Welcome to the Department of Astronomy and Astrophysics (DAA) at TIFR! Our research programs address formation, physics and evolution of a vast range of astronomical objects starting from the Sun, the stars, compact objects (black holes & neutron stars), the matter between the stars, the galaxies, to the distant galaxy clusters. We also carry out research in general relativity, cosmology and quantum gravity. We emphasize on the building of astronomy instruments, performing observations and formulation of theoretical and computational models to explain the outcome of observations of astronomical objects. We have built instruments onboard the first Indian multiwavelength astronomy satellite ASTROSAT and are leading multiple scientific projects with the ASTROSAT. We also have vibrant science and instrumentation collaborations on the upcoming projects on the Thirty Meter Telescope (TMT), the 3.6 m Devasthal Optical Telescope and the Square Kilometer Array (SKA).
## SOLAR & STELLAR SEISMOLOGY  (H. M. Antia & S. Hanasoge)

The seismology group works on inferring the internal structure and dynamics of the Sun and stars using surface measurements of the oscillations. The research focuses on carefully analyzing observational data and applying a variety of theoretical and computational techniques to enable accurate interpretation. High resolution observations are taken by space and ground-based instruments: Kepler (NASA) for instance observes distant stars whereas the Solar Dynamics Observatory (NASA) looks at the Sun. The theoretical work centres around inverse theory, modelling the propagation of waves through magnetized, convecting and stratified media, and mode theory. The seismology group maintains a 648-core Intel compute cluster, which is used to perform numerical calculations in the aid of forward and inverse problems in seismology. Currently, the group is focused on inferring the interior structure of distant stars, measuring convection and magnetism in the Sun, and developing computational techniques to improve the quality of seismic inferences.

## INTERSTELLAR MEDIUM & STAR FORMATION  
(S. K. Ghosh, B. Mookerjea, D. K. Ojha & M. Puravankara)

The group has a vibrant research program in the observational studies of star and planet formation, physics and chemistry of the interstellar medium, the Galactic structure and kinematics of stellar populations in the Galaxy. We use multwavelength (optical to radio) photometric and spectroscopic observations using space- and ground-based telescopes together with theoretical models as the primary tools. The physical processes and mechanisms that regulate the formation and evolution of the newly born stars, their impacts on the surrounding interstellar medium (ISM) and the onset of planet formation in the protoplanetary disks are studied in detail. Study of heating and cooling mechanisms of the ISM and detection of and determination of abundances of complex molecules in space using spectroscopic observations is actively pursued by the group. A program to study the structure of our Galaxy from images in multiple near-UV (NUV) and far-UV (FUV) filters of the Ultraviolet Imaging Telescope (UVIT) onboard ASTROSAT is also under way.

## BLACK HOLES & NEUTRON STARS  (S. Bhattacharyya)

Black holes and neutron stars, which are collapsed cores of massive stars, are exotic objects. A black hole contains a singularity covered by an invisible surface, called an ‘event horizon’, from which nothing, not even light, can escape. A neutron star is the densest known object in the universe with a hard surface. Together black holes and neutron stars provide us a unique opportunity to probe some aspects of fundamental physics, such as testing the general theory of relativity, probing super-dense degenerate matter, etc., which cannot be done in terrestrial laboratories. When matter from a companion star falls on these compact objects, they mainly emit X-rays. The variation of this X-ray intensity with photon energy and time provides the necessary information to study the above mentioned fundamental problems, as well as to understand the flow of matter in extreme environments. DAA has one of the strongest groups in India, which studies black holes and neutron stars in X-rays and other wavelengths, and the data from our own instruments on board the Indian ASTROSAT satellite are very useful for this research.

