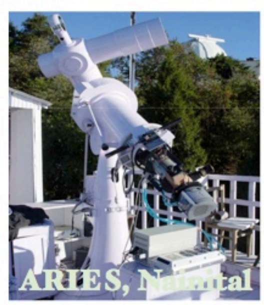
# SOLAR PHYSICS IN INDIA

*Recent and Current Research Activities*



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*Front Cover: Pictures of, (top row) Udaipur Solar Telescope, Kodaikanal Tunnel Telescope, (middle row), IIA Bangalore Campus, Ooty Radio Telescope, Gauribidanur Radio Telescope T array, (bottom row), NLST Site Characterization instruments at Pangong Lake, Merak Village, Ladakh, and 15 cm Tower Telescope at ARIES, Nainital.*

*Disclaimer: Though a fair attempt is made to collect recent and current research activities in solar physics in India, it is by no means an exhaustive and complete account of all solar physics that is done in India.*

# SOLAR PHYSICS IN INDIA

*Recent and Current Research Activities*

## Table of Contents

## 1. Indian Institute of Astrophysics (IIA)

Solar Physics has been the longest pursued discipline at IIA, which remains as the largest centre in the country, in terms of manpower as well as research infrastructure in the form of observational facilities and field stations, supporting almost all aspects of modern solar physics. Solar physicists at IIA have carried out theoretical and observational research using the Institute's own facilities (see *Section 1.d*) as well as a host of ground- and space-based international facilities like SOHO,TRACE, HINODE etc., have contributed and kept pace with recent revolutionary advances in this field.

*The Indian Institute of Astrophysics Campus, Bangalore*

The Institute is currently planning ambitious observational facilities, both on ground (the National Large Solar Telescope) and in space (Visible Emission Line Space Coronagraph), in partnership with several other Indian institutions and the Indian Space Research Organisation (ISRO). These initiatives have taken several years of planning and field work in the recent past resulting in concrete developmental activities, including a formal Government approval to build a space coronagraph to study the solar corona and a detailed concept study and proposal for a ground based National Large Solar Telescope (NLST).

Solar physics at IIA has covered almost all major branches of current research in this field and could broadly be collected under three major areas: I. Magnetic Fields, II. Large Scale Convection, Rotation and the Solar Cycle, III. Corona and Solar Wind.

## a. Magnetic Fields

*Faculty: D. Banerjee, S.S. Hasan, K.M. Hiremath, R. Kariyappa, S.P. Rajaguru, K.P. Raju, K.E. Rangarajan, B. Ravindra, J. Singh. Post-Docs: Vigeesh, G., Ph.D.Students: Girjesh Gupta, Chandrasekhar, K.C.*

At IIA, while theoretical and numerical studies, with inputs from observations, have focussed largely on the small-scale magnetic structures (in the photosphere and chromosphere), observational studies, exploiting data from Kodaikanal Observatory as well as from various external sources (especially the spaceborne observatories SOHO and Hinode), have focussed on the dynamics of a whole range of structures, from sunspots in the photosphere to various upper atmospheric structures (x-ray bright points, plumes, loops, coronal holes, etc.).

*Local Helioseismology and Waves in the Atmosphere*

The study of waves in the solar interior and atmosphere, and the associated dynamics has been a very rich and important area of research. A detailed analysis of the influence of active region magnetic field on the resonant p modes of solar interior has been done (1.a.1). A time-distance helioseismological study of a sunspot using imaging spectropolarimetric observations has led to resolving contributions from the atmospheric layers while inferring subsurface conditions (1.a.2). Current research in this field at IIA involves exploiting the data from HMI/SDO for sunspot seismology, and for studies of the solar tachocline.

*Dynamics, oscillatory phenomena and heating*

The rich spectrum of waves that the magnetic fields excite through their interaction with the turbulent convection in the photospheric layers lead to a variety of oscillatory phenomena in the overlying atmosphere. Several interesting results concerning the excitation, propagation and mode transformations of magnetohydrodynamic waves in the magnetic network that permeates the photospheric and chromospheric layers have been obtained (1.a.3; 1.a.4). This line of research has progressed to performing 2-D MHD simulations that include studying and identifying the viable wave heating mechanisms in the chromosphere (1.a.5). Detailed explanations for the photospheric magnetic field strength and size (flux) distribution of small-scale flux concentrations were obtained from a study of the magneto-convective instability (1.a.6), and an examination of this instability in the stellar parameter space followed (1.a.7).

Observationally, oscillations in the upper chromospheric and transition regions overlying sunspots and open field network regions have been studied extensively using data from space instruments, SUMER and CDS onboard SOHO and EIS/Hinode. Observations of wave propagation in polar coronal holes, which are permeated by the open field lines of the largely unipolar magnetic network, using SUMER/SOHO and EIS/Hinode and a statistical study of wave dynamics have yielded some interesting inferences on the nature of waves and on the existence of Alfven waves in these regions (1.a.8; 1.a.9). Oscillatory signatures in intensity measurements of the upper chromospheric bright points and coronal X-ray bright points have been analysed using data from Hinode/XRT.

*Sunspots and Activity*

Daily photographic observations of the Sun in white light continuum, CaII K emission and in H-alpha, the latter in form of spectroheliograms, have gone on continuously since 1905 at the Kodaikanal Solar Observatory. Starting from the late 1980's this photographic plate records have been upgraded to digital (CCD) records. The earlier historic records together with the modern ones form the longest continuous record of sunspots and activity available to us, and hence comprise an invaluable treasure of data to study long term variations in sunspots and various aspects of solar activity. Based on an earlier limited digitisation of the photographic white light images from Kodaikanal, several interesting results concerning sunspots and associated dynamics of the solar convection zone have been obtained: measurements of sunspot size and tilt angle variations (1.a.10), and a study of subsurface dynamics of sunspot producing flux tubes through their tilt angle relaxation on the surface (1.a.11).

Based on space data, largely from SUMER/SOHO, small scale transition region dynamics (1.a.12) and high velocity explosive events related to macro-spicules have been studied.

## b. Large scale convection, rotation and the solar cycle

*Faculty: K.M. Hiremath, J.Javaraiah, R. Kariyappa, S. Muneer, K.P. Raju, K.B. Ramesh, J. Singh, K. Sundara Raman (K.R. Sivaraman), Post-Doc: Neeharika Sinha*

Studies of the large scale solar interior convection and rotation have exclusively been based on observational data. Using a combination of Kodaikanal Ca II K spectroheliogram data and SOHO/MDI Dopplergram data, several studies of the supergranular convective cells have been carried out. The supergranular size distribution (1.b.1) and its dependence on activity and the magnetic network (1.b.2) have been two such interesting results.

A series of papers containing important results on the solar differential rotation, its depth dependence and meridional flow have been written based on Kodaikanal, Greenwich and Mt.Wilson sunspot data (1.b.3; 1.b.4; 1.b.5).

