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Solar physics in India: developments from the nineteenth century to the present era

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Abstract. Modern solar astronomy took root in India with the discovery of helium during the total solar eclipse of 1868 and followed by the setting up of the Kodaikanal Observatory in 1899. We provide a brief overview of the growth of this field, describe the various Indian solar observing facilities and summarize the highlights of solar research in India during the last few decades.

Keywords : Sun: general – history and philosophy of astronomy

1. Solar research during the pre-independence era

Within the Asia-Pacific region, it was in India where modern research in solar physics began. Until 1947 India was a part of the British Empire. This section briefly highlights the major developments during the pre-independence period — a more detailed account can be found in Hasan et al. (2010).

Solar research in India grew out of an already well established tradition of astronomical observations from the Madras Observatory by its several generations of Government Astronomers and, importantly, from the work of Norman Pogson during his tenure (1861–1891). His observations of the total solar eclipse on 18 August 1868 represents an important landmark associated with the birth of solar physics in India. An impressive line of discoveries of new phenomena in the solar chromosphere, including the discovery of helium, chromospheric flash spectra and red prominences, was made during this eclipse. Pogson successfully recorded the unknown spectral line close to the D_2 line of sodium through his observations during this eclipse (Fig. 1), which the visiting astronomers Janssen (France) and Norman Lockyer (England)

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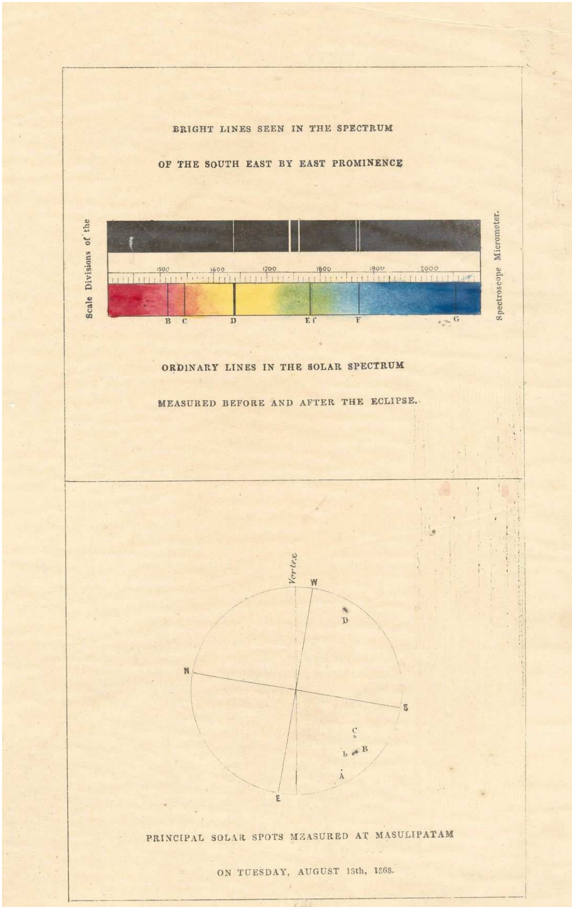

Figure 1. Hand coloured sketch of the solar spectrum recorded during the total solar eclipse at Masulipatnam, India on 18 August 1868 (from IIA archives).

too observed and successfully identified with the new element helium. It was the first time when spectroscopes were used during an eclipse event.

Regular and systematic studies of the Sun in India followed the setting up in 1899 of the Kodaikanal Solar Physics Observatory. The British Government, following the death of Pogson in 1891, through a series of initiatives, with Michie Smith as the Government Astronomer, identified Kodaikanal and authorized construction of buildings and procurement of a combination of instruments, including a photoheliograph, a spectrograph, a 6 in Cooke Equatorial, a transit telescope, and a chronograph. The Observatory was formally opened in 1899. Further addition of instruments followed promptly, especially a Ca II K spectroheliograph, whose design for Kodaikanal was as per the specifications of George Ellery Hale, the inventor of the instrument. Soon John