## ASTROPHYSICS WITH ASTROSAT AND INTERNATIONAL X-RAY OBSERVATORIES 
(A. R. Rao)

India’s first astronomy satellite for multi-wavelength observations, ASTROSAT, is getting operational and will provide enormous data on all kinds of celestial objects to study the astrophysics of supermassive black holes in Active Galactic Nuclei, hot gas in Clusters of galaxies, stellar coronae, Magnetic Cataclysmic Variables, and stellar mass black holes in our galaxy. We supplement our studies by analyzing data obtained with Chandra, XMM-Newton, Suzaku, Swift, Fermi and a host of other X-ray observatories and ground based radio and optical observatories.
INFRARED INSTRUMENTATION

(D. K. Ojha, M. Puravankara, S. K. Ghosh)

Design and development of Infrared (IR) instruments used for observations is one of the core areas of experimental research in DAA. This offers a tremendous opportunity to the students to learn the use of advanced technology to build IR imagers (camera) and spectrometers which can be used to address questions concerning interstellar medium and the unsolved problems of star formation. The group has recently built and installed a Near Infrared Spectrometer and Imager (TIRSPEC) for the Himalayan Chandra Telescope at Hanle. For basic experimental training in astronomy to the graduate students the group has installed and maintains a 14-inch optical telescope (equipped with optical and NIR imagers/photometers) within the institute campus. The infrared instrumentation group is currently building several instruments such as: (A) a competitive 0.6 - 2.5 microns medium resolution spectrograph (TANSPEC) for the ARIES 3.6-meter telescope, (B) a laboratory model of Infrared Spectroscopic Imaging Survey (IRSIS) payload for an Indian Small Satellite, (C) in collaboration with a Japanese team integration of an upgraded 157.74 micron [C II] fabry-perot spectrometer (FPS) to the 100-cm TIFR far-infrared balloon-borne telescope and plan to integrate 34.8 micron [Si II] FPS in near future.

GENERAL RELATIVITY, QUANTUM GRAVITY & QUANTUM FOUNDATIONS, COSMOLOGY

(T. P. Singh)

The research areas of this group primarily focus on two aspects: (A) theoretical studies of black hole physics, gravitational collapse, physics near space-time singularities (visible as well as hidden within black holes) within the framework of Einstein gravity and (B) search for a modified formulation of quantum theory which explains the collapse of the wave-function during a quantum measurement. An alternative formulation of quantum theory is being explored to explain the collapse of wave-function during a quantum measurement and it involves the modification of the Schroedinger equation into a stochastic nonlinear theory. Such a modified theory reduces to quantum mechanics for microscopic systems, and to classical mechanics for macroscopic ones. Work is ongoing to investigate whether this modification is caused by gravity and also to suggest possible experiments to test this idea.

In cosmology we address various outstanding problems using available observations as well as from a purely theoretical point of view. The energy content of the universe is currently understood to be dominated by the dark matter (inferred from its gravitational effect) and a completely unknown dark energy. We examine anisotropic and inhomogeneous cosmological scenarios towards modeling the real Universe from theoretical considerations based on general relativity. The group also investigates the possible origin of cosmic acceleration (dark energy and/or a modified theory of), the origin of flat galaxy rotation curves, and possible resolutions of the cosmological constant problem.

COMPACT BINARIES & GRAVITATIONAL WAVES

(A. Gopakumar)

We explore observational aspects of Einstein’s theory for gravity, namely General Relativity, to make precise quantitative statements in the weak- and even strong-field regimes. A particular emphasis of our research is on the analytical and semi-analytical modeling of gravitational wave (GW) sources, relevant for the operational ground- and proposed space-based GW observatories and the planned Square Kilometer Array (SKA). A good fraction of these efforts are focused on constructing ready-to-use GW search templates for coalescing spinning compact binaries in non-circular orbits and exploring their data analysis implications. These investigations are being adapted to provide theoretical constructs that should be helpful while observationally probing black hole space-times during the SKA and Thirty Meter Telescope (TMT) era.

