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Optical observational programs at the Indian Institute of Astrophysics

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Abstract. The Indian Institute of Astrophysics has been making optical observations of the sun for more than a century by taking images of the sun in continuum to study the photosphere, Ca-K line and H-alpha line in order to study the chromosphere by using the same instruments which are used to study the long term variations of the magnetic fields on the sun. The digitizers have been developed using uniform light sources, imaging optics without any vignetting in the required FOV and large format 4K×4K CCD cameras to digitize the data for scientific studies. At the Solar Tower Telescope we have performed very high resolution spectroscopic observations around Ca-K line to investigate the variations and delineate the contribution of various features to the solar cycle variations. Solar coronal studies have been done during the occurrence of total solar eclipses and with a coronagraph to study the coronal heating. Here we discuss the systematic temporal variations observed in the green and red emission profiles using high spectral and temporal observations during the 2006, 2009 and 2010 total solar eclipses. The TWIN telescope a new facility has been fabricated and installed at Kodaikanal observatory to continue the synoptic observations of the sun and a space-based coronagraph is also being designed and fabricated in collaboration with various laboratories of ISRO (LEOS, ISAC and SAC) and USO. In this article we present the summary of results of optical observational programs carried out at Kodaikanal Observatory and during the eclipse expeditions where authors have played a leading role. Furthermore, this review is not complete in all respects of all the observational programs carried out at the Kodaikanal observatory.

Keywords : Sun: photosphere – Sun: chromosphere – Sun: corona

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1. Introduction

The synoptic observations of the sun are very important in order to study the long term variations of solar activity and the associated solar magnetic fields and its effect on space weather and climate. Varieties of structures are observed on the sun at all times of the solar cycle. On large spatial scale the sunspots are the prominent structures at the photospheric level and its numbers are also large during the solar maxima. Other large scale structures observed are the plages, filaments, prominences at the solar limb and energetic events such as solar flares. We also observe the coronal features such as streamers, high temperature coronal loops, coronal mass ejections (CME's) etc during the occurrence of total solar eclipses and ground and space-based coronagraphs. Indian Institute of Astrophysics has the history of making solar optical observations of the sun since 1904 and has arranged expeditions to make observations of the solar corona during the occurrence of total solar eclipses. The purpose of this article is to summarize activities of the Institute using different facilities to make observations and the results obtained.

2. Synoptic observations of the Sun

The Kodaikanal observatory began its scientific activity by taking the images of the sun in continuum (photoheliograms) using a 15 cm telescope in 1904 on a daily basis whenever sky conditions permitted. The image size is 20 cm and a uniform set of data with image quality mostly limited to seeing of about $2''$ has been collected. A spectroheliograph was installed and positions and areas of sunspots visible in the white light images have been measured and cataloged. The data have been used to study solar activity, rotation rate, differential rotation, rotation of young and old sunspots, and tilt angle of the sunspots and its variations with the solar cycle (Sivaraman, Gupta & Howard 1999; Howard, Sivaraman & Gupta 2000; Sivaraman et al. 2007; Muneer & Singh 2002). Muneer and Singh found that tilt angles of the sunspots vary as a function of solar cycle phase rather than the latitude of sunspots predicted by Joy's law.

The Ca-K line images of the sun have been obtained since 1907 using a set-up of 30 cm siderostat and a 30 cm objective lens to form a 6 cm image of the sun. The second slit of the spectroheliograph isolated 0.07 nm of the spectra centered on the Ca-K line. The observations could not be continued after 2006 because of the non-availability of the suitable photographic plates. Singh & Bappu (1981) using Ca-K line spectroheliograms found that the network size varied with the phase of solar cycle and was 5 per cent smaller at the time of the maximum phase. Singh & Prabhu (1985) found the semi-periodic variations in the chromospheric rotation rate with a period of 2, 7 and 11 years.

