The 3.6m Devasthal optical telescope and time domain astronomy

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Abstract: Longitudinal advantage of India is very much suitable for the time domain astronomy and particularly for time critical observations. Recently installed 3.6m Devasthal optical telescope along with back-end instruments are well suited for observations of energetic cosmic transients like Supernovae and Gamma-ray bursts. In this presentation, I summarize about the 3.6m DOT project along with proposed plans to study transients in near future.

Keywords: 3.6m Devasthal optical telescope, Imager, Transients, Supernova, Gamma-ray bursts

1. Introduction

As a part of time domain astronomy and with the help of ground/space based multi-wavelength telescopes, the astronomical community has made tremendous progress over the last hundred years to understand many aspects of our observable universe. These findings include: energetic cosmic explosions, 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 yet un-explored areas. With the combination of 4-10m class ground-based optical telescopes and other multi-band facilities, our understanding 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 ($> 8 - 10M_{\odot}$) and the underlying physical mechanisms (Woosley & Bloom2006, Sokolov 2012, Kumar & Zhang 2015).

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 observing facilities, which culminated in the indigenous building of the 2.3m Vainu Bappu Telescope (VBT) in 1987. The most recent astronomy facilities which have been set up in the country are, IIA's 2.0m Himalayan Chandra Telescope (2003) at Hanle, Ladakh and the 2.0m IUCAA Girawali telescope (2006) at Girawali, near Pune and recently the 3.6m Devasthal optical telescope (2016) at ARIES Nainital (Sagar 1999).

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). 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 (Sagar 2000 & 2011; 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).

2. The 3.6m Devasthal Optical Telescope

A modern 3.6-m Devasthal Optical Telescope (DOT) has been installed during 2015 and operational since March 2016. Deasthal is a new observing station for ARIES (see Fig1). The characterization of Devasthal site was carried out on 80 nights during 1998-1999 with a Differential Image Motion Monitor (DIMM) using a 38-cm telescope with the mirror about 2 m above the ground, and it yielded a median seeing estimate of about 1.1 arc-sec; the 10 percentile values lie between 0.7 to 0.8 arc-sec while for 35% of the time the seeing was better than 1 arc-sec (Sagar et al. 2000). The atmospheric extinction studies at Devasthal are described by Mohan et al. (2000).

Fig1*.A panoramic view of ARIES Devasthal Observatory, Nainital. The larger white dome houses 3.6m DOT whereas the smaller dome houses a 1.3m wide-field optical telescope.*

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 Fig2). 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 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 Fig2). The active optics system (AOS) controls the alignment of M1 and M2 using pneumatic actuators and hexapod mechanism respectively. The corrections can also be applied in closed loop using data from the Shack-Hartmann wavefront sensing system. The vital characteristics of the telescope are given in Table1.

Table1. *Key characteristics of the 3.6m Devasthal optical telescope at ARIES Nainital.*

Parameters	**Value**
Primary Mirror clear aperture	3.6 m
Focal ratios	Primary : F/2; Effective : F/9; Plate Scale : 6:366 arc-sec /mm
Back focus distance	2.5 m
Science Field of View	10 arcmin on side ports, 30 arcmin on axial port; (35 arcmin for the AGU) in wavelength range 350 nm to 5000 nm
Mounting	Alt-azimuth
Sky coverage	15 degree to 87. 5 degree in elevation
Pointing accuracy	< 2 arc-sec RMS (Root mean squared)
Tracking accuracy	< 0.1 arc-sec RMS for 1 minute in open loop, < 0.1 arc-sec RMS for 1 hour in close loop, < 0.5 arc-sec Peak for 15 minutes in open loop.
Optical image quality	- Encircled Energy 50% (E50) < 0.3 arcsec, - Encircled Energy 80% (E80) < 0.45 arcsec, - Encircled Energy 90% (E90) < 0.6 arcsec, For the wavelength range from 350 nm to 1500 nm and without corrector for 10 arcmin Field of view.