INFRARED INSTRUMENTATION

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Using high-performance computing, sophisticated data analysis techniques, and detailed numerical modeling we solve mysteries of astrophysical systems as diverse as exoplanets, star clusters, and gravitational wave sources. Thousands of exoplanets are now discovered and it is clear that the most abundant type of exo-planetary systems are very different in their properties compared to those of the planetary system around the Sun. We study how exoplanets form and subsequently evolve for billions of years before we observe them at their current orbital architectures and structural properties. Dense star clusters, such as globular clusters and nuclear clusters at galactic centres are efficient factories of stellar exotica such as gravitational wave sources (e.g., black hole binaries, neutron star binaries), X-ray binaries, and pulsars. Using state-of-the-art numerical codes we study the evolution of dense star clusters and the processes that form a plethora of exotic stellar sources interesting for many branches of astrophysics. One specific area of current interest for this group is how black holes and star clusters control the evolution and fates of each other and in the process efficiently produce gravitational wave sources detectable by LIGO.
Seismology of the Sun and Stars

Seismology is the inference of the interiors of objects based on surface measurements of oscillations of that object. Our group, consisting of Prof. H. M. Antia and Dr. Shravan Hanasoge, develops and applies theoretical and computational techniques to seismically infer the interior structure of the Sun, stars and Earth using surface measurements of the wave field. We solve large inverse problems, a term that refers to the reconstruction of properties of the full 3-D interior of the Sun using a small set of surface measurements. Seminal discoveries in the past include the rotation and structure of the interior of the Sun and the depth of its convection zone with great precision. Also see: http://www.tifr.res.in/~hanasoge/

Left: Rotation rate of the Sun as a function of latitude and radius, red means relatively fast and blue means relatively slow. Right: Kepler's field of view in the Milky Way. We have high-precision measurements of pulsations of hundreds of distant stars. What do these oscillations tell us about the host?

Space-based observatories such as NASA’s Solar Dynamics Observatory (pictured below) and Kepler, provide continuous high-resolution, high-fidelity measurements of the wavefield at the surface of the Sun. These data are interpreted using sophisticated mathematical techniques to obtain 3-D images of the interior. Outstanding problems in contemporary seismology relate to the structure of sunspots, global circulations within the Sun and inferring the nature of turbulence in a rotating, stratified object etc. This research directly touches on areas of applied mathematics, non-linear optimization, large-scale computation, astrophysics, observational science, inverse theory, fluid mechanics and magnetohydrodynamics.

Above: an artist’s depiction of the Solar Dynamics Observatory facing the Sun. Right: Seismic response of the Sun to a primordial black hole traversing through it. The global oscillations thus excited would be unique and detectable. Can the global oscillations of the Sun help place constraints on the composition of dark matter?
**Infrared Astronomy Lab**

**Research Areas:**

Interstellar medium (ISM), Multi-wavelength study of Galactic star-forming regions, Galactic structure & kinematics of the stellar populations of our Galaxy, Astronomical instrumentation development for ground-based telescopes and development of balloon & space-borne payloads for space-based infrared astronomy.

Central research theme of the group is the study of ISM in relation to star formation in our Galaxy and nearby galaxies. Research activities are currently executed using TIFR’s own 100 cm balloon-borne FIR telescope, ground-based NIR cameras and spectrometers, National ground-based Optical and Radio telescopes as well as International facilities. In addition to the above, the group actively participates in instrument development for ground and space astronomy.

**Experimental Programs:**

**TIRSPEC** is mounted on the 2-meter Himalayan Chandra Telescope (HCT) IAO, Hanle, Ladakh, India. It covers wavelengths from 1 to 2.5 μm, for near-infrared medium resolution spectroscopy as well as imaging. The detector used in the instrument is a 1024 x 1024 Hawaii-1 PACE array. With 0.3 arcsec per pixel plate scale, the instrument provides a Field of View (FoV) of 307 x 307 arcsec² in the imaging mode. The spectroscopic mode gives a wavelength coverage from 1 to 2.5 μm with a spectral resolution of ~1200. The instrument is operated remotely from CREST, IIA, Hosakote, Bangalore. ([http://web.tifr.res.in/~daa/tirsboxed](http://web.tifr.res.in/~daa/tirsboxed))

Balloon-borne far-infrared (FIR) observations:

We have been carrying out Far-IR observations of Galactic star-forming regions using the TIFR 100 cm balloon-borne telescope (T100).