More than 100 years of data on sunspots (white light images) and magnetic network (Ca II K spectroheliograms), which went through a sparse low resolution digitisation, have been used in analysing the long term variations in the solar rotation (1.b.6), solar activity cycles and dynamics of polar magnetic fields (1.b.7; 1.b.8). They have also been used in studies of completely data-based predictions of amplitudes of solar activity cycles (1.b.9; 1.b.10). Comparative studies of historic data sets on Ca II K emission, viz. the Kodaikanal, Mt. Wilson and Arcetri Observatory data sets, have been carried out (1.b.11) and their implications for solar UV driving of Earth's climate have also been analysed (1.b.12).

## c. Corona and Solar Wind

*Faculty: S.P. Bagare, D. Banerjee, S.S. Hasan, R. Kariyappa, C. Kathiravan, S. Muneer, A.S. Narayanan, K.P. Raju, K.B. Ramesh, R. Ramesh, J. Singh , B.A. Varghese, Ph.D. Student: Krishna Prasad*

At IIA, a large fraction of work on the solar corona in the past decade has focussed on spectroscopic studies of the corona, especially in the bright emission lines in the visible and near-infrared regions of the spectrum (1.c.1 ; 1.c.2; 1.c.3). These studies have focussed on addressing the source of non-thermal velocities and the associated heating of the solar corona through measurements of spectral line widths, line depths and Doppler shifts. Identifying and assessing the contributions of wave dynamical phenomena to these spectral measurements has formed a major line of inquiry. These spectroscopic observations have largely used the 25-cm coronograph at the Norikura Solar Observatory, Japan. Coronal waves have been detected in the Doppler velocity data with frequencies in the 1-3 mHz range, and also in higher frequencies (5-7 mHz) at localized regions. There have also been studies of the solar corona through imaging in the bright green and red emission lines during the 2006 and 2009 total solar eclipses and signatures of waves have been detected and studied (1.c.4).

Dynamics of plasma in polar coronal holes and in polar off-limb regions has been studied using SOHO/CDS and SUMER observations (1.c.5; 1.c.6). These spectroscopic studies have yielded an assessment of background physical conditions as well as an understanding of transient dynamical phenomena in these regions. These results have implications for the coronal heating and the acceleration of the solar wind.

Study of the long wavelength (metre and decameter) radio emission from the solar corona, through imaging at these wavelengths using the Gauribidanur radioheliograph, has been a unique and significant area of research in the study of solar eruptive events (e.g. flares, prominence eruptions and CME's). Several aspects on the time and frequency structures of various kinds of radio bursts in the meter-decameter wave band and the imaging of CMEs have been studied. Estimation of physical quantities such as density, temperature and magnetic field of the emitting plasma in the eruptive coronal structures during their various evolutionary stages is the main aim of these studies (1.c.7, 1.c.8). Several results concerning the temporal and frequency characteristics of Type I and Type II radio bursts have been obtained and association of these bursts with M and X class flares and CME's have been studied.

## d. Research and Instrumentation Facilities

*Kodaikanal Solar Observatory*

The Kodaikanal Observatory is located in the Palani range of hills in Tamilnadu at a latitude of 10$^{o}$ 13' 50'', Longitude 77$^{o}$ 28' 07'' and altitude : 2343m, and has the following facilities for Solar and Solar-Terrestrial studies.

*i. Solar Tunnel Telescope*

*The Solar Tower Tunnel Telescope at Kodaikanal*

The solar tower telescope consists of a Grubb Parson 60 cm diameter two-mirror fused quartz coelostat mounted on 11 m tower platform that directs sunlight via a flat mirror into a 60m long underground horizontal `tunnel'. A 38 cm aperture f/90 achromat forms a 34 cm diameter solar image at the focal plane at a resolution of 5.5 arcsec/mm. The telescope has an option to mount a 20 cm achromat providing an f/90 beam to form a 17 cm image. The telescope is primarily used for high spatial and spectral resolution work. A Littrow-type spectrograph and a spectroheliograph are the main instruments available.

*Main Spectrograph*

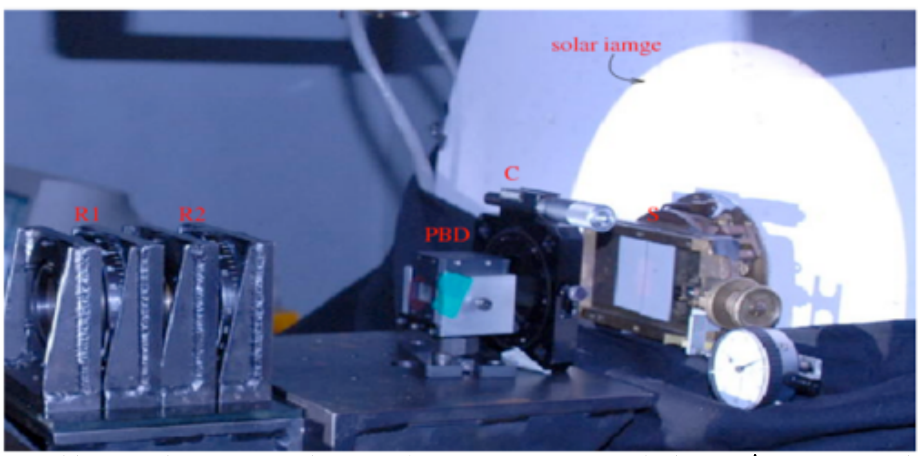
The Littrow-type spectrograph with a 600 lines/mm grating gives 9 mm/A dispersion in the fifth order. Together with the 5.5 arcsec/mm spatial resolution of the image, it forms a high resolution set up for solar spectroscopy. Spectra are recorded on a Photometrix 1k x 1k CCD system. A large format CCD system is being procured to enhance the coverage of spectrum especially for the broad resonance lines and the nearby continuum.

*The Littrow-type spectrograph on the Solar Tunnel Telescope*

*Spectroheliograph*

The converging solar beam from the objective can be diverted to a high-dispersion spectroheliograph with Littrow arrangement using a 3.43m achromat. The photographic camera behind the second slit is being replaced by a Reticon linear array and a data acquisition system.

*Dual-beam Spectropolarimeter*




*The Dual beam polarimeter. C: linear polariser; S: spectrograph slit; R1 & R2: wave plates*

The Tower Telescope has a dual beam polarimeter which uses a linear polariser ('C' in the photograph) to compensate the differential response of the spectrograph grating to orthogonally polarised beams. The polarisation modulation is done using two wave plates, the first of which acts as a quarter wave plate (R1) and another which acts a half wave plate (R2) at 630 nm. The spectropolarimeter uses a polarizing beam displacer (PBD) as the polarisation analyzer which.splits the input light into two orthogonally polarised beams which propagate parallel to each other at the end of the PBD. Thus spurious polarisation introduced due to intensity fluctuations are reduced compared to single beam polarimetry.

### *ii. Photoheliograph*

A 15 cm aperture English mounted refractor by Lerebour and Secretan, acquired in 1850 and remodelled by Grubb in 1898 to serve as a photoheliograph, is in use since the beginning of this century to obtain 20 cm white light pictures of the Sun on a daily basis. These images are being used to study solar activity and solar rotation using sunspots as tracers.