H-alpha images obtained (using the spectroheliograph developed by Evershed) since1912 on a daily basis have been used for solar cycle studies and its evolution by

Makarov et al. (eg. 1989, 2001, 2003). The data has also been used to study the solar activity to show that pre-heating of the plasma leads to eruptive events (Singh, Sakurai & Ichimoto, 2001). Singh & Gupta (1985) found that heating of the filament begins early, few hours to a day, before its eruption. Therefore, it is important to continue to obtain data and generate a series of images that have uniformity or overlap of the data with two instruments, old and new; to extend such studies.

Earlier, the images of the sun were recorded on specialized photographic emulsion suitable for this purpose. With the advancement of electronic technology and development of faster and bigger format CCD cameras, the specialized films went out of production. In 1995 we used a narrow band filter using the old siderostat and CCD camera of 1K×1K format to take Ca-K line filtergrams. These data have the drawback that images rotated with time of observations and have a low spatial resolution as compared to the earlier data with the spectroheliograph. Keeping in view the above mentioned limitations, a telescope was designed and fabricated to take Ca-K line and continuum images of the sun and named it twin telescope. This telescope has been in operation since 2008 at the Kodaikanal observatory for collecting images during clear skies.

3. New facility for synoptic observations of the sun

The TWIN telescope consist of two tubes mounted on a single equatorial mount, one for the white light images and the other for Ca-K line filtergrams of the sun. Each tube is fitted with a 15-cm objective lens from Zeiss to make images of the sun. For the white light a heat rejection filter of 15-cm with a passband centered at 430 nm and bandwidth of 10 nm is used. In addition a Mylar filter with density 5 is kept in front of the objective lens to reduce the intensity of the image and the heat in the telescope tube. Similarly for Ca-K line image a heat rejection filter with passband centered at 395 nm and bandwidth of 10 nm is used. Once again a Mylar filter with density 3.8 is kept in front of the objective lens. In addition, a narrow band thermally controlled interference filter with passband centered at 393.37 nm and bandwidth of 0.12 nm is kept near the focus to get the line images. Two CCD cameras, one for the Ca-K line and other for the broadband images were used to take simultaneous images of the sun for the chromospheric and photospheric studies in case of active events on the sun. The CCD cameras having scientific grade-I chip and 2K×2K pixel format with a 16-bit read out at 1 MHz yielded uniformity in the images, high dynamic range and high photometric accuracy. The peltier cooled CCD cameras are operated at -40°C for low dark current and low read out noise. The pixel size of 13.5×13.5 μm provides a spatial resolution of 2.5 arcsec. The ND filters in front of the objective lens permit us to give sufficient large exposure to avoid the visibility of the shutter pattern in the images of the sun. The exposure time ranges between 300 ms and 1 second is chosen depending on the sky conditions. Fig.1 shows the image of the sun taken in Ca-K line (left side) and the processed image (right side) after the dark and flat-field correction.

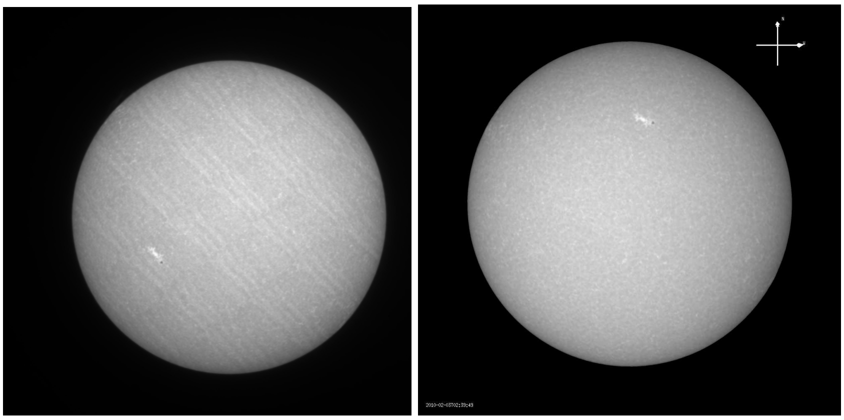

Figure 1. Left side is the observed image and right side is the processed image.