Recently, as a part of the TIFR-Japan collaboration, a Japanese Fabry-Perot spectrometer has been successfully interfaced with the T100 for [ C II] line (158 μm) observations. We have been regularly flying the FIR telescope from TIFR Balloon Facility at Hyderabad.

**TIRCAM2:**

TIRCAM2 is a closed-cycle cooled imager that has been developed by the IR Astronomy Group at TIFR for observations in the NIR band of 1 to 3.7 μm with existing Indian telescopes. 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.


**Current Instrumentation Activities:**

**IRSIS:** Development of Infrared Spectroscopic Imaging Survey (IRSIS) payload for an Indian Satellite (Goal: Spectroscopic Survey at 1.7-6.4 μm covering > 50% of the full sky including the Galactic plane). (Current status: IRSIS Laboratory model is completed and the report is submitted to ISRO.)

**TANSPAC:** Development of TIFR-ARIES Near Infrared Spectrometer (TANSPAC; 0.6 – 2.5 μm) for the ARIES 3.6-meter telescope. (Current status: TANSPAC will be commissioned on 3.6m DOT in the first quarter of 2019.)


[http://web.tifr.res.in/~ojha/](http://web.tifr.res.in/~ojha/)

(December 2018)
Astrochemistry is a young and interdisciplinary research field which investigates the chemical processes in molecular clouds and solar-system environments.

**Tools & Techniques**

We observe spectral lines in emission and absorption in the infrared to millimeter wavelengths using international space- and ground-based telescopes. The observed spectral profiles are used to isolate the velocity components. From the strength of the spectral lines we estimate the temperature, density of H$_2$ & the number of molecules/ions of the relevant chemical species in the astrophysical source or along the line of sight that contribute to the spectral line. State-of-the-art radiative transfer tools & chemical models are used for this analysis.

**Recent results**

Our current focus is on observational studies with the high spectral resolution far-infrared spectrometer, upGREAT, onboard the airborne observatory SOFIA. We have several ongoing programs studying (a) the photodissociation regions in our Galaxy as well as in M33 and (b) searching for isotopes of carbonchain molecules. These studies are complemented by observations with mm telescopes (APEX, IRAM) and radio telescope (GMRT). We recently studied nitrogen-, carbon-bearing hydrides, pure linear carbon chains (C$_3$), C$^+$ and N$^+$ in diffuse and dense molecular clouds using Herschel. We observe the emission from C$^+$ & O$^0$ in galactic and extragalactic sources to explain the contribution of C$^+$ to the cooling of the ISM and distribution of the different components (ionized, atomic & molecular) of the ISM.

**International Collaborations**

We have several ongoing collaborations with astrophysicists, astrochemists, laboratory spectroscopists from Germany (Univ. of Cologne, Uni. Kassel, MPIfR Bonn), France (ENS, Paris & CESR Toulouse), Spain (IRAM, Granada), USA (JPL, NASA, Cornell).

**Principal Investigator**
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**PhD positions available**

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Formation of Stars and Planetary Systems
Manoj Puravankara, DAA, TIFR, Mumbai

My Research
(1) To understand how stars and planetary systems form out of molecular clouds in our Galaxy.
(2) To study the physical processes and mechanisms that control and regulate the evolution of new born stars and the formation and subsequent evolution protoplanetary disks – the birth places of planetary systems. [url: http://web.tifr.res.in/~manoj.puravankara/]

Where do stars form?
Stars form in the deep & dark interiors of molecular gas clouds.

Orion molecular clouds in the infrared light imaged by the Spitzer & Herschel space telescopes. Stars are being formed in the cold & dense molecular gas shown here in red & green.

Measuring protostellar evolution
Protostellar evolution is driven by the competition between envelope infall, disk accretion and outflows. These processes can heat up the surrounding gas to high temperatures. The hot gas associated with protostars cools by emitting line photons in the infrared (IR) wavelengths. IR spectroscopy, thus, is a powerful tool to study the physical processes that regulate protostellar evolution.

