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Prospects for star formation studies with infrared instruments (TIRCAM2 and TANSPEC) on the 3.6-m Devasthal Optical Telescope

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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 ground-based near infrared instrumentation for star formation studies. We describe the unique capability of TIRCAM2 for observations in the polycyclic aromatic hydrocarbon ($\lambda_{\rm cen} \sim 3.3\ \mu$m) and narrow-band L ($\lambda_{\rm cen} \sim 3.59\ \mu$m) bands, currently being used by the astronomy community, and of the upcoming TANSPEC, which is being built for India's largest telescope, i.e. the 3.6-m Devasthal Optical Telescope (DOT). The TIRCAM2 on the 3.6-m DOT was successfully commissioned in June 2016, and the subsequent characterization and astronomical observations are presented here. Based on the successful engineering runs on the 3.6-m DOT, TIRCAM2 has been made available to the Indian and Belgian 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.

1 Introduction

The central research theme of the infrared astronomy (IRA) group at Tata Institute of Fundamental Research (TIFR) is the study of the interstellar medium (ISM) in relation to star formation in our Galaxy and nearby galaxies. The study of the 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,

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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-m Himalayan *Chandra* Telescope (HCT; Hanle, Ladakh, India) at an altitude of 4 550 meters above mean sea level. The TIRSPEC uses a Teledyne 1024×1024 pixel Hawaii-1 PACE array detector with a cutoff wavelength at 2.5 μm and provides a field of view (FoV) of $307'' \times 307''$, with a plate scale of $0.3''$/pixel. The TIRSPEC was installed at the 2-m 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 $300''$ length, and widths ranging from 1 to $7.92''$, 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 $10''$ to give a coverage from 1.0 to 2.5 μm at the resolving power R of 1200. The slit lengths were upgraded to $50''$ 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 (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-mr Inter-University Centre for Astronomy and Astrophysics's Girawali observatory telescope, near Pune. This instrument has been tested by the IRA group at the 3.6-m DOT and is being used by Indian and Belgian 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 (Ghosh et al. 1988; Ghosh 2010). 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 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-m 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 $\sim$2750 to be used on the axial port of the 3.6-m DOT.

In this paper, we describe the technical details of 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 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 512×512 InSb based Aladdin III Quadrant focal plane array and contains selectable standard filters J, H, $K_{\rm cont}$, K, $Br\gamma$, polycyclic aromatic hydrocarbon (PAH) and narrow-band L (nbL) 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 nbL (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. The camera was mounted at the backend of the 2-m IUCAA Girawali telescope before commissioning with the DOT. A more elaborated technical detail of the camera can be found in Naik et al. (2012).

2.1 TIRCAM2 on 3.6-m DOT

In May 2016, the TIRCAM2 was shipped to Devasthal for installation and commissioning with the 3.6-m DOT (f/9; site latitude: $29^\circ\!.19706$ N, longitude: $79^\circ\!.6841$ E, altitude: 2450 m). The performance tests of the TIRCAM2 with the 3.6-m DOT were carried out during 2016-17. The TIRCAM2 was first installed on to the telescope on 1 June 2016. In the following night of 2 June 2016, we obtained first light with the TIRCAM2 instrument. The TIRCAM2 test observations were further carried out with the 3.6-m DOT between 9 to 16 January 2017. 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. Fig. 1 shows the TIRCAM2 system mounted on the axial port of the 3.6-m DOT on 1 June 2016. With the 3.6-m DOT, the TIRCAM2 FoV is $\sim$86.5″×86.5″ with an image scale of 0.169″/pixel. With a typical 1.0″ seeing condition, the TIRCAM2 heavily oversamples the star profile. It must be noted that the TIRCAM2 was originally developed for the 2-m IUCAA Girawali telescope (f/10), and that is the primary reason for such a finer pixel scale with the 3.6-m DOT (f/9). This pixel sampling is ideal for high accuracy photometry of bright NIR sources.