### *iii. Spectroheliograph*

Twin spectroheliographs giving 6 cm diameter full disc photographs of the Sun in Calcium K and Hα lines are in regular use. A 46 cm diameter Foucault siderostat feeds light to a 30 cm aperture f/22, Cooke triplet lens. The two prism K spectroheliographs were acquired in 1904 and the Hα grating spectroheliograph was operational in 1911. Since 1912, prominent pictures over the full limb are also being obtained in K by blocking the solar disc.

### *iv. Ca K Heliograph*

Light from the 46 cm siderostat is diverted to a 15 cm Zeiss achromat objective which provides an f/15 beam and a 2 cm image. A prefilter and a daystar Ca K narrow band filter are used together with a Photometrix 1k x 1k CCD to record the K filtergram. Regular observations started in 1996-97. Besides synoptic observations, temporal sequences are being obtained.

### *v. Instrumentation for Solar-Terrestrial Studies*

Facilities for work on solar-terrestrial relations include: (1) a IPS-42 digital ionosonde for round the clock monitoring of the ionosphere, (2) a digital DMI fluxgate magnetometer to measure the geomagnetic field with high time resolution (1 min) and sesitivity (1 nT) and (3) an HF Doppler radar to monitor the small scale ionospheric vertical plasma motions with high sensitivity (tens of metres) and good time resolution (6 sec) associated with a variety of geophysical phenomena.

*i. Gauribidanur Telescope (GEETEE)*

Since 1976, the Institute operates a decametre wave radio telescope (GEETEE) jointly with the Raman Research Institute at Gauribidanur (Latitude:13.60° N; Longitude:77.44° E), about 100 km north of Bangalore. The telescope consists of 1000 dipoles arranged in a 'T' configuration, with a 1.4 km East-West arm and a 0.5 km South arm. It has been engaged in the study of radio waves at 34.5 MHz emanating from Sun and various other diverse objects in the sky. The most notable observations with the array till date are: (i) first two-dimensional images of radio emission from slowly varying discrete sources in the outer solar corona, (ii) all-sky survey of radio sources at 34.5 MHz in the declination range -30° S to 60° N, and (iii) low frequency carbon recombination lines in astrophysical sources.

*ii. Gauribidanur Radioheliograph (GRH)*

A radioheliograph for obtaining two dimensional pictures of the outer solar corona simultaneously at different frequencies in the range 40-150 MHz is also functional here since 1997. The basic receiving element used is a log-periodic dipole and the array consists 192 of them. The dipoles are arranged in a 'T' configuration similar to the GEETEE.The present spatial and temporal resolution of the instrument are 5 arc min and 256 ms, respectively. A 1024-channel digital correlator is used as back end receiver to extract the strength and positional information of radio emission from the solar corona and the various discrete structures there. The frequency coverage of GRH is unique that it provides useful information on the solar corona in the height range ~0.2-0.8$R_{sun}$ (above the solar surface), which is difficult to probe using ground based and space borne white light coronagraphs. No other radio telescopes are presently operational in the above frequency range, anywhere in the world. Some of the notable observations with GRH till date are: (i) density/temperature diagnostics of pre-event structure of a CME, (ii) velocity/acceleration of a CME close to the solar surface, (iii) `true' speed of a CME in the three-dimensional space, (iv) estimation of the parameters of a CME at ~40 $R_{sun}$ from the Sun through angular broadening observations of a distant cosmic radio source, (v) seismology of the solar corona using radio burst emission as tracers, (vi) coronal electron density gradient in the ~0.2-0.8 $R_{sun}$ height range above the solar surface, and (vii) plasma characteristics of radio emission associated with emerging magnetic flux from sub-surface layers of the solar photosphere.

*iii. High-Resolution Radio Spectrograph*

A high resolution radio spectrograph is used in conjunction with the GRH for obtaining dynamic spectrum of transient burst emission from the solar corona. The antenna system consists of 8 log periodic dipoles. A commercial spectrum analyzer is used as the back end receiver to obtain spectral information with an instantaneous bandwidth of ~250 KHz. The temporal resolution is ~43 ms. The radio spectrograph and GRH together provide spectral and positional information on eruptive solar activity, again an unique combination. The observations so far have provided clues to: (i) electron acceleration associated with small scale non-thermal energy releases in the solar atmosphere, (ii) occurrence of radio bursts associated with successive magneto hydrodynamic shocks in the solar corona, and (iii) source region of a CME through observations of transient `absorption' bursts.

*iv. Polarisation Interferometer*

Based on theoretical formulations for the response of a correlation telescope to polarised radiation, an east-west one-dimensional array of 32 log periodic dipoles have been set up to probe the coronal magnetic field in the height range ~0.2-0.8 $R_{sun}$, above the solar surface. The dipoles are arranged as 4 groups and they are oriented at 0°, 45° , 90° & 135° with respect to the terrestrial north. The idea is to get information on the coronal magnetic field through observations  of circularly polarised radio emission of circularly polarised radio emission from discrete

*Antennae in the polarization array*

sources in the corona. The spectral dependence of the observed emission in the above height range can also be obtained through multi-frequency observations.

*MGK Menon Laboratory for Space Sciences*

IIA has embarked on new challenging projects to build both ground-based and space-based observation platforms and instruments. Most of these efforts are towards developing  multi-wavelength capabilities both in solar and stellar astronomy. IIA is building a UV Imaging Telescope (UVIT) for the ASTROSAT mission of ISRO. IIA will also be building the Visible Line Space Solar Coronagraph for ISRO's Aditya-I Mission. All these space payloads require ultra-clean and state-of-the-art laboratory facility to build, test and calibrate. The MGK Menon Laboratory is designed and built as per International Organization for Standardization which has evolved standards and common definitions for different classes of cleanrooms. This has been widely accepted internationally, including various space missions.

*Radio Astronomy Instrumentation*

The scientists and engineers of the solar radio astronomy group at IIA are involved in the development of hardware and software for radio astronomical instrumentation. They are involved in the Brazilian Decimetre Array, being built by the Instituto Nacional Pesquisas Espacias (INPE), Brazil, for observations of Sun and various Galactic, extragalactic radio sources. IIA scientists have contributed to the array configuration design, software for data calibration and image synthesis. They have also designed and constructed the digital back end receiver for the telescope. In its present configuration, the array has 5 parabolic dish antennae of 4 m diameter each, set up as a one-dimensional array in the east-west direction. The frequency of operation is 1.6 GHz. The length of the longest baseline in the array is 216 m. The temporal and angular resolution are 100 ms and 1.5' respectively. The array is located at Cachoeira Paulista (Lat: 22.69° South; Long: 45.01° West).

IIA has also been involved in the Mauritius Radio Telescope, which is a large synthesis telescope operating at 151.5 MHz on the island of Mauritius (Lat: 20.14 South; Long: 57.74 East) and is in collaboration with the University of Mauritius and Raman Research Institute.

