBs (LGRBs). Afterglows of SGRBs are in general less luminous, less energetic and favor rather lower circumburst densities than those seen in case of LGRBs (Berger 2014). In comparison to LGRBs, the observed lower redshift range (z $\sim$ 0.1 - 1.5) of SGRBs do not seem to be connected to morphology of the host galaxies rather the relatively lower values appears to be effected by the detection threshold of *Swift*/BAT (Fong et al. 2013). Based on the proposed theoretical models and the observational evidences, neutron star-neutron star (NS-NS) and/or neutron star-black hole (NS-BH) mergers (Narayan et al. 1992; Eichler et al. 1989) and magnetars (Kouveliotou et al. 1998) are the most-probable progenitor candidates for SGRBs.

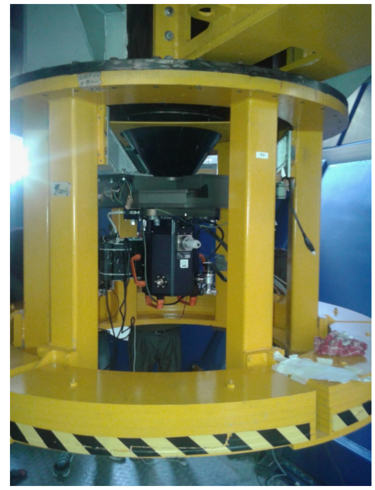

Fig. 3. The fully assembled 4K×4K CCD camera along with shutter and automated filter wheels mounted at the axial port of the 3.6m DOT on 9th December 2015.

"Kilonova" or "macronova" are electromagnetic transients powered by radioactive decay of r-process elements produced by accretion disk winds during a compact binary mergers with one component being a neutron star. The ejection of radioactive material during the merging process of the compact binaries could lead to faint optical-infrared emission. The brightness and duration of such an emission is function of opacity, velocity and mass of the ejecta (Matgzer et al. 2010; Bernes & Kasen 2013; Tanaka et al. 2014). Recently, hydrodynamical modeling of such a process have been studied by Kasan et al.

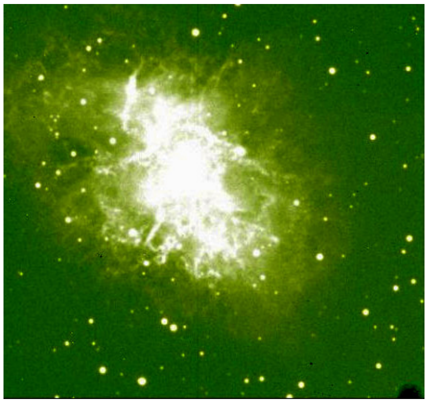

Fig. 4. The V-band image of the Crab nebula (a supernova remnant) with an exposure of 180sec taken using the 4K×4K CCD camera mounted at the axial port of the 3.6m DOT on 11th December 2015 during testing phase.

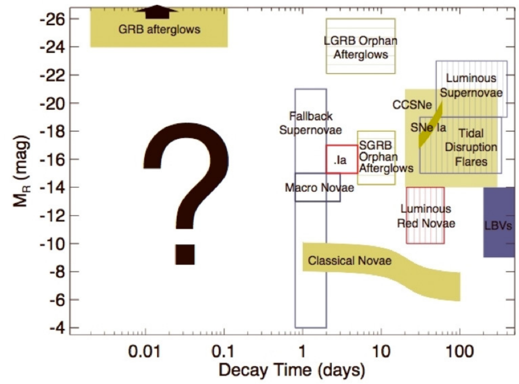

Fig. 5. This figure demonstrates the transient phase space as observed using various multi-wavelength facilities. The X-axis denotes the time in days whereas Y-axis is brightness in absolute magnitude. Various transients are shown as scatter plot. It also demonstrates the importance of upcoming facilities to search for new transients and know more about known transients. This figure has been adopted from NOAO web-site https://www.noao.edu/currents/img/time-domain.jpg and the reference is thankfully acknowledged.

(2015) speculating a brief bluer emission component produced in the outer lanthenide free ejecta and a rather larger duration infra-red transient produced in the inner lanthenide-blancketed regions. Using their model for a case with non-spinning black-hole, the optical bump observed in case of SGRB 080503 (Perley et al. 2009) was interpreted in terms of underlying "Kilonova" emission. However their models were unable to explain the observed infrared-excess in case of SGRB 130603B which required higher accretion disk mass and perhaps a rapidly spinning black-hole (Just et al. 2014). It is also to be noted that the observed infrared excess in case of SGRB 130603B was explained by Tanaka et al. (2014) and Hotokezaka et al. (2013) assuming equation of states and a rather larger accretion disk mass of $\sim 0.1 M_{\odot}$ both in case of NS-SN and NS-BH models.
Optical and IR observations of a much larger sample of nearby SGRBs are required to improve our understanding about nature of their host galaxies, progenitors and to put a constrain on the electromagnetic counterparts and number density of gravitational wave sources in near future (Matzger & Berger 2012). Taking longitudinal advantage of India and with the upcoming 3.6m telescope at Devasthal Nainital and the first generation instruments, it would be possible to study SGRBs properties and the associated "Kilonovae" emission in great detail.