The TIRCAM2 had its early science runs with the 3.6-m DOT during 11 - 14 May 2017 and it performed as expected. The stellar image point spread function was exceptionally good with full width at half maximum (FWHM) of $\sim$0.6 - 0.9″. A cut-out of a K-band stellar image is shown in the left panel of Fig. 2 along with its radial profile in the right panel. The FWHM of the stellar profile is 3.5 pixels which converts to $\sim$0.6″ on the sky. Because of such exceptional seeing condition, the nbL band (3.59 μm) imaging was possible up to $\sim$8 - 9 mag even though humidity was relatively high ($>$70%) during this cycle. We could also make quite deep observations in J, H and K bands ($J \sim 19$ mag). A colour composite image of the M 92 globular cluster generated using TIRCAM2 J (blue), H (green) and K (red) images, is presented in Fig. 3. A 2MASS image of the same region is also presented for comparison. An array of nbL band (3.59 μm) images (100×100 pixels cut-outs) for different magnitude stars is shown in Fig. 4. The left panel of Fig. 5 shows the continuum-subtracted PAH band image of 30″×30″ area toward the Sh2-61 centre region. PAH emission is detected with a signal-to-noise ratio of 6.

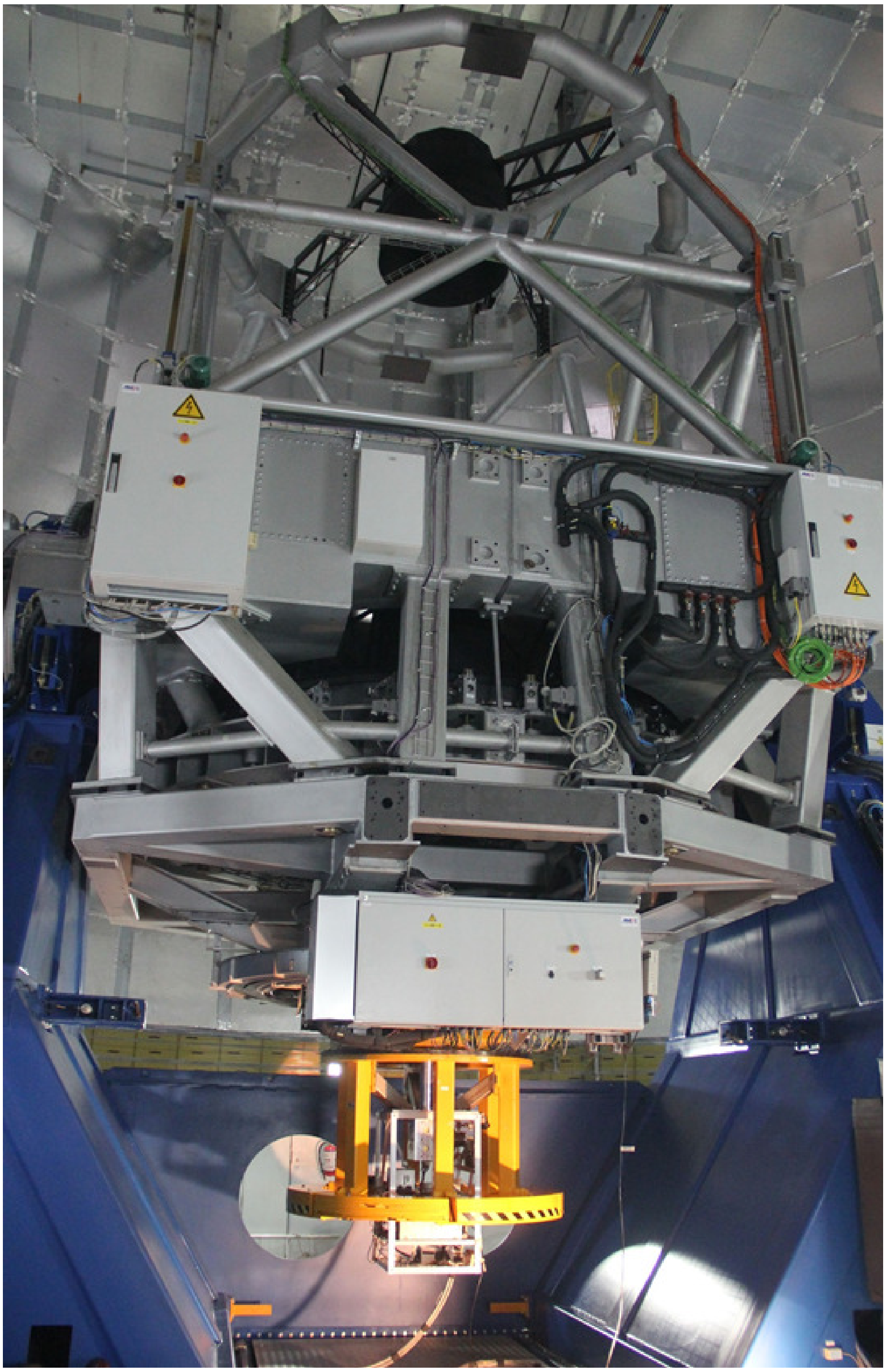

Figure 1: The TIRCAM2 system mounted on the axial port of the 3.6-m DOT on 1 June 2016.

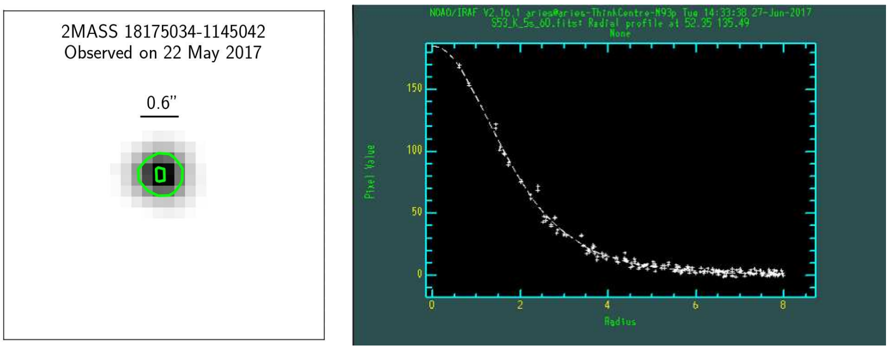

Figure 2: Left: Cut-out of a stellar image observed with TIRCAM2 in the K-band on 22 May 2017 towards the Serpens OB2 association. The typical seeing on this night was $\sim 0\farcs6$. The outer green contour shows the stellar FWHM of the image. Right: The radial profile of the image shown in the left panel.

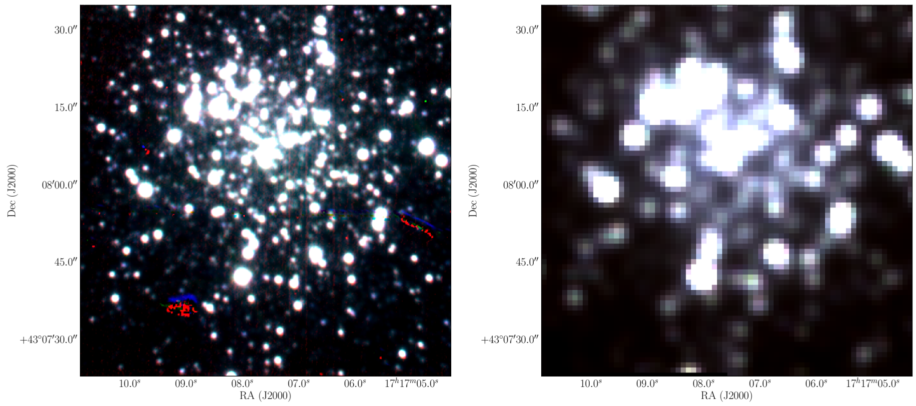

Figure 3: RGB colour composite image (red: K, green: H, blue: J) of M 92, a Galactic globular cluster, generated using TIRCAM2 with the 3.6-m DOT (left), and 2MASS (right).