## e. Upcoming Facilities

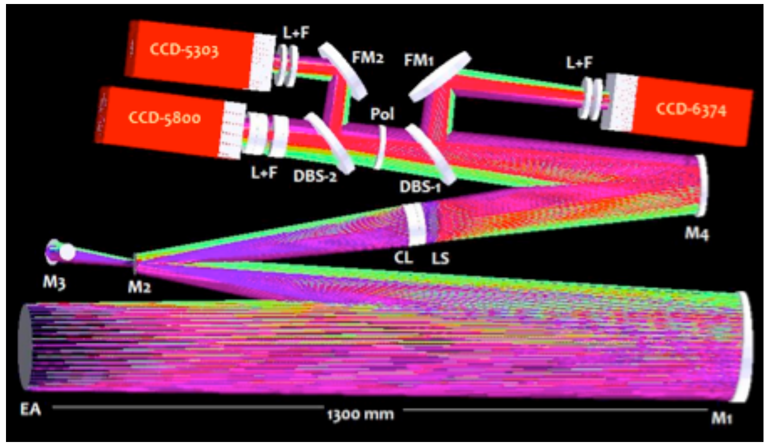
*Kodaikanal 100-years Data Digitisation Programme*

A set of digitisers has been installed at Kodaikanal Observatory to digitise the photoheliograms, Ca+K and Hα spectroheliograms of the Sun that have been obtained at the obsevatory nearly everyday from 1904 onwards on photographic plates. A 4Kx4K CCD cameral with a pixel size of 15μ and a 4-port readout at 500kHz is being used. There are 44,000 white-light images, 41,000 Ca K images, 38,000 Hα images and 34,000 prominence images being digitised. It is intended to make this database world-wide web enabled.

*Visible Emission Line Space Coronograph - Aditya*

IIA is leading a consortium that has proposed to build a 20cm aperture, space-based coronagraph to image the solar corona in various optical emission lines (1.e.1). The coronagraph is proposed to have an off-axis parabolic mirror which simultaneously images the visible emission lines at 5303 Å [Fe xiv] and at red [Fe x] 6374 Å.

The primary science goals are: (i) detect the existence of waves in the solar corona and the nature of waves, (ii) investigate the role of waves in heating the solar coronal plasma, (iii) understand the formation of coronal loops, (iv) understand the magnetic nature of coronal loops, (v) understand the cooling of post flare loops, (vi) investigate the pre-eruption dynamics of CMEs in detail, and (vii) investigate CMEs role in driving the space weather.




*Optical path diagram of Aditya*

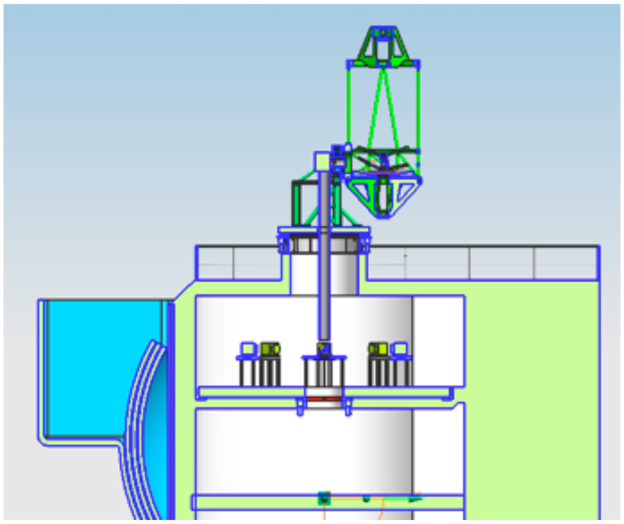
## f. New Initiatives

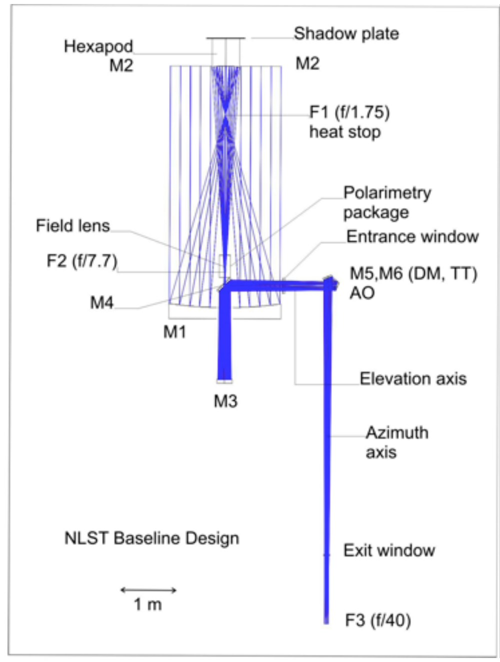
*National Large Solar Telescope (NLST)*

IIA has proposed to set up a state-of-the-art 2m-class telescope – the National Large Solar Telescope (NLST)(1.f.1), incorporating adaptive optics, for carrying out optical and near-IR observations from a suitable site in the country. Sites in the Himalayan region (about 4000 metres above mean sea level) which are not affected by the monsoons are being considered, with a preference for high altitude desert sites. Site characterization is currently in progress to monitor clear sunshine hours, good day-time seeing conditions and other parameters, at Hanle and Pangong Lake in Ladakh, and Devasthal in Uttarakhand state.

**Specifications:**

| | |
|---|---|
| **Aperture** | 2m |
| **Focal Ratio** | F/2 |
| **Configuration** | Gregorian, on-axis |
| **Aberration-free field of view** | 300 arcsec |
| **Wavelength range to be covered** | 380 nm – 2.5 microns |
| **Spatial Resolution** | <0.1arcsec at 500nm |
| **Strehl Ratio within the isoplanatic patch** | >0.5 |






The NLST is proposed to be a multi-purpose telescope, equipped with instruments such as: (i) a spectrograph operating in the Czerny- Turner mode for spectro-polarimetry, (ii) a high resolution spectrograph for simultaneous multi- line spectroscopy, (iii) a tunable Fabry - Perot filter of pass band 0.02 nm, (iv) narrow pass band filters for H – alpha , Ca II K , CN band , G band and 1083.0 nm. The detailed project report of the NLST has been completed and submitted to the Govt of India for approval.

## 2. Physical Research Laboratory/Udaipur Solar Observatory

The Physical Research Laboratory, a Unit of the Department of Space, Government of India, has research teams under its Astronomy and Astrophysics division (at Ahmedabad) and the Udaipur Solar Observatory working on a wide range of topics in solar physics.

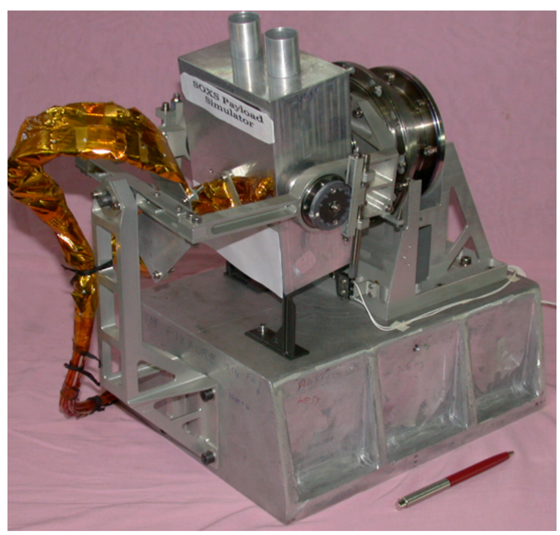
### a. Solar Radio Astronomy (PRL/Ahmedabad)

*Faculty: Hari Om Vats, P. Janardhan. Ph.D. Students: Susanta Kumar Bisoi*

Members of this group focus on space weather studies involving Interplanetary Scintillations (IPS)(2.a.1), solar flare activity and coronal mass ejections(2.a.2,2.a.3), and studies on pulsar bursting phenomena. Investigations of solar atmospheric (coronal) differential rotation to examine possible connections with photospheric differential rotation have formed part of recent activities (2.a.4).