2.1. First generation back-end instruments

For the 3.6-m DOT, Several first-generation back-end instruments were proposed for the 3.6m DOT for broad-band imaging and spectroscopy covering 350-3600 nm wavelength range i.g. (1) 4K4K CCD optical general purpose Imager for deeper photometric observations, (2) TIFR near-infrared imaging camera (TIRCAM2), (3) ARIES Devasthal Faint Object Spectrograph and Camera (ADFOSC), (4) high resolution Echelle spectrograph, (5) a TIFR-ARIES near-infrared spectrometer (TANSPEC) and (6) multi- integral field unit optical spectrograph (DOTIFS).

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 arc-sec 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 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 Fig6). The concept of the high resolution Echelle spectrograph will be similar to many contemporary high resolution spectrometers such as HERMES (Raskin et al. 2011). 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 and 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 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 when attached to the telescope. The proposed TANSPEC when coupled with the 3.6m telescope is expected to reach the 5 detection of 22.5 mag in J, 21.5 mag in H and 21.0 mag in K with one hour integration.

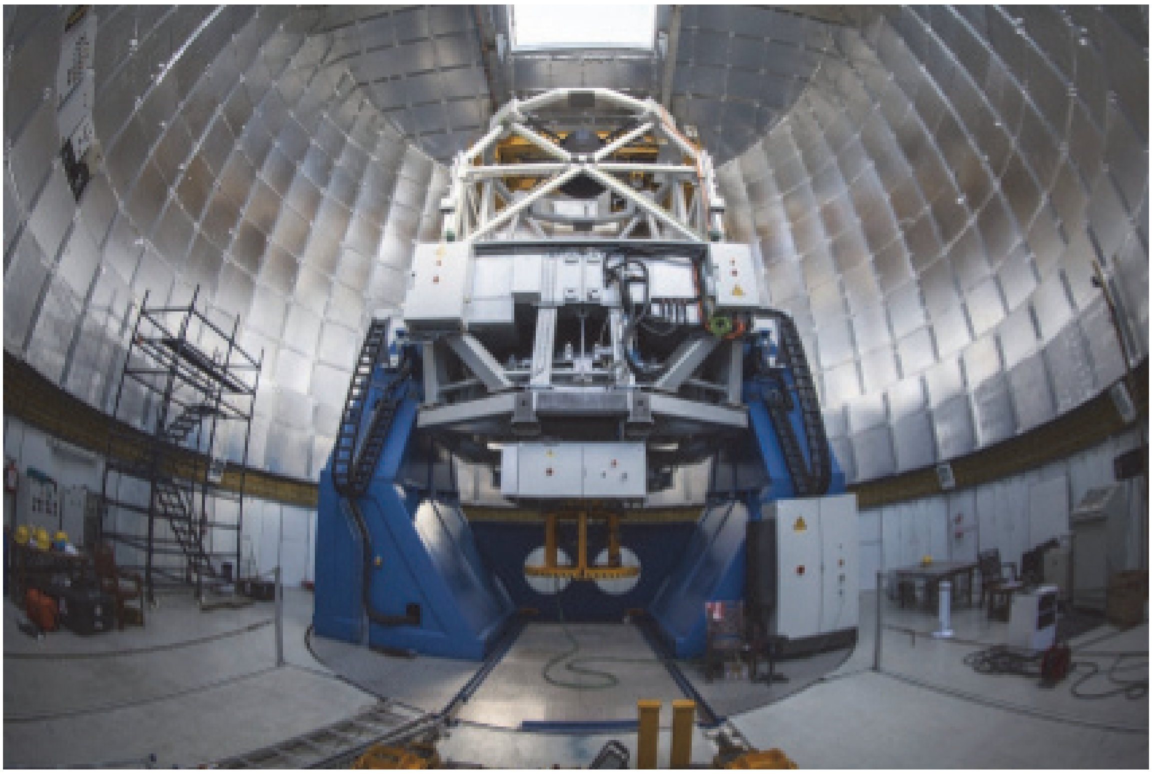


Fig2. *The 3.6m DOT as installed at Devasthal Nainital by a Belgian company AMOS (fall 2015) inside the dome build indigenous by an Indian firm. This telescope is installed at nearly 11-m height from the ground level to improve seeing.*