The data has been used to study the variation of quiet network elements during the extended period of minimum phase of the solar cycle number 23. The intensity contrast between quiet network elements and the background is low and is difficult to delineate the network elements in the presence of active features such as plages, enhanced and active network. We have developed the software to determine the quiet network element components by choosing the lower and upper threshold values as shown in Fig. 2. We find that a percentage of quiet network elements decrease in the quiet region by about 7% in 2010 as compared to that in 2008 and interpret in terms of extended minimum during the solar cycle number 23 (Singh et al. 2011b).

4. Digitization of the data obtained at Kodaikanal observatory

We have collected about 120,000 images of the sun in continuum, Ca-K and H-alpha line over the last hundred years and these are well preserved in the dry and cold conditions at the Kodaikanal observatory. To analyze the data and to investigate the long period variations on the sun we planned to digitize these images to enable us to derive various parameters of solar features using fast computers and sophisticated software. We have designed, fabricated and installed state-of-the-art digitizers at Kodaikanal observatory and completed the digitization of Ca-K line series and started to digitize the white light images of the sun. One meter labsphere with exit port 35 cm provides uniform light with less than 1% variation from center to limb. Constant current is maintained to the lamp to stabilize the intensity of the light source. After testing good quality lenses, lenses with modular focus arrangement from LINOS were selected to re-image the photographic plates on the CCD camera. The images of the grid taken indicate that these lenses do not cause any geometrical vignetting in the image in the field of interest. The CCD camera of 4K×4K format with pixel size 15×15 μm provides the digitized images with pixel resolution of 0.8 arcsec (spatial resolution of 1.6 arcsec) which matches the general seeing conditions at Kodaikanal observatory. The

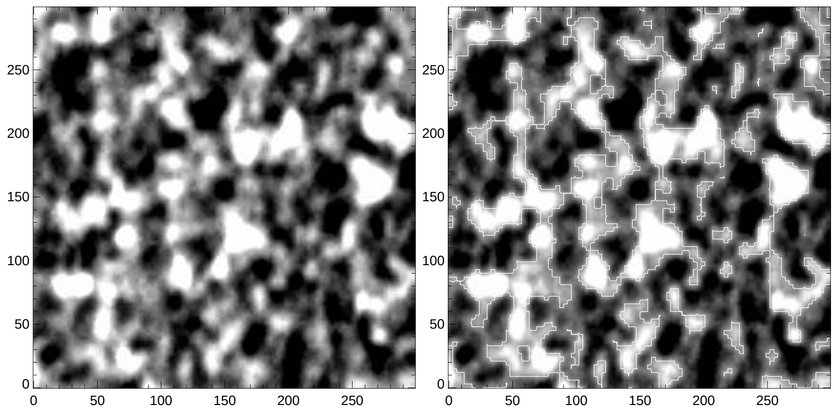

Figure 2. Left side image shows the central part of the image and right side image shows the contours of detected network cells for a threshold 1.006 to 1.14 of the mean value of the solar disk intensity.

operating temperature of -100°C of the CCD cameras ensures low dark current and low noise in the data. The moderate read out speed of 500 KHz with 4 ports provides data in the 16-bit format with read out noise of about 15 counts. To maintain the uniformity in the digitized data the temperature, humidity and dust in the room are controlled.

Earlier images have been digitized using scanner and the data are available in the 8-bit format with low spatial resolution and thus has limited use. Number of authors have used different techniques to compute the Ca-K plage index from the data of Kodaikanal, Mt. Wilson, Arcetri and Sac Peak observatories and compared the results obtained from different data sets (Foukal et al. 2009, Tlatov, Pevtsov & Singh, 2009; Ermolli et al. 2009). Ermolli et al. (2009) found that the data obtained at Kodaikanal observatory was uniform and in good condition to study the long term variations in the Ca-K flux with different periods. The present set of digitized data will permit us to obtain this parameter with better accuracy and in addition investigate variations in other parameters such as enhanced, active and quiet network index. This will help us to make realistic modeling of the solar cycle variability. The following research projects may be taken up using these data: (a) Long term variations in the photospheric and chromospheric rotation rate, chromospheric differential rotation rate (b) Variation of tilt angle with the solar cycle phase and its implication to the helicity and solar dynamics (c) Irradiance variation with the solar cycle phase (d) Variation in the network cell size with the phase of the solar cycle (e) Study of cell size in active and quiescent regions

Archival of a large data base in the digital form will be maintained and will be available to all the scientists for research purposes.

