Prospects of star formation studies with near-infrared instruments on 2-4 meter class Indian ground-based telescopes

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ABSTRACT

We present a brief description of the activities of the infrared astronomy group of Tata Institute of Fundamental Research with special emphasis on the near-infrared instrumentation for star formation studies using 2–4 meter class Indian ground-based telescopes. We describe the unique capability of TIRCAM2, for observations in the PAH ($\lambda_{\rm cen} \sim 3.3$ μm) and nb$L$ ($\lambda_{\rm cen} \sim 3.59$ μm) bands, currently being used by the astronomy community, and also the upcoming TANSPEC, which is being built for India's largest telescope, the 3.6-meter Devasthal Optical Telescope. The TIRCAM2 on the Devasthal Optical Telescope was successfully commissioned in June 2016, and the subsequent characterization and astronomical observations are presented here. Based on the successful engineering runs on the Devasthal Optical Telescope, TIRCAM2 has been made available to the Indian astronomical community for science observations since Early Science Cycle 2017A (May 2017) onwards. The fabrication of TANSPEC is in an advanced stage and the spectrometer is expected to be commissioned by the end of January 2018.

Keywords: ISM, Star-formation, NIR instrumentation

1. INTRODUCTION

The central research theme of the infrared astronomy (IRA) group at Tata Institute of Fundamental Research (TIFR) is the study of interstellar medium (ISM) in relation to star formation in our Galaxy and nearby galaxies. The study of ISM provides a powerful probe into the physical and chemical properties of the interstellar dust and gas, which predominantly emits in the infrared waveband. Infrared emitting ISM is a tracer of several important astrophysical phenomena, namely, star formation activity, shock front, material recycling, photo processes in the proximity of young stars, and plasma cooling. The corresponding research activities are currently executed using TIFR's own ground-based near-infrared (NIR) imagers & spectrometers, TIFR's indigenously developed 100-cm balloon borne far-infrared (FIR) telescope, national optical imagers & spectrometers, the Giant Metrewave Radio Telescope as well as international facilities such as the large aperture ground-based telescopes and astronomical satellites. The observations are complemented with interpretation backed by image processing as well as numerical modelling (e.g., radiative transfer) schemes based on codes developed in-house as well as those available publicly. In addition to the above activities, the group actively participates in instrument development for ground-based and space-based astronomy.

With the above aim, the IRA group designed and built the TIFR Near Infrared Spectrometer and Imager (TIRSPEC) in collaboration with M/s Mauna Kea Infrared, LLC, Hawaii (hereafter MKIR) during the 2007–2012 five-year period, now in operation on the side port of the 2-meter Himalayan *Chandra* Telescope (HCT), Hanle (Ladakh), India, at an altitude of 4550 meters above mean sea level (see details in Ojha et al. 2012a; Ninan et al. 2014). Recently, the IRA group has also upgraded the TIFR Near Infrared Imaging Camera-II (TIRCAM2) (Ojha et al. 2012b; Naik et al. 2012) which was being used with the 2-meter Inter-University Centre for Astronomy and Astrophysics's Girawali observatory telescope, near Pune, India. This instrument has been tested by the IRA group at the 3.6-meter Devasthal Optical Telescope (DOT) and is being used by Indian astronomers since May 2017 onwards. Besides this, TIFR has also been observing in the FIR band (120 to 220 μm) using the 100-cm balloon borne FIR telescope . Recently, as a part of the TIFR-Japan collaboration in balloon-borne FIR astronomy, the TIFR 100-cm balloon-borne FIR telescope along with the Japanese Fabry-Perot Spectrometer, tuned to the astrophysically interesting [C II] fine structure line at 157.74 μm, has been successfully flown

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several times to map large regions in [C II] line and continuum of several northern and southern star-forming complexes (Mookerjea et al. 2001, 2003; Kaneda et al. 2013). To complement these studies in the NIR band, the need was felt for a dedicated Optical-NIR spectrometer in the 0.5 to 2.5 μm range, which could be used with the 3.6-meter DOT. To meet this need, the TIFR-ARIES Near Infrared Spectrometer (TANSPEC) (Ojha et al. 2012b) was conceived to provide spectroscopy in the range from 0.55 to 2.54 μm, with a spectral resolving power of ~2750 to be used on the axial port of the 3.6-meter DOT.