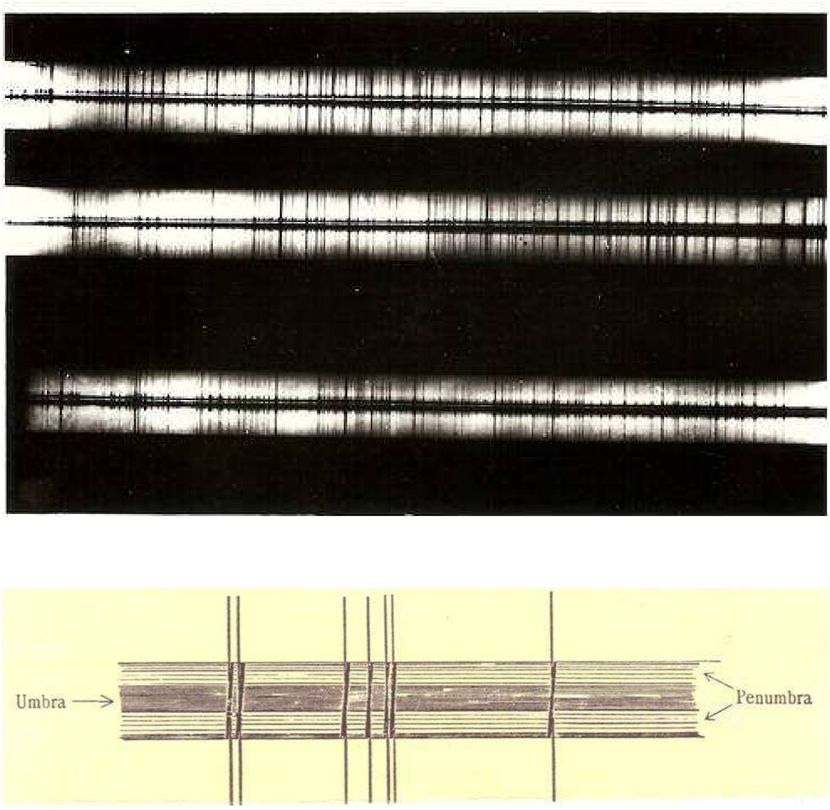

Figure 2. Top: Solar spectra of a sunspot region recorded by Evershed on 5 January, 1909 at Kodaikanal. Bottom: Line sketch of the spectrum showing the shift of the absorption line penumbra around the sunspot (from IIA archives).

Evershed arrived at Kodaikanal in 1907, after visiting the Mount Wilson Observatory in California. In 1909, using a high dispersion spectrograph that he designed and built, Evershed discovered the characteristic Doppler shifts of photospheric spectral absorption (Fraunhofer) lines observed over the penumbrae of sunspots – the well known Evershed effect (Evershed 1909) (see Fig. 2). He also interpreted it accurately as the radial outflow, parallel to the solar surface, of gaseous material in sunspot penumbrae. This discovery and that by Hale, just a year earlier of magnetic field in sunspots, arguably stand as two important contributions that seeded the development of a whole new subject, viz., magnetohydrodynamics (MHD).

Following the retirement of John Evershed in 1922, activity in solar physics continued on the lines of the earlier years. The Directors at the Observatory until 1960 were T. Ryods (1922–1937), A.L. Narayan (1937–1946), and A.K. Das (1946–1960). The scientific highlights of this era are, (a) discovery of oxygen emission lines in the chromosphere, without the aid of an eclipse, (b) centre to limb variations of Hydro-

Figure 3. The Kodaikanal solar tower tunnel telescope.

gen lines and their use to study the solar atmosphere, and (c) detailed study of the properties of dark markings, the filaments, seen in Hα. A committee appointed by the Government of India, with M.N. Saha as chairman, examined in 1945 a plan for the development of astronomical research and teaching at the existing observatories and universities. One of the main recommendations of the Saha committee was aimed at improving the facilities for solar observations, especially during the first five-year plan following India's independence in 1947. The construction of Solar Tower Telescope, a coronagraph, and a laboratory for solar-terrestrial studies at Kodaikanal was implemented by 1960.

2. Beginning of the modern era and development of facilities

There had been a relative lull of solar research in India around the middle of the twentieth century. To a large extent, the credit for revitalizing solar research in India goes to Vainu Bappu. As a postdoctoral researcher at the Mount Wilson Observatory, Bappu had discovered the Wilson–Bappu Effect (Wilson & Bappu 1957). Bappu first returned to India in 1954 as the Chief Astronomer of the Uttar Pradesh State Observatory, which was located in Varanasi at that time. He took the initiative of shifting the Observatory to the much better observing site near Nainital. Then in 1960 Bappu took over as Director of the Kodaikanal Observatory and established the Bangalore headquarters of the Indian Institute of Astrophysics (IIA), of which the Kodaikanal Observatory is now a part. Bappu continued as Director of IIA till his untimely death in 1982. Bappu trained several students in solar research – K. R. Sivaraman, A. Bhatnagar, Jagdev Singh, B. N. Dwivedi among others – who played key roles in the revival of solar research in India. Apart from these people who were trained in India, several solar physicists who had been trained abroad returned to work in India. S. M. Chitre, S. S. Hasan and A. R. Choudhuri came back to India with doctoral degrees respectively from Cambridge (supervisor: Fred Hoyle), Oxford (supervisor: D. ter Haar) and Chicago (supervisor: E. N. Parker). There has been a reverse flow also. N. Gopalswamy, S. Basu and M. Dikpati, leading solar researchers working in the United States, received their doctoral degrees and initial training in India.