2.2. 4K×4K CCD Imager

The first light instrument, as an in-house developmental activity, called 4K4K CCD Imager with motorized filter-housing and camera mounting arrangements is designed to be mounted at the axial port of the 3.6m DOT. The f/9 beam of the telescope system is directly used without any focal reducer and has a plate-scale of 6.4 arcsec/mm. It is planned to use the f/9 beam directly to utilize the central unvignated 10x10 arcmin2 of the science field using appropriate filters. So, based on the scientific goals mentioned above, it was decided to purchase a blue-enhanced, back-illuminated 4K4K CCD chip with a pixel size of 15 micron in 2011 from Semiconductor Technology Associates Inc. (STA) USA (for more details about the camera and

ARCHON controller, please refer, http://www.sta-inc.net/). For the STA CCD chip, the quantum efficiency curve as a function of wavelength is also shown in Fig3a. For the given plate scale of 6.4 arc sec/mm, a 15 micron 4Kx4K CCD camera is able to image 6.5x6.5 arc min of the sky. Using the given parameters of the telescope and the CCD, throughput simulations are described in Fig3.b.

Mechanisms of the two motorized filter wheels (both software and hardware) were designed, developed and implemented in-house. The 3.6m DOT Imager instrument consists of two filter wheels. Both filter wheels have separate set of six filter positions namely U; B; V; R; I; C (Clear) and u; g; r; i; z; c (Clear), respectively. Microcontroller based control unit and GUI software are used for the positioning of two filter wheels in the Imager Instrument. Control unit consists of a PIC microcontroller having Serial Communications Interface (SCI) module USART (Universal Synchronous Asynchronous Receiver Transmitter) and a circuit that converts from RS-232 compatible signal levels to the USART's logic levels and vice-versa. Homing is achieved after powering ON using Hall Effect sensors. A detailed log of commands, status and errors are continuously generated by the GUI software. Both the control unit and the software have been successfully tested and integrated with the Imager instrument. More details about the CCD Imager are published by Pandey et al. (2017).