5. High resolution observations with Solar Tower Telescope

The chromospheric variability can best be studied by monitoring the Ca-K line profiles of the sun as a star on a regular basis. The line profiles can be normalized to the continuum intensity to correct for the variations in the measurement due to changes in the transparency. Professor Vainu Bappu started the program to monitor the high spectral resolution Ca-K line profiles of the sun as a star on a daily basis at the Solar Tower Telescope. It was found that the sun is a variable star and the Ca-K index varied by about 25% with the phase of solar cycle. Skumanich et al. (1984) proposed a three component model of the solar cycle variability of Ca-K emission using extant contrast and fraction areas for the cell, network and plage components. They were able to fit the quiet sun Ca-K emission with the cell and network features alone using extant limb darkening laws. The occurrence of plages during the growth of the cycle was found to be insufficient to account for the increase in Ca-K emission. Hence active network component was proposed to explain the increased emission but the observation did not indicate the existence of active component. To resolve this problem we started to obtain Ca-K line profiles as function of latitude and integrated over the visible longitudes of the sun since 1986 on a daily basis. The plage free profiles at a given latitude during the different phases of the sun will yield information about the variation in the background flux and active component. The data obtained over 2 solar cycles will yield valuable information about the variability in the polar region (Singh, Gholami & Muneer 2004).

6. Coronal studies

The heating of plasma in the solar corona to 1–2 million degrees still remains an unsolved problem even though a number of models have been proposed. Wave heating, micro flares and reconnection of magnetic field processes are commonly discussed. The coronal studies can be made during the occurrence of total solar eclipses, ground-based coronagraphs and space-based instruments in the UV, EUV and X-rays. Every method has some advantages and disadvantages over the other. Here we discuss the results obtained from the systematic spectroscopic observations of emission lines in the visible wavelengths and from experiments conducted during the total solar eclipses to study the heating of coronal plasma at National Astronomical Observatory (NAO) located at Norikura, Japan.

6.1 Observations with ground-based Coronagraph at NAO, Japan

The Kodaikanal Observatory does not have any coronal observational facilities. So in collaboration with NAO, Japan, using their 25 cm coronagraph, we made systematic spectrographic observations of the steady coronal loops, overlying the sunspots without any flare during and before the observations, in the two coronal lines simulta-

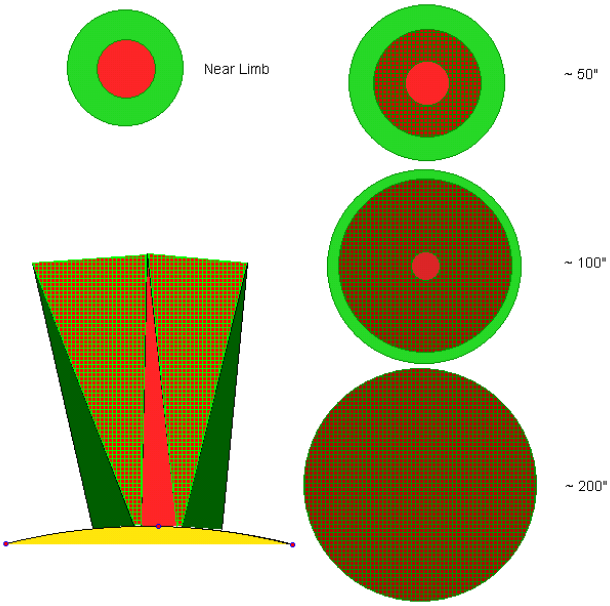

Figure 3. In this cartoon the area marked by yellow color represents the solar limb and the vertical structure represents the coronal loop. The area shown in red is the loop where abundances of ions emitting at 6374 Å are more and green area represents area where abundances of ions emitting at 5303 Å are more. In between area shown in both colors is the portion of loop where both relatively high and low temperature plasma interacts.The circular cross-sections show plasma at different heights. At heights larger than 200 arcsec plasma attains a middle temperature in between the two high and low temperature depending on the physical properties of loop.