2.1 Optical facilities

The main optical solar facilities are located in Kodaikanal Observatory (operated by the Indian Institute of Astrophysics), the Udaipur Solar Observatory (operated by Physical Research Laboratory) and the Aryabhatta Institute of Observational Sciences (ARIES) in Nainital (Uttarakhand).

2.1.1 *Kodaikanal Observatory*

The first modern instrument to be set up at the Kodaikanal Observatory was the Solar Tower Telescope, installed in 1960. By the end of 1965 a high dispersion spectrograph and a Babcock type magnetograph were operational, which were used primarily for measuring magnetic and velocity fields on the Sun. The Solar Tower Telescope consists of a Grubb Parson 60 cm diameter two-mirror fused quartz coelostat mounted on a 11 m tower platform that directs sunlight via a flat mirror into a 60 m long underground horizontal 'tunnel'. The telescope is primarily used for high spatial and spectral resolution work. The main areas of investigation include high resolution studies of (a) the solar chromosphere, (b) the Evershed effect, and (c) 5-minute oscillations in the solar photosphere. A significant contribution using this instrument was the identification that bright fine mottling in the chromosphere is responsible for the Wilson–Bappu effect that relates the Ca II K line-widths to the luminosity of stars.

A Littrow-type spectrograph and a spectroheliograph are the main focal plane instruments. Recently an in-house built dual beam spectropolarimeter was installed as a back-end instrument to the Littrow spectrograph on the tower telescope that is used mainly for studying sunspots. Additionally, the Observatory has a photoheliograph (15 cm, operational since 1898), a 6 cm diameter twin spectroheliograph (for Ca II K and Hα spectroheliograms) and a Ca K spectrograph with 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 to record the Ca K filtergrams.

Current programmes include measurements of magnetic fields at different heights in the solar atmosphere, using Kodaikanal white light images to determine the solar diameter and its variation with the solar cycle, dynamics of sunspots, solar irradiance variability, solar rotation and synoptic studies. In addition, investigations of explosive events, activity and solar cycle effects are being carried out.

One of the prized possessions of this Observatory is a collection of plates containing solar images obtained on a regular basis by the 15 cm photoheliograph telescope since 1904. Robert Howard, who had done extensive studies of these plates, used to refer to the plate vault in Kodaikanal as 'a gold mine'. These plates are now being digitized. From the positions of filaments on these plates, a classic study of the poleward migration of the Sun's global magnetic field was carried out (Makarov, Fatianov & Sivaraman 1983; Makarov & Sivaraman 1989a,b). Another important study was an investigation of the size variation of Ca networks with the solar cycle (Singh & Bappu 1981).

2.1.2 *Udaipur Solar Observatory*

Udaipur Solar Observatory (USO) was established in 1975 by A. Bhatnagar, who had earlier worked in the Big Bear Solar Observatory (BBSO) and set up this observatory in the middle of the Fatehsagar Lake in Udaipur following the model of BBSO. This observatory, which began with a 12 foot spar telescope obtained from CSIRO Australia, started initially under the aegis of the Vedhshala Trust and afterwards became a part of the Physical Research Laboratory (PRL).

Udaipur Solar Observatory has (a) a full disk Hα telescope (6 foot Razdow telescope with a 15-cm aperture lens), (b) a 25 cm aperture Hα Spar telescope with a 12-foot solar spar for observing high resolution chromospheric structures, (c) a solar vector magnetograph, which is basically an imaging spectropolarimeter consisting of a Schmidt-Cassegrain telescope of 20 cm aperture and a state-of-the-art tunable filter, and (d) a Coude telescope (15 cm Zeiss) with adaptive optics (AO) system.