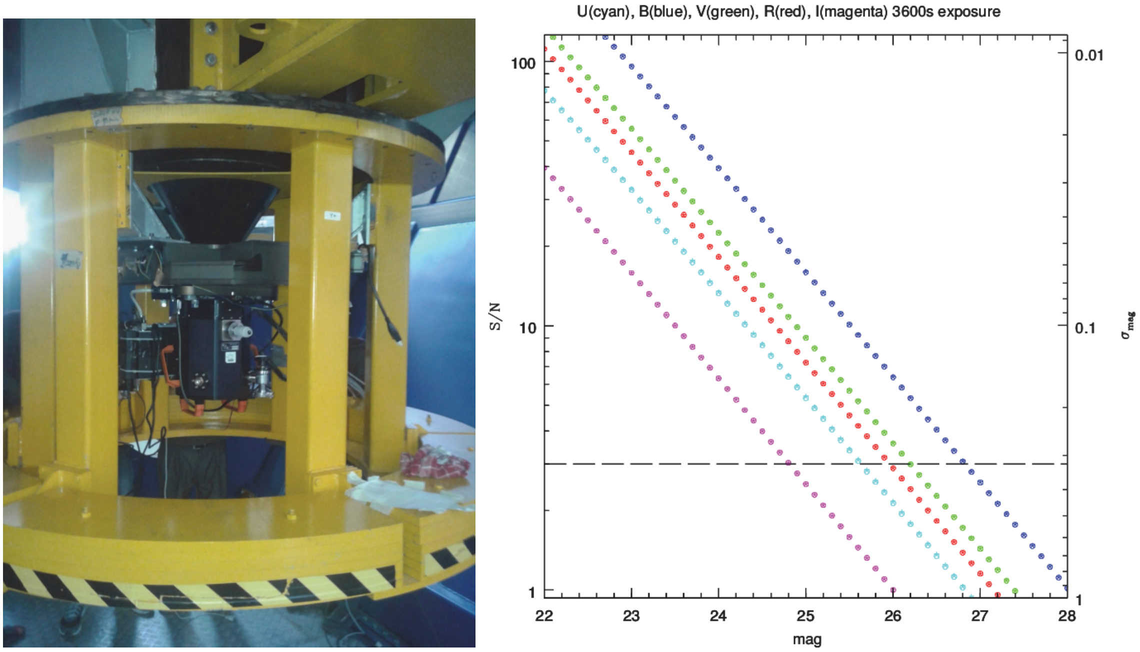


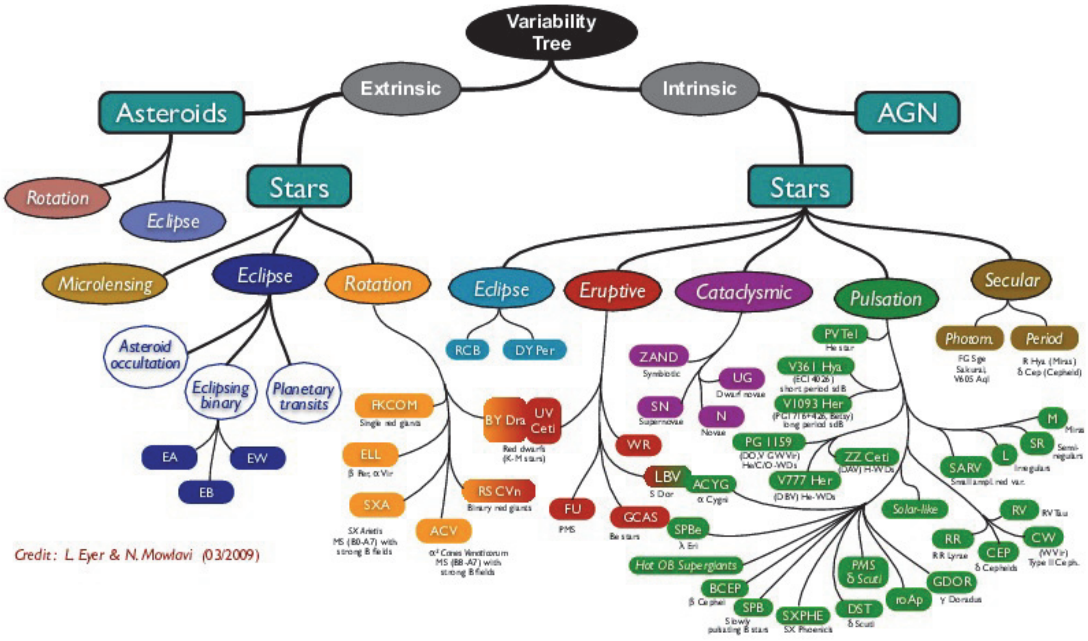
***Fig3**. (a) The fully assembled 4K×4K CCD camera along with shutter and automated filter wheels mounted at the axial port of the 3.6m DOT.*

(b) 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 UBV RI filters, for assumed equivalent exposure time of 1 hour each, seeing value of 1.5 arc-sec.

Deeper imaging of Galactic and extra-galactic point sources (B ~ 25 mag) and objects with low surface brightness could be performed using the 4K4K CCD Imager in several broad-band filters (set of Bessel UBVRI and SDSS ugriz filters) at the axial port of the 3.6m telescope. It is also proposed that with the 3.6m DOT sources identified with GMRT and ASTROSAT would also be followed-up to a deeper limits (Pandey et al. 2017).

3. Time domain astronomy and transients

Time domain astronomy covers a very broad verity of astronomical objects and their properties at diverse times-scales as described in Fig4. Transients are usually the result of some kind of explosion or collision that leads to a change in the physical character of the source (e.g. supernovae, gamma-ray bursts, neutron star mergers), or a result of accretion of matter (nova outbursts, tidal disruption events, AGN flares). These events are unpredictable, show a temporal evolution of the physical conditions, and often fall below the detection threshold when faint. Such Target of Opportunity (ToO) transient events generally require a rapid response to a trigger of observations. Variability in sources can be intrinsic; caused by either a change in the physical conditions (e.g. Cepheid Variables, stellar flares), or accretion induced (e.g. cataclysmic variables, AGN), or extrinsic; as a result of geometry (e.g. binaries, lensed objects, transiting planets). Variability observations can be time dependent, or time critical requiring observations that are time-resolved. Photometric and spectroscopic study of some of these objects is quite crucial for the 3.6m Devasthal optical telescope available at Indian longitude during this age of multi-wavelength era.