### b. Solar X-ray Astronomy (PRL/Ahmedabad)

*Faculty: Rajmal Jain*




*The Solar X-ray Spectrometer (SOXS)*

Studies of high resolution X-ray spectra of solar flares in the energy range 4-20 keV observed by Solar X-ray Spectrometer (SOXS), a low energy detector payload of PRL onboard GSAT-2, have been the highlights of this group at PRL. The specific science goals have involved: (i) emission characteristics of Fe and Fe/Ni line features (2.b.1), (ii) energy release and particle acceleration in solar flares, (iii) thermal/non-thermal nature of solar flares, (iv) low energy cut-off as function of flare duration to determine the nature of X-ray photons that varying over time, (v) contribution of micro flares in heating the solar corona, (vi) short and long term variation of the solar corona, and (vii) Sun-Earth connection and space weather (2.b.1,2.b.2)

## c. Udaipur Solar Observatory (USO)

Udaipur Solar Observatory (USO) has been involved in the study of the Sun with a central theme of `solar activity and eruptive processes'. The contiguous number of clear days is very large, thereby allowing a long time monitoring of solar activity. USO has also benfited academically by hosting one of the Global Oscillation Network Group (GONG) instrument. A combination of analyses of archived data, mathematical modeling and construction of sophisticated instruments is employed to achieve the desired goals.

*Helioseismology*

*Faculty: A. Ambastha, P. Venkatakrishnan, S. Gosain, Brijesh Kumar. Post-Docs: Ram Ajor Maurya*

Helioseismology at USO commenced with the installation of one of the 6 telescopes of the GONG in 1996. It is used as a tool to monitor pressure impulses generated by eruptions as well as the physical dynamics beneath the active region producing the eruptions. Recent results from USO have shown the possibility of using the acoustic spectrum of the Sun as a new diagnostic tool for probing solar activity mechanisms (2.c.1 - 5).

Modulation of p-mode parameters with, (i) solar cycle, (ii) magnetic flux, (iii) magnetic field inclination, and (iv) eruptive phenomena are studied. Local helioseismic inferences on sub-surface flow and its evolution beneath flare productive active regions have yielded interesting results. Clarity on proper motions of "acoustic sources" associated with a major flare was provided with the detection of "Doppler ribbons" evolving co-spatially with H-alpha ribbons. Discovery of flare induced high frequency power enhancement in global waves.

*Dynamics of Magnetic Fields on the Surface and Above*

*Faculty: R. Bhattacharrya, S. Gosain, B. Joshi, S.K. Mathew, P. Venkatakrishnan. Post-Docs: S.K. Tiwari, R.E. Louis. Ph.D. Students: A. Joshi, V.R. Panditi.*

Photospheric magnetic fields are measured to monitor magnetic energy storage and evolution of the stresses leading up to the eruptions. Measurement of magnetic shear in flare productive active regions was a longstanding activity of USO and continues to this day (2.c.6-7). The prospects for detailed monitoring has increased with the development of a solar vector magnetograph at USO and will further increase after installation of the new 50 cm aperture Multi Application Solar Telescope (MAST) in 2011. A new parameter, Spatially Averaged Signed Shear Angle (SASSA) has been proposed which gives clear predictive capability of the flare severity (2.c.8). Apart from this focus on flare physics, the fine structure of sunspot magnetic field has also been studied most recently using data from HINODE leading to the discovery of: (i) zero net current in sunspots with global twist implying fibril bundle structure of sunspot magnetic field (2.c.9), (ii) curly interlocking combed structure of penumbral fields, and (iii) supersonic downflows in sunspot light bridges (2.c.10).

*Space Weather*

*Faculty: N. Srivastava, P. Venkatakrishnan*

The prediction of solar eruptions is a distant goal for which basic research on eruption mechanisms can be enhanced using multi-wavelength studies, e.g. with SOXS, GMRT and, in the future, MAST. Near future goal is to link the parameters of solar phenomena to the severity of space weather events (2.c.11-13), e.g., (i) the CME speed near Sun is proportional to the magnetic energy of the active region implying a magnetic blast, and (ii) CME speed is also a good predictor for severity of resulting geomagnetic storm and for estimating the arrival time of the IP shock. A prediction algorithm using the available data base from a variety of satellites is being developed. STEREO data shows that earlier single satellite results under-estimate the CME speed (2.c.14-15)

## d. Research Facilities and Instruments

*Faculty: Raja Bayanna, S. Gosain, S.K. Mathew, P. Venkatakrishnan*

*Full Disk H-alpha Telescope*

A 6-foot Razdow telescope, with a 15-cm aperture lens, takes full disk H-alpha synoptic observations of solar activity. For real time monitoring CCD cameras, monitors and a digital image acquistion and processing system have been commissioned.

*H-alpha Spar Telescope*

A 12-foot solar spar with 25-cm aperture telescope is being used for observing small high resolution chromospheric structures with the help of a narrow passband Halle-birefringent filter centered at 6563A H-alpha spectral line.

*Solar Vector Magnetograph*

A Solar Vector Magnetograph (SVM) was developed in-house and installed at the Island site of USO. The magnetograph is basically an imaging spectropolarimeter, which consists of a Schmidt-Cassegrain telescope of 20 cm aperture and a state-of-the-art tunable filter. This filter is designed using an air-gap servo-controlled peizo-tuned Fabry-Perot etalon procured from M/s IC Optical Systems, UK. This Fabry-Perot etalon together with an order-sorting interference filter acts as a spectrometer. The polarimeter consists of two rotatable quartz-waveplates (quarter-wave plates) and Savart plate. The dual output beams from the Savart plate are imaged simultaneously onto a single CCD chip which helps in minimizing the seeing induced errors in polarimetry. Further, the entire optical train is mounted on a German Equatorial mount which directly points and tracks the Sun. Also, the straight (no oblique reflections) and symmetric optical design ensures minimal instrumental polarization. The Fe I 630.25 nm line is used for spectropolarimetry. The instrument became operational in February 2007.

*Coude Telescope*

A 15-cm Zeiss Coude telescope is being operated for feeding light into the Adaptive Optics (AO) lab of USO. The advantage of this telescope is that it tracks the Sun and feeds the solar beam to the sensitive optical arrangement for AO experiment placed on a stationary platform.