An important milestone for Udaipur Solar Observatory came in 1995, when it became one of the sites of the Global Oscillation Network Group or GONG (Harvey et al. 1996). Apart from the facilities mentioned above, one of the GONG telescopes is an important facility of this observatory. Amongst works based on GONG data carried out in Udaipur, one may mention a study of p-mode frequency changes with solar activity (Bhatnagar, Jain & Tripathy 1999).

Figure 4. The Udaipur Solar Observatory, located on an island in Lake Fatehsagar, Udaipur.

This Observatory has had a tradition of training students in observational solar astronomy, beginning with Bhatnagar whose students included Rajmal Jain, Nandita Srivastava, Shibu Mathew. The present Head of the Observatory, P. Venkatakrishnan, moved there from IIA after Bhatnagar's retirement and trained several students in instrumentation and magnetic field measurement including K. Sankarasubramanian (student in IIA), B. Ravindra, S. Gosain, S.K. Tiwari.

2.1.3 *Aryabhatta Institute of Observational Sciences (ARIES)*

Formerly known as the Uttar Pradesh State Observatory, it formally came into existence at Varanasi in 1954 and was re-located in 1965 to its current site at Manora Peak (elevation 1950 m), just south of Nainital. Presently operated by ARIES, its main focus was on flare patrol observations, which started during the early 1970s. Later atomic and molecular spectroscopic investigations started, and in 1988 and 1991 observations in Calcium K and CN bands were taken up. The facility consists of a 15 cm solar tower telescope with an Hα filter, which is primarily used for flare studies and the study of oscillations in post-flare loops (Srivastava et al. 2008).

2.2 Radio facilities

The important solar facilities in the radio wavelengths are Ooty Radio Telescope (operated by Tata Institute of Fundamental Research or TIFR) and Gauribidanur Radioheliograph (operated by Indian Institute of Astrophysics or IIA). The Giant Metrewave

Radio Telescope (GMRT) near Pune, which has 30 dishes of 45 m diameter, and is the world's largest telescope in the metre wavelengths, is also used for solar studies.

Figure 5. The Ooty Radio Telescope is a cylindrical paraboloid of reflecting surface, 530 m long and 30 m wide, placed on a hill whose slope is about 11 degree (in the north-south direction), which is the same as the latitude of the location.

2.2.1 *Ooty Radio Telescope (ORT)*

The Ooty Radio Telescope, completed in 1969 and operated by TIFR, was built on a hillside with such a slope that its long axis is parallel to the Earth's rotation axis. It is a cylindrical paraboloid of reflecting surface, 530 m long and 30 m wide. The reflecting surface is made up of 1100 thin stainless steel wires, each 530 m long. 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.

Although this telescope was initially primarily used for extragalactic astronomy and other non-solar studies, it is being used most extensively in the last few years for studying interplanetary scintillations (IPS). P. K. Manoharan initiated a unique programme of using IPS data to determine the 3-dimensional structure of the solar wind and its variations with the solar cycle (Manoharan & Ananthakrishnan 1990; Manoharan 1993, 2006).

2.2.2 *Gauribidanur*

Since 1976, IIA operates a decametre wave radio telescope jointly with the Raman Research Institute at Gauribidanur, 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 the Sun and various other diverse objects in the sky. Additionally, there is a radioheliograph, a high-resolution radio spectrograph, and a polarization interferometer. The radioheliograph is used regularly to obtain 2-dimensional images of the solar corona (Ramesh et al. 1998).

Figure 6. A decametre wave radio telescope (GEETEE) at the Gauribidanur radio observatory.

2.3 Space observations

Solar X-ray Spectrometer (SOXS), a low energy detector payload of Physical Research Laboratory (PRL) onboard GSAT-2 launched in 2003, was used for studies of high spectral and temporal resolution X-ray spectra of solar flares. The instrument consists of two types of detector modules: a low energy detector (SLD) module consisting of two semiconductor devices viz. a silicon P-intrinsic-N (PIN) detector to measure the low energy X-rays (4–25 keV) and a cadmium-zinc-telluride (CZT) detector for soft to medium hard X-rays in the energy range 4–60 keV (Jain et al. 2005).

2.4 Eclipse observations

Teams from India have regularly taken part in observations of total solar eclipses from different parts of the world. A team from Indian Institute of Astrophysics reported the detection of short-period coronal oscillations (Singh et al. 1997).