Credit: L. Eyer & N. Mowlavi (03/2009)

Fig4. A variability tree showing a zoo of objects classified based on their characteristic properties and most of them are considered as a part of time domain astronomy to understand them in more detail. Cataclysmic category is particularly important to emphasize on the nature of objects showing transients due to explosions like supernovae (SNe) and gamma-ray bursts (GRBs).

Energetic cosmic explosions under the cataclysmic category are particularly important considering longitudinal advantage of India and availability of the 3.6m DOT and the back-end instruments. The main areas of interests are study of core-collapse supernovae and their correlation with long GRBs, short duration GRBs and study of "kilonovae" as a counterpart of Gravitation wave candidates. Tidal disruption events and candidate soft gamma-ray repeaters are also planned to be studied using this telescope. Detailed study of type Ia supernovae discovered by the upcoming 4.0m International Liquid Mirror Telescope (ILMT) are also targeted to be studied using the 3.6m DOT. Explosive transients discovered within the other multi-wavelength facilities like ASTROSAT (the first Indian multi-wavelength satellite) are also planned to be observed using this facility and other complementary observational facilities.

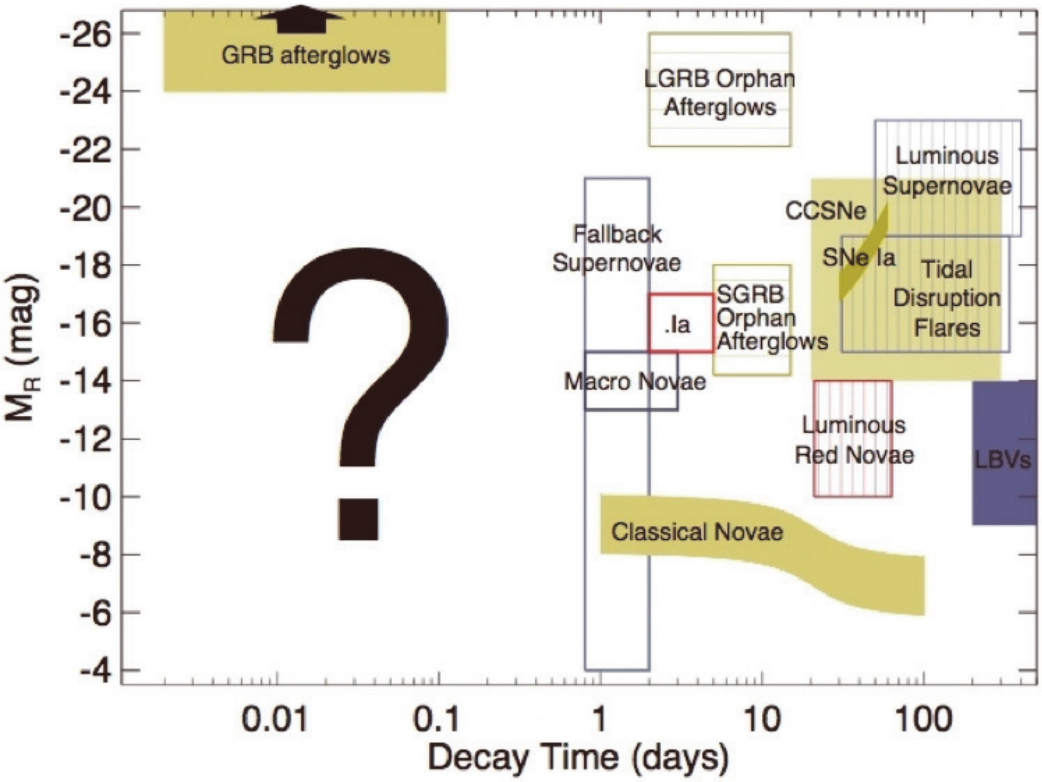


Fig5. *This figure demonstrates the transient phase space as observed using various multi-wavelength facilities. The X-axis denotes the time in days whereas Y-axis is brightness in absolute magnitude. Various transients are shown as scatter plot. It also demonstrates the importance of upcoming facilities 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).*