One of the brightest infrared line spectrum towards a protostar observed with the Herschel space telescope. Emission lines of O, C, CO, H$_2$O & OH in the spectrum can be used to derive the density, temperature & abundance of the hot gas in the vicinity of the protostar.

How do stars form?
Gravitational collapse of a rotating cloud core results in the formation of a protostar: a central source surrounded by an accretion disk which is fed by an envelope. Protostars drive powerful, supersonic outflows along the polar axes of the system.

Different evolutionary stages in the formation of stars and planetary systems (Shu et al. 1987)
The envelope eventually dissipates and a young star surrounded by a protoplanetary disk emerges out of the parental cocoon. Planetary systems are formed out of these disks.

Protoplanetary disk evolution
The observational tracers of the onset of planet formation in protoplanetary disks, such as grain growth, sedimentation & crystallization can be studied using infrared spectra.

Mid-infrared spectra of protoplanetary disks observed with the Spitzer space telescope. The broad silicate emission features at 10 & 20 μm can be used to study the size, shape, composition & crystallinity of dust grains in the disks. The slope of the continuum traces the disk structure.
Quantum theory is an extremely successful theory of microscopic phenomena, which is not contradicted by any experiment. On the other hand, the general theory of relativity is a highly successful description of gravitational phenomena on macroscopic scales. Yet, we do not quite know how to put the two theories together – we do not know how to describe gravitational effects on microscopic scales. For instance it is not known what the gravitational field of a quantum mechanical electron is.

The difficulties in arriving at a quantum theory of gravity [a unification of quantum and gravitational physics] perhaps have to do with the fact that our understanding of quantum theory is incomplete. Firstly, quantum theory does not provide a satisfactory explanation of the measurement problem: why does the wave-function of a quantum system apparently collapse during a measurement, suggesting a violation of the linear superposition principle? Secondly, quantum theory depends on an external classical time, and this is an unsatisfactory feature of the theory.

In our group we carry out research on the following problems: (i) What is the resolution of the quantum measurement problem? (ii) How to arrive at a description of quantum theory which does not depend on an external classical time? (iii) In what way can the resolution of these two problems assist in the construction of a quantum theory of gravity. (iv) What experiments can one propose to test these ideas?

The Universe is apparently undergoing an accelerated phase of expansion. In our group we investigate the possible origins of this surprising observation. Is the acceleration being caused by a cosmological constant term? If so, why is this constant non-zero and so much larger than its theoretically favoured value? Or is the acceleration only an apparent effect, caused by a local inhomogenous distribution of matter? We also carry out research on some aspects of inflationary physics – in particular, how do the quantum density perturbations produced during inflation become classical? We also study whether a modified law of gravitation is a possible alternative to dark matter, for explaining flattened galaxy rotation curves.
Exoplanets to Gravitational Waves
Sourav Chatterjee, DAA, TIFR, Mumbai
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Research Highlights:
Research in my group spans a wide range, and many branches of astrophysics, all connected by gravitational dynamics. Astrophysical systems we study include exoplanet atmospheres, exoplanet orbits, dense star clusters, and black hole binaries. In my research group we routinely use advanced high-performance computing, and statistical and data analysis tools to explain a variety of questions in diverse branches of astrophysics.

Exoplanets:
1. How do exoplanets form and evolve?
2. How can we explain the extraordinary diversity of their observed structural and orbital configurations?
3. How do planet-planet and planet-planetesimal interactions shape the observed planet properties?
4. How does orbital dynamics affect exoplanet habitability?

Star Cluster Dynamics:
1. How do stars evolve in dense star clusters?
2. How and when did the dense and massive star clusters form?
3. How do they evolve?
4. What can we learn about the ~12 Gyr old history from today’s observed properties of the old globular clusters?
5. How does stellar dynamics affect the formation of a plethora of exotic stellar sources including blue stragglers, X-ray binaries, and pulsars in dense star clusters?

Astrophysics of Gravitational Waves:
1. How to form black hole binaries?
2. What can gravitational wave detections tell us about the astrophysical processes that create them?
3. What are the distinguishing properties of merging black hole binaries depending on their formation channel?