2.5 Proposed future facilities

Some of the future facilities coming up are described by other authors in this proceedings volume—the Multi Application Solar Telescope (MAST) in Udaipur; the space coronagraph Aditya; the National Large Solar Telescope to be set up in the Himalayas.

3. Theoretical research

Constraint of space forces us to restrict our discussion to only a few areas of theoretical solar physics in which Indians have made significant contributions.

3.1 Helioseismology

We have already mentioned that the Udaipur Solar Observatory is one of the GONG sites. India also has a strong tradition of theoretical research in helioseismology initiated by S. M. Chitre in Tata Institute of Fundamental Research (TIFR) and continued by H. M. Antia, S. Basu (during her postdoctoral stint with this group). Amongst the many important results which this group obtained, one may mention the work on constraining the solar abundances using helioseismology (Basu & Antia 1995, 2004; Antia & Basu 2005). Their other important contributions include the use of helioseismic measurements to accurately determine the depth of the convection zone (Basu & Antia 1997) and the extent of overshoot below its bottom (Basu, Antia & Narasimha 1999). They have also developed techniques for mapping the differential rotation in the solar interior from helioseismic mode splittings and studied its temporal evolution in the form of torsional oscillations (Antia, Basu & Chitre 1998; Antia & Basu 2000; Basu & Antia 2003). Currently, several groups around the country are working on helioseismology (Maurya et al. 2009; Kumar et al. 2010), including local helioseismology of active regions aiming at deciphering the structure and flows beneath sunspots (Rajaguru, Basu & Antia 2001; Rajaguru et al. 2007).

3.2 Solar dynamo theory

A central role in the development of the flux transport dynamo model was played by A. R. Choudhuri at Indian Institute of Science (IISc) and his students that included S. D'Silva, M. Dikpati, D. Nandy, P. Chatterjee and J. Jiang (who did a part of her thesis with Choudhuri). Early research by this group on the rise of magnetic flux through the convection zone (Choudhuri 1989; D'Silva & Choudhuri 1993), which provided the first theoretical explanation of Joy's law, showed that the magnetic field at the bottom of the convection zone has to be as strong as 10^5 G. Since such a strong field would quench the traditional α-effect, this result provided an impetus for the development of the flux transport dynamo model, in which the Babcock–Leighton mechanism replaces the α-effect and the meridional circulation plays a crucial role. Choudhuri, Schüssler & Dikpati (1995) wrote an important paper demonstrating the feasibility of the flux transport dynamo. Further details of the flux transport dynamo model were worked out by Nandy & Choudhuri (2001, 2002) and Chatterjee, Nandy & Choudhuri (2004). This model has been used to predict that the next cycle 24 will be a weak cycle (Choudhuri, Chatterjee & Jiang 2007). Recently Nandy, Muñoz-Jaramillo & Martens (2011) have proposed a theory for the last unusually long sunspot minimum.

3.3 Flux tubes and the magnetic network

Magnetic field in the photosphere exists in the form of a network of flux tubes. Several dynamical studies of flux tubes were undertaken by S. S. Hasan and his students that included D. Banerjee, S. P. Rajaguru and G. Vigeesh. Important studies on the formation of flux tubes due to convective collapse were carried out by Hasan (1985) and Venkatakrishnan (1986). Buffeting by granules of the photospheric footpoints of the magnetic flux tubes which extend into the corona can excite waves in these flux tubes—a physical process studied by Choudhuri, Auffret & Priest (1993) and Hasan & Kalkofen (1999). The dynamics and energy transport of waves through the magnetic network has been investigated in quantitative detail by Hasan et al. (2005) and Hasan & van Ballegooijen (2008). Using 2-D numerical simulations, the contribution of various MHD modes to chromospheric heating was assessed.

4. Miscellaneous activities

4.1 Research with international facilities

Several Indian solar physicists have been involved in analyzing data coming out of the space missions such as SOHO, Hinode and STEREO. B. N. Dwivedi was in the team which used SUMER on SOHO to study polar coronal holes (Wilhelm et al. 1998) and to prepare a spectral atlas of solar-disk features (Curdt et al. 2001). He has also been involved now in the observations of active region loops using Hinode/EUV Imaging Spectrometer (Tripathi et al. 2009). We may mention that several groups around India are now working with Hinode data. P. Subramanian has been in a team to detect shock waves associated with CMEs using LASCO on board SOHO (Vourlidas et al. 2003). N. Srivastava has taken part in developing a method for estimating the propagation direction of CMEs from STEREO images (Mierla et al. 2008). Srivastava & Venkatakrishnan (2004) have also studied the solar and interplanetary sources of major geomagnetic storms. D. Banerjee and co-workers have used EIS/Hinode and SUMER/SoHO to study waves in polar coronal holes (Banerjee et al. 2009).