2.2 TIRCAM2 performance

We estimate that with the 3.6-m DOT, we can carry out photometric observations up to 19 and 18 mag (S/N $\sim$ 10) in the J and K band for 550 s and 1000 s exposures, respectively, and up to 8.2 mag (detection limit) in the nbL band for 20 s net exposures under typical seeing conditions. It is also interesting to compare the *Spitzer*-IRAC values of the saturation limit in the 3.6 μm band. For a frame time of 2 s, the point source saturation 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. Table 1 lists the overview of the performance of TIRCAM2 on the 3.6-m DOT.

3 TIFR-ARIES Near Infrared Spectrometer (TANSPEC)

During 2012, the TIFR and ARIES decided to jointly develop an Optical-NIR medium resolution spectrograph, based on a 2048×2048 Hawaii-2RG (H2RG) focal plane array, to be used on the axial port of the 3.6-m 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 the TIFR-ARIES Near Infrared Spectrometer (TANSPEC) was taken up by MKIR in early 2016.

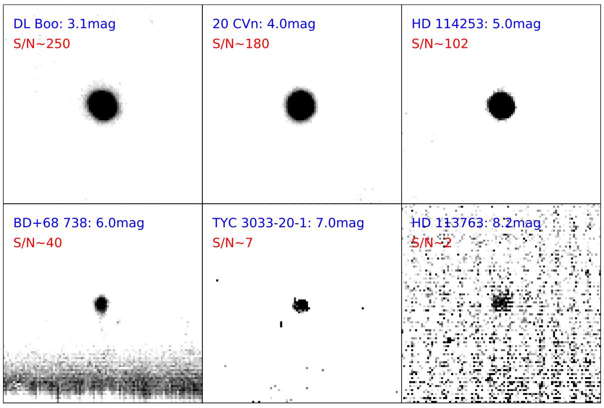

Figure 4: Mosaic of nbL band images (100×100 pixels cut-outs) observed during 13 -14 May 2017. Sources brighter than nbL $\sim$ 6 mag are aligned and combined and the remaining sources are co-added blindly.

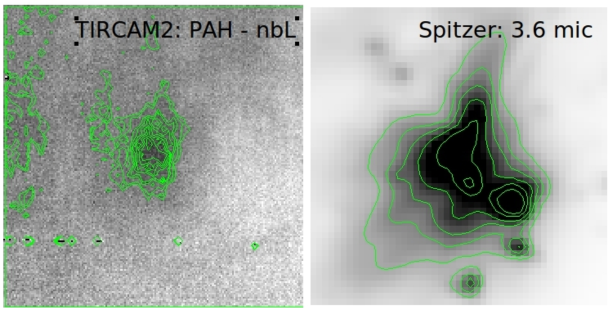

Figure 5: The left panel shows the continuum-subtracted PAH band image of the $30'' \times 30''$ area toward the Sh 2-61 star-forming region. Contours are overlaid for clarity. The *Spitzer* 3.6-μm image for the same area is also presented for comparison in the right panel.