*GONG Telescope*

A milestone was added to USO's history in October 1995, when it appeared on the world map as an important link in the international project GONG. USO was selected owing to its excellent observing and sky conditions, as found by the GONG site evaluation which was started in 1986 at USO, along with 15 contending observatories around the world. The GONG system was further upgraded in 2001. The other five sites selected under GONG are located at the Canary islands (Spain), CTIO (Chile), Big Bear (USA), Hawaii (USA), and Learmonth (Australia), for a near continuous 24 hour solar coverage with the aim of probing the solar interior. A sophisticated, 1.5 million dollar, state-of-the-art instrument has been installed at Udaipur under this project. It monitors the Sun automatically, and takes digital velocity images of the sun every minute. The USO data is then combined with the data obtained from other five sites at the central facility located at National Solar Observatory, Tucson, USA. The GONG project promises to unravel several fundamental problems of solar interior and general astrophysics.

### e. Upcoming Facilities

*Multi Application Solar Telescope (MAST)*

With its well recognised strengths in terms of expertise in solar observational studies, a conducive site with a large number of contiguous clear days and a location (site longitude) advantage enabling synoptic coverage of solar phenomena, USO has embarked on building a

Multi Application Solar Telescope (MAST) that will enable focussed studies on high angular resolution, solar polarimetry and mechanisms of solar variability. MAST will have an entrance clear aperture of 50 cm diameter, field of view of 6 arcmin, output wavefront error (at λ=633 nm) of λ/12 rms on-axis and λ/10 rms over field of view, less than 0.01 arcsec per minute image stationarity in output beam and a total transmission of more than 50% (in wavelength range from 400 - 900 nm). The mechanical assembly is an altitude over azimuth mechanical configuration, with azimuth limits of 65 - 295 deg (reckoned from North in the sense NESW) and altitude limits of 5 - 88.5 deg (reckoned from the horizon).

MAST will have Adaptive Optics built in-house, and a prototype has been tested at USO with a first lock on May 15, 2010. The system specifications of the AO: tip-tilt system for global tilt correction CMOS camera (1500 fps), piezo actuator tilt stage, Shack-Hartmann wavefront sensing with 21 sub-apertures, CCD camera, 950 fps membrane mirror (corrector) and 19 actuators.

*MAST at the factory site (ETA at USO: June 2011*

## 3. Tata Institute of Fundamental Research (TIFR)

Solar physics at TIFR has had a very distinguished tradition both in theoretical and experimental research. Early work on theoretical and computational studies of solar convection and oscillations paved the way for an opportune entry into helioseismology in the early 90's and the work by the team of S.M. Chitre, H.M. Antia and Sarbani Basu led to numerous seminal contributions (3.1,3.2), which continue to this day. The Radio Astronomical facilities of TIFR, viz. the Ooty Radio Telescope (ORT) and the Giant Meterwave Radio Telescope (GMRT) near Pune, have research teams exploring the solar corona, CME's, solar wind and the interplanetary space.

### *a. Helioseismology*

*Faculty: H.M. Antia, S.M. Chitre (currently at University of Mumbai)*

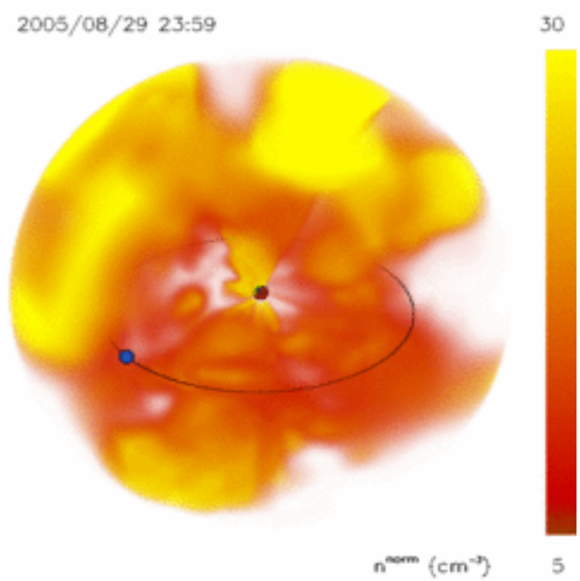
The work on helioseismology has provided accurate knowledge of structure and dynamics of the Sun (3.a.1-6). Current research continues to focus on refining the knowledge on the interior structure and dynamics of the Sun, with special emphasis on unravelling the temporal variations over the solar cycle time scales (3.a.7-8), especially in the deep layers of the convection zone and the tachocline (3.a.9), exploiting long data sets available from GONG and SOHO/MDI as well as those from the recent space mission SDO/HMI.

### *b. Solar Radio Astronomy*

*Faculty: S. Ananthakrishnan, P.K. Manoharan*

*i. Solar Wind and Interplanetary Scintillation*

A new technique developed at Ooty to study the interplanetary scintillation observations (3.b.1) provides valuable information about the solar wind and solar-wind magnetic storms that affect the near-Earth environment. Studies at ORT also involve analyses of contemporary multi-wavelength data from various space missions to understand the initiation processes of CMEs, especially observational signatures of magnetic reconnection, high energy particle acceleration at the initial stages and their propagation in the inner heliosphere (3.b.2-3). Ooty scintillation measurements are also used in identifying and understanding the evolution of disturbances caused by powerful CME events in the Sun-Earth distance and forecasting the arrival of such large events at the near-Earth space (3.b.4). Ooty measurements have been successfully employed to track CMEs from Sun to Earth distance and they have elucidated the evolution of the 3-D structure and speed of CMEs in the inner heliosphere (3.b.5-6). Interplanetary scintillation observations also provide a valuable database to understand the Space Weather changes and its predictability.




*3-D Heliosphere: reconstruction using ORT IPS Data*

ii. *Radio Observations of the Sun and Solar Wind Using GMRT*

Radio imaging of noise storm sources in the solar corona obtained by combining GMRT and Nancay Radio-Heliograph visibilities achieve a resolution of 49" and dynamic ranges between 250-320 MHz (3.b.7). GMRT has also been used, in combination with soft X-ray light curves from GOES 10 satellite, in making simultaneous radio 'light curve' tat 1060 MHz. These radio observations using GMRT help in understanding several physical processes in flare dynamics and propagation (3.b.8).

## c. Observational Facilities

### *i. Ooty Radio Telescope*

The Ooty Radio Telescope is a cylindrical paraboloid of reflecting surface, 530 m long and 30 m wide, placed on a hill whose slope of about 11 degree in the north-south direction which is the same as the latitude of the location of ORT. This makes it possible to track celestial objects for about 10 hours continously from their rising in east to their setting in the west by simply rotating the antenna mechanically along its long axis. The antenna beam can be steered in the north-south direction by electronic phasing of the 1056 dipoles placed along the focal line of the reflector. The reflecting surface is made up of 1100 thin stainless steel wires, each 530 m long. It is supported by 24 parabolic frames separated by 23 m from each other.

The telescope is operated at 327 MHz (a wavelength of 0.92 m) with 15 MHz usable bandwidth. The large size of the telescope makes it highly sensitive. As an example, it is in principle capable of detecting signals from a mere 1 watt radio station located ten million kilo meter away in space. An array of 1056 half-wave dipoles in front of a 90 degrees corner reflector forms the primary feed of the telescope. The front-end receiver system of the ORT was upgraded with a low noise amplifier (Tex = 50 K) and a strip line diode-switch controlled phase shifter following each of the 1056 dipoles. This up-gradation improved the sensitivity of the ORT substantially. Backends:  Analog Correlator - Used for IPS observations and new Digital Backend System. Ongoing Projects: IPS observations, pulsar observations and spectral line observations

The ORT has been designed and fabricated fully indigenously. The ORT completed in 1970 and continues to be one of the most sensitive radio telescopes in the world. Observations made using this telescope have led to important discoveries and to explain various phenomena occurring in our Solar system and in other celestial bodies.