3.2. *Afterglows of LGRBs and Supernova connection*

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 and radio wavelengths (Sari & Piran 1997, 1999). 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.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; Sari, Piran & Halpern 1999; Pandey et al. 2003a) and for a pre-existing stellar wind (i.e. WIND model) models (Chevalier & Li 1999).

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 the following ones: 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 (Pandey et al. 2003b).

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Observations show that at least some of the nearby LGRBs happen simultaneously with associated core-collapse supernovae features. The first direct evidence for a GRB-SN association was made when GRB 980425 was spectroscopically and photometrically linked with type Ic-broad line SN 1998bw (Galama et al. 1998). This connection was also predicted theoretically by the collapsar model (Woosley & Janka 2005). Observations of GRB-SNe can act as a powerful discriminant of the different theoretical models proposed. So far, most GRBs with spectroscopically-confirmed SN associations are found to have a much lower apparent luminosity than the majority of normal long-duration GRBs. These observational evidences of supernova associations have provided clear evidence that the progenitors of some, if not all long GRBs, are associated to the explosion of a massive star (Schulze et al. 2014).

With the help of 3.6m DOT and the back-end instruments, we hope to add value to the ongoing research towards this key scientific problem to understand evolution of massive stars and the underlying physical mechanism in the nearby Universe (Pandey 2006, 2013).

3.3. *Super-luminous core-collapse Supernovae*

Observationally, it is known that core-collapse Supernovae (CCSNe) are the final stages of the evolution of massive stars (Heger et al. 2003). 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 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). 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. The rate of core-collapse SNe (II, Ib/c) is a direct measurement of the death of stars more massive than 8 $M_{\odot}$, although it is still a matter of debate whether stars with mass above 40 $M_{\odot}$ produce a 'normal' SNe-II and Ib/c, or rather collapse forming a black hole with no explosion, i.e. a "collapsar" (Heger & Woosley 2002). These explosions and their possible progenitors are rather poorly understood research problems in astrophysics and a subject of great scientific interests (Modjaz et al. 2011; Crowther 2013).

A type of super-luminous CCSNe categorized as 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). The PISN are characterized by peak magnitudes that are brighter than of Type II SNe and comparable, or brighter than type Ia, fall in category of super-luminous SNe of Type I and II observed in nearby universe (Quimby et al. 2013). Using the CCD Imager, photometric identification of such SNe along with monitoring of super-luminous CCSNe to deeper limits at very early epochs putting constraints on the shock break-out phases is one of the main scientific goals of the 3.6m DOT.

Hydrogen-stripped Type Ib/c SNe are another potential targets to be studied in a systematic survey mode using 3.6m DOT and the back-end instruments. 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 et al. 2006). Deeper photometric studies of host galaxies of CCSNe using 3.6m DOT and the back-end instruments could provide very useful information about the environments of these explosions, indirect clues about nature of their progenitors and evolution of high mass stars.

3.4. *Tidal Disruption events (TDEs) and Soft Gamma-ray repeaters (SGRs)*

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 towards 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). Several such TDEs and SGRs discovered recently have revolutionized the field demanding for deeper muli-wavelength observations with facilities like 3.6m DOT.

3.5. *Transients discovered using other facilities within the country*

It is also proposed that new radio sources/transients discovered by GMRT facility (Swarup 1991) and the new X-ray sources discovered by the recently launched first Indian Space mission called *ASTROSAT* (Rao 2016) would be monitored and studied using the 3.6m DOT and the back-end instruments. It is also planned that the new transients and variables including thermonuclear SNe Type Ia and CCNSNe discovered the using upcoming 4.0m international liquid mirror telescope (ILMT) at Devasthal Nainital would also be studied (Kumar 2014; Kumar et al. 2015) using 3.6m DOT and the back-end instruments.

Acknowledgments. The author thankfully acknowledge contributions from all those who were involved towards installation of the 3.6m DOT as well as towards the design and development of the 4K×4K CCD Camera project thankfully acknowledged. The author also acknowledges Prof. A. J. Castro-Tirado for giving the opportunity to present this work during ASTROROB-2015.

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