In this paper, we describe the technical details of TIRSPEC, TIRCAM2 and TANSPEC. We also present the characterization and performance results of TIRCAM2 obtained before releasing the instrument to the users for scientific observations.

2. TIFR NEAR INFRARED SPECTROMETER AND IMAGER (TIRSPEC)

The TIRSPEC uses a Teledyne 1024x1024 pixel Hawaii-1 PACE array detector with a cutoff wavelength at 2.5 μm and provides a field-of-view (FoV) of 307 arcsec x 307 arcsec, with a plate scale of 0.3 arcsec pixel^{-1}. The TIRSPEC was installed at the 2-meter HCT during June 2013 for the engineering and scientific runs on the telescope. The first light took place on 21 June 2013. The characterization of the TIRSPEC was done over the next few months. Some engineering runs and science observations of several astronomical sources were also carried out during July and August 2013.

The TIRSPEC provides for various modes of operation which include photometry with broad and narrow band filters, spectrometry in single order mode with long slits of 300 arcsec length, and widths ranging from 1 to 7.92 arcsec, with order sorter filters in the Y, J, H & K bands, and a grism as the dispersing element as well as a cross dispersed (XD) mode with slit lengths of 10 arcsecs to give a coverage from 1.0 to 2.5 μm at the resolving power R of 1200. The slit lengths were upgraded to 50 arcsec during 2014, and minor mechanical modifications in the filter movement mechanisms were made to improve the movement of the filter wheels. The placement of various slits was also optimised for efficient observations. The TIRSPEC was commissioned successfully and the subsequent characterization and astronomical observations were completed. The TIRSPEC is available to the worldwide astronomical community for science observations since May 2014. Subsequently, subarray readout capability has been incorporated into the system to allow for photometry of brighter objects. Currently, about 50% of the observing proposals on HCT use TIRSPEC as the focal plane instrument.

3. TIFR NEAR INFRARED IMAGING CAMERA-II (TIRCAM2)

The TIRCAM2 is a closed cycle cooled imager that has been developed in-house by the IRA group at TIFR, for observations in the NIR bands lying in the range from 1 to 3.7 μm. The TIRCAM2 uses a 512x512 InSb based Aladdin III Quadrant focal plane array and contains selectable standard filters J, H, $K_{\rm cont}$, K, Brγ, polycyclic aromatic hydrocarbon (PAH) and narrow-band L (nb$L$) for imaging. It is cooled by a closed cycle Helium cryo-cooler to 35 K while operating. The main highlight is the camera's capability of observing in the nb$L$ (3.59 μm) band enabling our primary motivation of mapping of PAH emission at 3.3 μm. The TIRCAM2 is currently the only NIR imaging camera in India which can observe up to L band.

3.1. TIRCAM2 on 3.6-meter DOT

The TIRCAM2 was shipped to Devasthal for installation and commissioning with the 3.6 meter DOT in May 2016. The performance tests of the TIRCAM2 with the DOT were carried out during 2016–17. The TIRCAM2 was installed on to the telescope on 2016 June 1. In the following night of 2016 June 2, we obtained first light with the TIRCAM2 instrument on the 3.6-meter DOT. The TIRCAM2 test observations were further carried out with the DOT from 2017 January 9 to 16. Due to problems such as cloudy skies and high humidity, systematic data collection could not be done. Considering these problems, some preliminary data processing was done and based on these results, the TIRCAM2 has been released for science observations for 2017 early science cycle onwards. Figure 1 shows the TIRCAM2 system mounted on the axial port of the DOT on 2016 June 1.

The TIRCAM2 had its early science runs with the 3.6-meter DOT during 2017 May - October and it performed as expected. The stellar image point spread function was exceptionally good (FWHM ~ 0.6–0.9 arcsec in K band) and hence the nb$L$ band (3.59 μm) imaging was possible up to ~8 - 9 mag even though humidity was relatively high (> 60%). We could also make quite deep observations in J, H, & K bands (J ~ 19 mag). A colour composite image of M92 globular cluster generated using TIRCAM2 J (blue), H (green) and K (red) images, is presented in Figure 1. A 2MASS image of the same region is also presented for comparison.