4. Early results with the 3.6m DOT and the 4Kx4K CCD Imager

The 3.6m DOT has been successfully installed at Devasthal. A rigorous on-sky performance of the telescope was tested using Test-WFS and the CCD Camera. The telescope was accepted for science observation in February 2016. The first light instruments 4Kx4K Imager and the FOSC are being tested at the moment. The telescope was technically activated jointly by the Prime Ministers of India and Belgium on 30 March 2016 in the presence of the Minister of Science and Technology, Government of India. In Fig6 below, the color magnitude diagram of the Globular cluster NGC 4147 is demonstrated showing detection of many faint point sources

(B >24 mag) whereas in Fig7 a color composite RGB image of the NGC 613 is shown with core-collapse type IIb SN 2016gkg clearly detected.

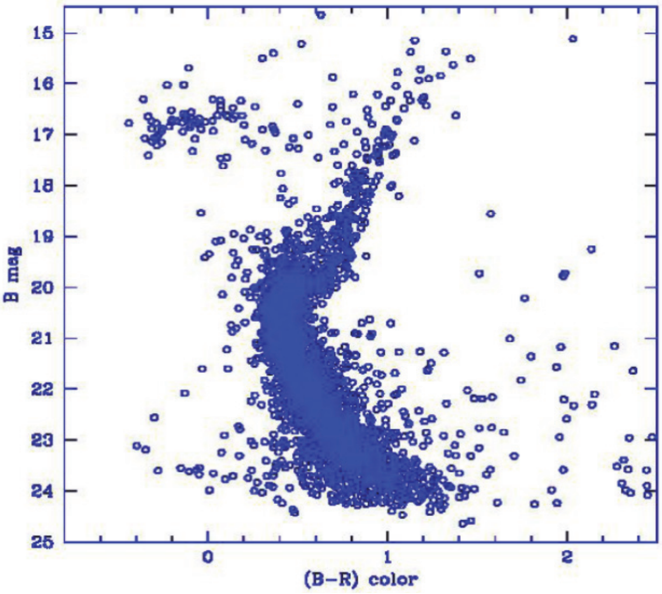


Fig6. *The B versus (B- R) color-magnitude diagram (CMD) of the Globular cluster NGC 4147 as obtained using the present calibration data taken using the 4K4K CCD mounted at the axial port of the 3.6m DOT. The total number of common stars plotted (detected in both filters) is around 3500 with a photometric accuracy of < 0.2 mag. In this figure, the number of detected stars having B < 24 mag are around 150 (with a photometric accuracy of < 0.2 mag) in the effective exposure time of 120 sec.*

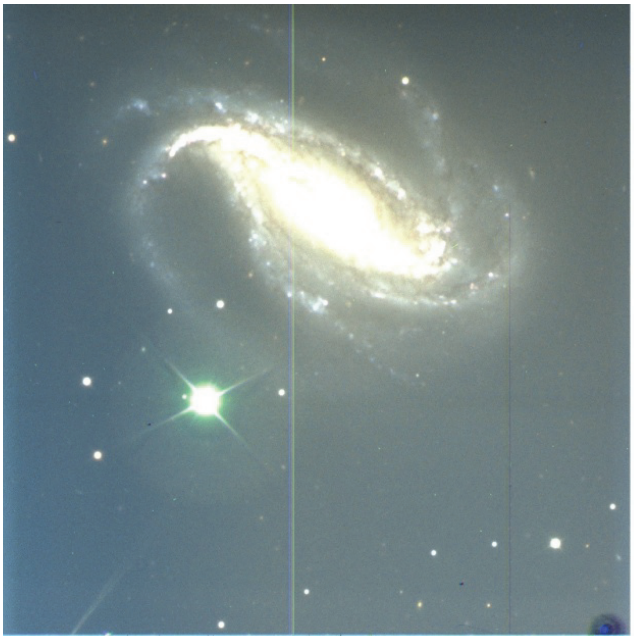


Fig7. *A color composite RGB image (3*200 sec) of the spiral galaxy NGC 613 taken in November 2016. Supernova 2016gkg (at V ~ 17 mag) is clearly visible in the upper right quarter of the frame.*

In summary, 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, specially, the fainter ones with shorter time scales and the follow-up of the sources with identified gravitational wave candidates. Study of new explosive 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.

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