3.1 TANSPEC optical layout and specifications

The TANSPEC is being built in collaboration with MKIR for the 3.6-m DOT. The overall optical layout of the instrument is shown in Fig. 6. With f/12 into the spectrograph, the Foreoptics which is an Offner relay, serves two major purposes. (1) Re-images the telescope's f/9 beam focal plane image as an f/12 beam on to the slit. (2) The secondary of the telescope is imaged to the secondary of Offner, hence, it works as a cold stop to block stray light from the sides. The center portion is also blackened to mask the central portion of the secondary mirror of the telescope. Reflective slit mirrors split the beam into the spectrograph through the slit gap and reflects the remaining light to the slit viewer camera. The spectrograph operates in two modes whereby the spectrum is focussed on to a 2k×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 highest resolution of R $\sim$2750. A range of slit widths are available from 0.5 to 4.0$''$. The narrowest slit (0.5$''$), which provides the R$\sim$2750, is undersized than the typical seeing for the Devasthal site for obtaining stable line profiles. It also has a low resolution prism mode (R$\sim$100) for high throughput observations. The instrument also has an independent imaging camera with a 1k×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 $1' \times 1'$, 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 on the telescope. A brief summary of the TANSPEC's observational modes are tabulated in Table 2.

Table 1: TIRCAM2 performance with the 3.6-m DOT.

FoV	$\sim 86.5'' \times 86.5''$
Image scale	$0.169''$/pixel
Best seeing	$0.6''$ (22 May 2017)
	10σ limits (with effective integration)
J-band	19.0 mag (550 s)
H-band	18.8 mag (550 s)
K-band	18.0 mag (1000 s)
nbL-band (detection limit)	8.2 (20 s)

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 the optical and NIR. The XD spectral format is shown in Fig. 7. The free spectral range is plotted for each order. This mode is optimized for 2.54-0.63 μm and orders 3-10.

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 2 gives the estimated 100σ-one hour sensitivity of the instrument in XD and prism modes. The spectroscopic sensitivity (100σ-one hour, $1''$ 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.

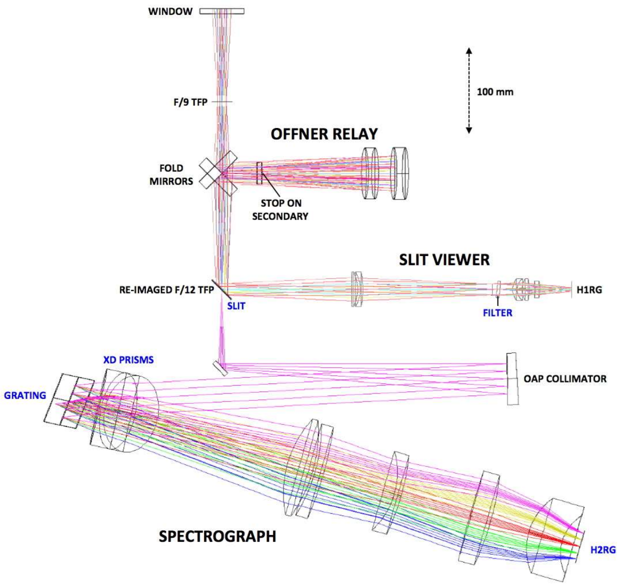

Figure 6: Overall optical layout of TANSPEC.

3.2 TANSPEC current status

All parts for the instrument have been received by MKIR. The assembly of the cryostat and all of the mechanisms has been completed (Fig. 8). The mechanisms, software and cold run tests have been

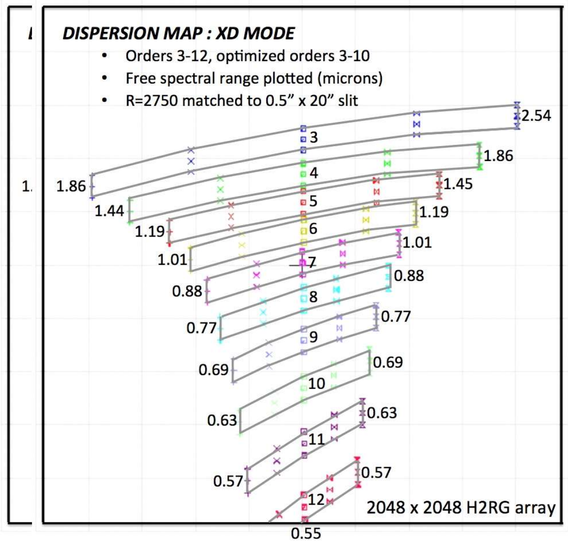

Figure 7: Cross-dispersed spectral format.