3.2. TIRCAM2 performance

With the 3.6 meter DOT, the TIRCAM2 FoV is ~86.5 × 86.5 arcsec^2 with an image scale of 0.169 arcsec pixel^{-1}. We estimate that with the DOT we can carry out photometric observations up to 19 mag in J (S/N ~ 10) and 18 mag (S/N ~ 10) in K band (for 550s and 1000s exposures, respectively), and 9.1 mag (detection limit) in nb$L$ band (for 25s net exposure) in a typical seeing condition. With a typical 1.0 arcsec seeing condition, the TIRCAM2 heavily oversamples the star profile. This pixel sampling is ideal for high accuracy photometry of bright NIR sources. It is also interesting to compare the *Spitzer*-IRAC values of saturation limit in the 3.6 μm band. For a frame time of 2s, the point source saturation

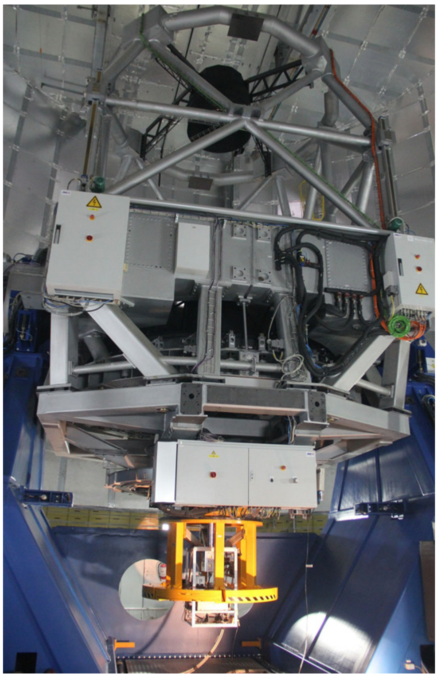

Figure 1. TIRCAM2 system mounted on the axial port of the DOT on 2016 June 1.

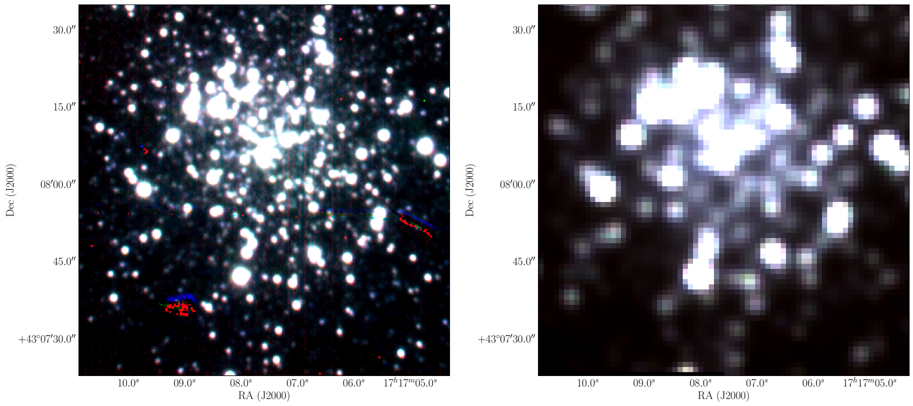

Figure 2. RGB colour composite image (red: *K*, green: *H*, blue: *J*) of M92, a Galactic globular cluster, generated using TIRCAM2 with the 3.6-meter DOT (left), and 2MASS (right).

limit in the IRAC 3.6 μm band is < 7.92 mag. The TIRCAM2 can therefore be used to observe sources having magnitudes brighter than the saturation limit of *Spitzer*-IRAC.

4. TIFR-ARIES NEAR INFRARED SPECTROMETER (TANSPEC)

During 2012, the TIFR and ARIES decided to jointly develop an Optical-NIR medium resolution spectrograph, based on 2048 x 2048 Hawaii-2RG (H2RG) focal plane array, to be used on the axial port of the 3.6-meter DOT. MKIR was chosen to design and fabricate the spectrometer, and the designs were thoroughly reviewed by international experts during 2015. The work of fabrication of this spectrometer named TANSPEC for "TIFR-ARIES Near Infrared Spectrometer" was taken up by MKIR in early 2016.