*ii. Giant Meterwave Radio Telescope*

National Center for Radio-Astrophysics (NCRA), a centre under TIFR, built GMRT, which has been a unique facility for radio astronomical research in the metre wavelengths range of the radio spectrum. It is located at a site about 80 km north of Pune. GMRT consists of 30 fully steerable gigantic parabolic dishes of 45m diameter each spread over distances of upto 25 km. The array can operate in six frequency bands centred around 50, 153, 233, 325, 610 and 1420 MHz. All these feeds provide dual polarization outputs. In some configurations, dual-frequency observations are possible. The highest angular resolution achievable ranges from about 60 arcsec at the lowest frequencies to about 2 arcsec at 1.4 GHz.

GMRT is a very versatile instrument for investigating a variety of radio astrophysical problems ranging from our nearby Sun and the solar system to the edge of the observable Universe. The research goals include studies of the solar and planetary radio emissions, relationship between solar activity and disturbances in the interplanetary medium.

# 4. Indian Institute of Science (IISc)

## a. Solar Magnetic Dynamo and Cycle - Theory and Modeling

*Faculty: A.R. Choudhuri (Dept. of Physics), Ph.D. Student: Bidya Karak (Dept. of Physics)*

The main research focus of this group at IISc is on understanding how the magnetic fields are generated and maintained on the Sun, i.e. understanding the solar dynamo, and modeling it so as to be able to predict in advance the amplitude, length and other observed characteristics. This is achieved by realistic inputs, based on helioseismic observations, of interior rotation and meridional circulation (4.a. 1-3), to kinematic dynamo models. This is important, in turn, to understand the origin and nature of solar variability in terms of various eruptive and energetic phenomena that control the space weather.

Much of the current research of this group is focussed on understanding various physical processes associated with flux transport and diffusion mechanisms (the Babcock-Leighton processes), and their observational consequences. Consequences of adding stochastic or random fluctuations in the above processes and studying their relevance for various observational features of solar cycle, such as Waldmeier effect, prolonged minima (e.g. Maunder minimum) are being modeled (4.a.4-5).

# 5. Aryabhatta Institute of Observational Sciences (ARIES)

## a. Magnetic Activity and Eruptive Phenomena

*Faculty: A.K. Srivastava, Wahab Uddin Ph.D. Student: Pankaj Kumar*

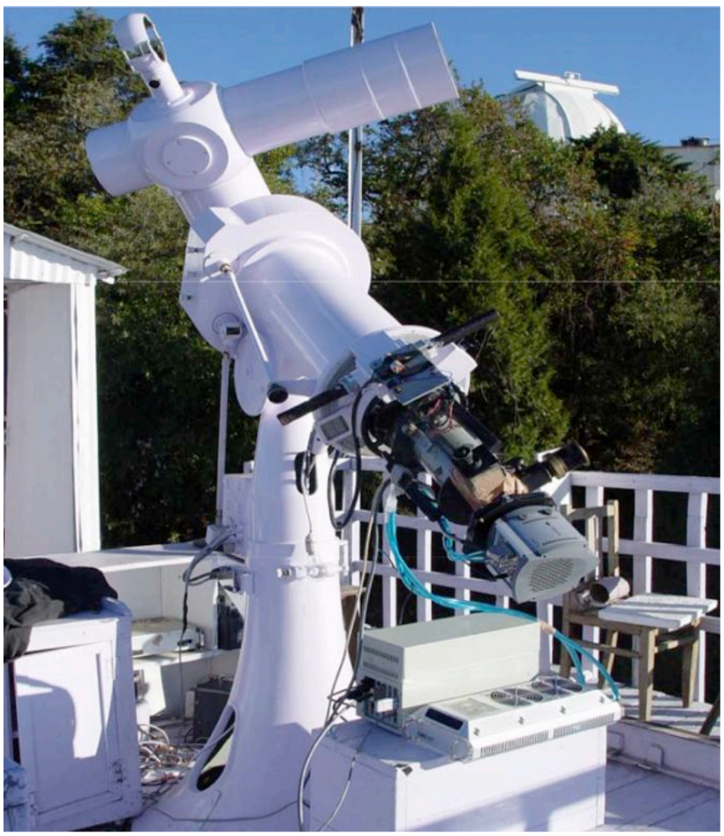
A group of solar physicists is pursuing research in the following areas: sola spectroscopy, energy transport through solar atmosphere, solar flares, MHD oscillations studies of prominences and filaments, studies of solar surges, studies of effects of solar flares on the Earth's ionosphere and total solar eclipses (5.a.1-3).

Observational studies of the leakage of acoustic oscillations into the upper atmosphere and their mode coupling and energy transport with other MHD modes (5.a.4-6) have formed a significant area of research at ARIES. This line of research, expanding into studying the various energetic transient induced oscillations to probe the physical conditions and processes (MHD seismology), currrently forms a major research activity at ARIES.

The solar physicists at ARIES are also involved in various national and international projects.

## b. Observational Facilities

*15 cm Solar Tower Telescope*



This telescope with a H-alpha filter is currently being used to study the evolution of the solar flares, particulary the large and energetic X class flares (5.b.1-2)

## 6. Indian Space Research Organisation (ISRO)

### *a. Space Physics and Instrumentation Division*

*Faculty: K. Sankarasubramanian, P. Sreekumar,   Ph.D. Student: P. Sreejith*

Solar spectropolarimetry, using data from NSO (USA), USO (Udaipur) and Hinode, active region dynamics through magnetic field determination and high resolution studies are the main areas of research in this group (6.a.1-2). Solar instrumentaion, for ground as well as space based observations, forms a major interest of this group and is currently involved in the following three major projects:

(i) SOXS mission on-board GSAT-2
(ii) Analysis of the X-ray Solar Monitor (XSM) on-board Chandrayaan-I mission
(iii) Aditya-1 mission for solar coronal studies

This group is also involved in work towards new detector development for future solar and other astronomy missions (6.a.3). An example is the SoLEXS (Solar Low-energy X-ray Spectrometer).

## 7. Indian Institute of Science Education and Research (IISER)

### *a. IISER - Kolkata*

*Solar Physics and Sun-Earth System*

*Faculty: Dibyendu Nandi. Post-Doc: Andres Munoz-Jaramillo (Harvard-CfA). Ph.D. Student: Soumitra Hazra*

The group of D. Nandi focusses on research that spans both theoretical and observational aspect of solar physics and the Sun-Earth system. On the theoretical front, solar dynamo theory (7.a.1-2) and initiation mechanisms of coronal mass ejections, with the aim of developing data driven models that can serve as space weather forecasting tools, is being worked on. On the observational front, analysis and interpretation of vector magnetic field data with special emphasis on magnetic helicity and the role it plays in coronal heating and destabilization of magnetic flux tubes leading to flares and coronal mass ejections are done

(7.a.3). More recently, this group is also involved in understanding the effects of solar variability on planetary climates.