Table 2: TANSPEC Specifications.

FoV of slit viewer	$60'' \times 60''$
Image scale of slit viewer	$0.25''$/pixel
Pixel scale of spectrograph	$0.25''$/pixel
	Filter configurations
Slit viewer filters	r', i', Y, J, H, Ks, H_2, Brγ, pupil viewer
Spectrograph modes	XD mode (R$\sim$2750), Prism mode (R$\sim$100-350)
Slit sizes	$0.5''$, $0.75''$, $1''$, $1.5''$, $2''$, $4''$

successfully completed in July-August 2017. With successful completion of the mechanism test, a cold test of the complete instrument (after installation of the optics and detectors) was successfully completed in December 2017. The array readout software is complete and has been successfully tested on the warm MUXs and detectors. From now on, it is planned to address issues discovered in the cold tests until the acceptance tests as mentioned in the TANSPEC contract are passed. The TANSPEC is expected to be shipped to Devasthal in January 2018. It will be ready for tests on the 3.6-m DOT in February 2018.

4 Conclusion

TANSPEC and TIRCAM2 at the focal plane of the 3.6-m DOT will be a major workhorse for a variety of challenging astrophysical problems. These will be extremely sensitive to low temperature stellar photospheres ($T \leq 2\,500$ 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 first observing runs of TIRCAM2 with the 3.6-m DOT were encouraging, particularly at longer wavelengths (>2 μm). This will further allow us to explore the

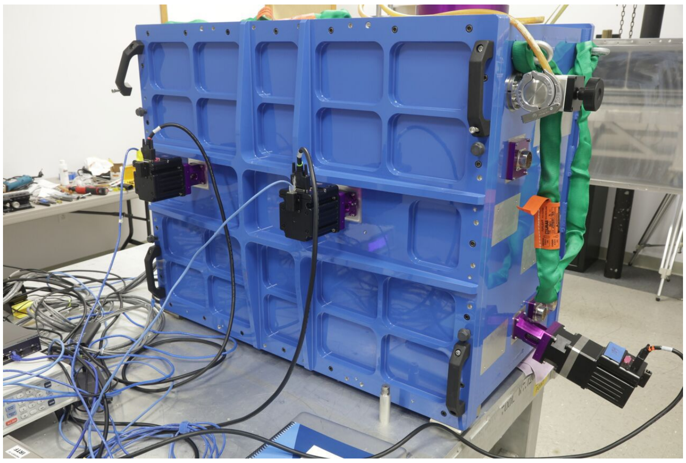

Figure 8: TANSPEC cryostat with all of the assembled mechanisms ready for the cold test.

Table 3: Expected spectroscopic sensitivity: limiting magnitudes (100σ-one hour, 1$''$ 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

capability of the TIRCAM2 at longer wavelengths, particularly in the L band. We aim to observe science targets in the PAH and nbL bands during the next early science cycle phase to explore the TIRCAM2's performance in the longer wavelengths from the Devasthal site. The TIRCAM2 is also proposed to be used on one of the side ports of the 3.6-m 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 mechanical design is being finalized and will be fabricated soon.

The overall progress of the TANSPEC is on schedule. First cool down tests were completed successfully in January 2017. A cold test of the complete instrument (after installation of the optics and detectors) was successfully completed in December 2017. The instrument will be shipped to the 3.6-m DOT in January 2018. We expect the instrument to be tested on the 3.6-m DOT in February 2018. It will be a unique spectrograph which will provide simultaneous wavelength coverage from 0.55 μm (optical) up to 2.54 μm (NIR) with a resolving power of R$\sim$2750.

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