4.1. TANSPEC specifications

The TANSPEC is being built in collaboration with MKIR for the 3.6-meter DOT. The spectrograph operates in two modes whereby the spectrum is focussed on to a 2k x 2k H2RG array. In the XD mode, a combination of a grating and two prisms are used to pack all the orders on to the H2RG array at a resolution of $R \sim 2750$, for simultaneous wavelength coverage from 0.55 μm (Optical) to 2.54 μm (NIR). It also has a low resolution prism mode ($R \sim 100$) for high throughput observations. The instrument also has an independent imaging camera with a 1k x 1k H1RG detector which is the slit viewer. The reflected beam from the slit is imaged to this camera through a filter wheel which consists of broad band r', i', Y, J, H, Ks and narrow band H_2 & Brγ filters. This camera has a field of view of 1 x 1 arcmin^2, and is used for guiding the telescope (IR guider) as well as imaging for photometry. It also functions as a pupil viewer for instrument alignment

Table 1. Spectroscopic Sensitivity : Limiting magnitudes (100σ-one hour, 1 arcsec seeing)

Wavelength (μm)	Magnitude ($R \sim 2750$)	R (in Prism Mode)	Magnitude (Prism Mode)
1.01	15.4	100	17.3
1.25	14.9	110	17.3
1.28	14.2	110	16.4
1.67	13.2	180	15.3
2.25	13.5	350	15.0

on the telescope. For calibration, a uniform flat field from an integrating sphere outside the dewar having an identical f/9 beam is imaged. Wavelength calibration is done by Argon and Neon lamps.

The TANSPEC will be used for a wide range of studies from local star formation to extra-galactic astronomy. Simultaneous coverage of wavelength from 0.55 to 2.54 μm makes TANSPEC a unique instrument and ideal for studies which require simultaneous measurement of lines in Optical and NIR. The sensitivity of the TANSPEC is estimated which requires the instrument parameters. In the absence of atmospheric data for the Devasthal site, data for Mauna Kea was used. Table 1 gives the estimated 100σ-one hour sensitivity of the instrument in XD and prism modes. Spectroscopy sensitivity (100σ-one hour, 1 arcsec seeing) is expected to be 15.4 mag ($R \sim 2750$), whereas in prism mode ($R \sim 100$) it would be 17.3 mag in the J band.

The TANSPEC is expected to be shipped to Devasthal by January 2018. It will be ready for tests on the 3.6-meter DOT at the end of January 2018.

5. CONCLUSION

TANSPEC and TIRCAM2 at the focal plane of the 3.6-meter DOT will be a major workhorse for a variety of challenging astrophysical problems. These will be extremely sensitive to low temperature stellar photospheres ($T \leq 2500$ K) and objects surrounded by warm dust envelopes or embedded in dust/molecular clouds. These NIR instruments are therefore particularly suited to the search for low and very low mass stellar populations (M dwarfs, brown dwarfs), strong mass-losing stars on the asymptotic giant branch, young stellar objects still in their protostellar envelopes and active galactic nuclei.

The preliminary results from the earlier observing runs of TIRCAM2 with the DOT were encouraging, particularly at longer wavelengths (>2 μm). This will further allow us to explore the capability of the TIRCAM2 at longer wavelength, particularly in the L band. We aim to observe science targets in PAH and nb$L$ bands during the next early science cycle phase to explore the TIRCAM2's performance in the longer wavelengths from Devasthal site. The TIRCAM2 is also proposed to be used on one of the side ports of the DOT since the axial port will be occupied by one of the other instruments (e.g., TANSPEC, ADFOSC, and CCD imager) in the near future.

The overall progress of the TANSPEC is on schedule. The instrument will be shipped to the DOT in January 2018. We expect the instrument to be tested on the 3.6-meter DOT at the end of January 2018. It will be a unique spectrograph which will provide simultaneous wavelength coverage from 0.55 μm (Optical) to 2.54 μm (NIR) with a resolving power of $R \sim 2750$.

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