We now come to Indian solar physicists who have used ground-based facilities outside India to do important studies. Sivaraman & Livingston (1982) used the Kitt Peak Vacuum Tower Telescope to study the relation between small-scale bright points and magnetic fields in the photosphere. As an example of a successful collaboration within the Asia-Pacific region, Jagdev Singh has collaborated with researchers at the Norikura Observatory in Japan to study the height variation of the green and red iron lines in the corona (Singh et al. 1997). This group also used the green-line spectrum to detect coronal waves (Sakurai et al. 2002). Several Indian solar physicists have worked with groups outside India to study different aspects of flares (Hagyard, Venkatakrishnan & Smith 1990; Ambastha & Hagyard 1993; Manoharan et al. 1996; Hagyard, Stark & Venkatakrishnan 1999). S. Mathew has been involved in a collaborative study of the statistics of sunspots in cycle 23 (Mathew et al. 2007). Bharti, Jain & Jaaffrey (2007) have used observations in NSO to study convection inside umbral dots.

4.2 Reviews and science popularization

Apart from research papers, several Indian solar physicists have written impact-making reviews. Early examples include two very comprehensive reviews by Narain & Ulmschneider (1990, 1996) on chromospheric and coronal heating mechanisms. More recently Banerjee et al. (2007) have written a review on observing trends in the field of magnetoseismology of the solar atmosphere, whereas Basu & Antia (2008) have reviewed the subject of helioseismology and solar abundances.

A. Bhatnagar and B. N. Dwivedi have taken special interests in popularizing solar physics amongst the general public and amongst students. Bhatnagar wrote a textbook on solar astronomy with Livingston (Bhatnagar & Livingston 2005) shortly before his death in 2006. Dwivedi took the initiative to bring out a volume containing pedagogical chapters on different aspects of solar physics by several leading solar physicists of the world (Dwivedi 2003). Another useful pedagogical volume on different aspects of solar physics is the volume edited by Hasan & Banerjee (2007) based on the lecture courses given in a winter school in Kodaikanal, which was attended by several students from outside India. We may also mention that a popular article by Dwivedi & Phillips (2001) was chosen as the cover article by *Scientific American*.

4.3 International conferences

Several important international conferences dealing with different aspects of solar physics have taken place in India during the last few decades. Here we list some of the conferences which led to major proceedings volumes: *IAU Symposium 142: Basic Plasma Processes in the Sun*, Eds. E. Priest & V. Krishan (1990); *Windows on the Sun's Interior*, Eds. H. M. Antia & S. M. Chitre (1996); *IAU Colloquium 179: Cycli-*

cal Evolution of Solar Magnetic Fields, Eds. P. Venkatakrishnan, O. Engvold & A. R. Choudhuri (2000); *Transient Phenomena on the Sun and Interplanetary Medium*, Ed. W. Uddin (2006); *Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects*, Eds. N. Gopalswamy & A. Bhattacharyya, *Challenges for Solar Cycle–24*, Eds. R. Jain, P. Venkatakrishnan & J. Karpen (2008); *Heliophysical Processes*, Eds. N. Gopalswamy, S. S. Hasan & A. Ambastha (2010), *Magnetic Coupling between the Interior and Atmosphere of the Sun*, Eds. S. S. Hasan & R. J. Rutten (2010).

5. Summary and future perspective

We have tried to give an overview of how solar physics developed in India from the nineteenth century to the present time. While Indian scientists have made significant contributions in certain areas of solar physics, these activities definitely need to grow significantly to a level that will realize the country's potential. Currently there are about 40 faculty members and about 10 students working in solar physics all over India. These numbers certainly have to be enhanced considerably in order for India to be a major international player in solar physics as well as to better utilize the upcoming solar facilities such as the Solar Coronagraph ADITYA and the National Large Solar Telescope.

Recently, five Indian Institutes of Science Education and Research (IISERs) have been set up to impart quality undergraduate education in basic sciences. In addition, many of the national institutes have initiated integrated Ph.D. programmes in physical sciences and astronomy instrumentation. There are already indications that many students coming out of high school are again considering basic science as a career option. The future of solar physics in India will crucially depend on whether we can channel some of these bright students to a research career in solar physics.

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