Major contributions of D. Nandi and his group are: (i) the role of meridional flows in determining the properties of the sunspot cycle (7.a.4-5), (ii) deciphering how competing flux transport processes, such as advection, turbulent diffusion and flux pumping control solar cycle memory, and thereby impact the predictability of the solar cycle, (iii) establishing the connection between helicity evolution, coronal heating and solar flaring activity, (iv) development of data driven models of coronal mass ejections, (v) the understanding of very long-term solar variability relevant for space climate (7.a.6)

### *b. IISER - Pune*

*Plasma Astrophysics and Solar Physics Group*

*Faculty: Prasad Subramanian , Post-Doc: Jayant Pendharkar , Ph.D. Students: K.P. Arun Babu, Madhusudan Ingale, Arpita Roy*

The research interests of this group range from solar physics to black hole accretion, within the overall framework of plasma astrophysics. They include black hole accretion disks, active galactic nuclei and microquasar jets and radiation processes, solar radio emission, solar coronal mass ejections (CMEs) and space weather. A combination of semi-analytical theory and analysis of data from ground and space-based instruments is being used.

*Solar coronal and solar-terrestrial physics*

Aspects of plasma astrophysics ranging from fundamental questions regarding the nature of solar wind turbulence and its dissipation to the dynamics and near-earth effects of coronal mass ejections (CMEs) from the Sun are being explored. This line of research also ties in closely with the goals of the proposed space coronograph ADITYA-I to be launched by the Indian Space Research Organization (ISRO). These studies are carried out using theoretical tools as well as data from the LASCO coronograph aboard the SOHO satellite, the Giant

Metrewave Radio Telescope (GMRT) (7.b.1), the Nancay radioheliograph and the GRAPES-3 cosmic ray telescope.

*Recently Completed Work*

1. Using measurements on data of solar Coronal Mass Ejections (CMEs) from satellites (together with theoretical interpretation), estimates of currents enclosed by the CME structures have been derived (7.b.2). This is one of very few estimates of currents in the solar corona, not to mention the first estimates of these driving currents.

2. Theoretical estimates of the level of turbulence excited by some well observed CMEs have been made using data from the GRAPES-3 cosmic ray telescope at Ooty, operated by the TIFR (7.b.3). While it has been speculated that CMEs drive MHD turbulence, this was the first time these levels were estimated. Among other issues, it also provides a unique window for studying the diffusion coefficient for energetic particles perpendicular to an ordered magnetic field, in the presence of turbulence; this is an issue that is of fundamental relevance in a wide variety of astrophysical environments.

3. This group has recently completed some paradigm shifting work in regard to using the broadening of radio sources as seen through the solar corona to infer the amplitude of coronal density turbulence (7.b.4). The manner in which the density turbulence is damped , which can have important implications for the operative viscosity in the solar wind and on the viscous drag on CMEs, has been looked at.

*Ongoing Work*

The following problems or questions are being addressed:

1. What are the principal forces acting on a CME in the outer solar corona? In particular, what is the role of Lorentz self-forces?. 2. What are the microphysical mechanisms involved in producing the viscous drag on a CME en route to the earth? The answer to this question can be used to provide a good physical basis to models of travel time predictions of CMEs, which are currently largely empirical. 3. What are the roles of the CME and its associated shock in producing transient decrease in the galactic cosmic ray flux observed at the earth? Can precursor variations in the galactic cosmic ray flux observed at the Earth provide ad-

vance information about impending geomagnetic disturbances that can be caused by Earth-directed CMEs?

## 8. Universities

Solar physics research in Indian Universities has had a moderate presence, as compared to the other fields of Astronomy and Astrophyics. The revolution brought in by the open source data available from various international space missions has helped a good number of researchers in the Indian Universities. No attempt on covering each and every group or researcher in Indian Universities involved in solar physics or related areas is being made here, but a few prominent groups and their research is described below.

### *a. Institute of Technology - Banaras Hindu University (IT-BHU), Varanasi*

*Solar Plasma and Space Physics, Applied Physics Department, IT-BHU*

*Faculty: B.N. Dwivedi, Anita Mohan. Ph.D. Student: Pankaj Kumar*

The group of B.N. Dwivedi in the Applied Physics department of IT-BHU is involved in space physics research, including solar, planetary and plasma physics, which has been recognised as a thrust area by the University.

The central theme of research in this group has been the study solar high-energy emission processes related to solar activity, and waves and oscillations in the magentized solar atmosphere. Both theoretical and observational analyses involving data from various international space missions are carried out.

A major line of research by B.N. Dwivedi has been in the physics and diagnostics of solar EUV and X-ray emission processes, largely based on observations using the CDS and SUMER instruments onboard SOHO (8.a.1, 1999 ApJ 517, 516; 8.a.2, 1998 ApJ 500, 1023), and also more recently using EIS/Hinode. Studies on abundance anomaly and FIP effect in the solar corona have been made (8.a.3 2000A&A,264,835;8.a.4 2003 ApJ 582,1162).Studying wave activity in the solar atmosphere has been another productive area of research of this-group (8.a.5, 2006 SolPhy 237,143). The above areas of research continue to be pursued in this group, in collaboration with other groups in India and abroad.

### ***b. Madurai Kamaraj University (MKU), Madurai.***

*Solar Radio Astronomy*

*Faculty: S. Umapathy (School of Physics, MKU), A. Shanmugaraju (Arul Anandar College). Ph.D. Students: O. Prakash*

Studying the solar radio emissions associated with the solar corona and eruptive phenomena such as CME's and flares has been an active area of research in this group. Apart from utilising radio observations from the Ooty Radio Telescope and the expertise there, this group has also made many importany studies using space data from LASCO instrument onboard SOHO (8.b.1,2003 SolPhy, 215, 185; 8.b.2 2008 A&A 484,511). Analyses of solar radio bursts (Type II) towards understanding the origin and evolution of CMEs and shocks associated them has been a major line of research (8.b.2 2003 solphy, 215, 161,8.b.3 2003 Solphy 217, 301).

The above areas of research are continuing to be pursued in the above group, with a growing involvment of graduate students leading to Ph.D.

### ***c. Kumaon University, Nainital***

*Solar Flare Studies*

*Faculty: Ramesh Chandra.*

Studies of evolution of magnetic field, in structure and geometry, especially the magnetic helicity, associated with flaring regions (8.c.1,2010 SolPhy 261,127) as well as those in emerging flux regions (8.c.2, 2009 Sol Phy. 258,53) has been an active area of research in this group.

Apart from the above Universities, solar physics research to a significant level is also conducted in ***Delhi University*** *(H.P. Singh and students)*, ***Mahatma Gandhi University, Kottayam, Kerala*** *(Girish, T.E. and students)*, ***University College, Trivandrum, Kerala***, ***Gujarat Arts and Science College (Ahmedabad), Mohanlal Sukhadia Uinversity ( Udiapur), Osmania University (Hyderabad)***, *and* ***Bangalore University.***

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