neously. We used [Fe X] 6374 Å, [Fe XI] 7892 Å, [Fe XIII] 10747 Å , 10798 Å and [Fe XIV] 5303 Å coronal emission lines for our study. We discovered that line widths of all the coronal lines studied did not increase with height (Singh et al. 2003, 2005, 2006). The width of the red emission line that represented plasma at a temperature of about 1 MK increased with height as observed in the other EUV and X-ray emission lines whereas that of the green line (plasma at about 2 MK) decreased with height. The width of the [Fe XI] that represented plasma at 1.3 MK did not increase with height as much as expected assuming the same physical processes are responsible for the increase in line width as in case of red line. The width of the [Fe XIII] emission line showed marginal variations with height. The trend in the variation of line width is independent of the shape, size, topology of the coronal loops. The line width of the 5303 Å line decreases in all types of loops small or big; open or closed; face-on or end-on; radial or non-radial and that of 6374 Å increased with height. Further, the FWHM of [Fe X] and [Fe XIV] emission lines did not show change with height after a distance of about 250 arcsec and normalized ratio was 1 suggesting that plasma at larger heights at uniform temperature and non-thermal velocities. In addition the intensity ratio of [Fe XI]/[Fe X] was found to vary with height as expected but that of [Fe XIII]/[Fe X] and [Fe XIV]/[Fe X] were found to be not in agreement with the predictions of abundance theory (Singh et al. 2004).

The monotonic increase in temperature or nonthermal velocity with height above the limb cannot explain the observed variations in linewidth and intensity ratios with height in all the lines simultaneously. The existing coronal loop models cannot explain these findings. We are proposing a new model for coronal loops which predicts the loop to be highly dynamic and also assumes that the different temperature plasma in loops is not magnetically isolated. The cartoon in Fig.3 shows the empirical model proposed to explain the observed variation of the line widths and intensity ratios of different emission lines with height in the solar corona. We propose that in coronal loops low temperature plasma is surrounded by relatively high temperature plasma as low temperature plasma loops are thinner as compared to the high temperature plasma loops. Near the solar limb where magnetic field is strong, contribution to the [Fe X] red emission line comes from the relatively low temperature plasma and to the [Fe XIV] green line comes from relatively high temperature plasma. At larger heights when the magnetic field becomes weaker, the multi temperature plasma starts interacting with each other and heights greater than 250 arcsec plasma attain common middle temperature and non-thermal velocity. This implies that low temperature plasma near the limb becomes hotter at larger heights and high temperature plasma becomes relatively cooler at larger heights resulting in increase in linewidth of low temperature emission lines and decrease in the linewidth of relatively high temperature emission lines. These findings can also be explained in terms of change in non-thermal velocity. The variation of temperature also explains the observed complex variation in intensity ratios with heights above the limb. The temperature of the green line plasma is relatively lower at larger heights as compared to that near the limb and vice versa for the red line plasma. This results in the decrease in intensity ratio of [Fe XIV]/[Fe X] with height above the limb. It may be noted that it is an empirical model and has some limitations to explain the interaction of multi-temperature plasma and some of the existing widely used theoretical assumptions such as loops are thin and magnetically shielded. This model implies that magnetic pressure is not very large as compared to gas pressure. All the coronal loop models assume the magnetic pressure $\gg$ gas pressure.

6.2 Observations during the eclipses

It has been recognized that magnetic fields play an important role in heating up the plasma in the solar corona but identification of the process or processes still remains an open question. The existence of magnetohydrodynamic waves in the solar corona is expected to cause oscillations in either intensity or velocity or in FWHM (arise due to broadening in linewidth) or in all. The scattered light from the solar disc and its variation with time makes it difficult to study the small amplitude variations in the intensity. The Doppler shift and linewidth measurements may also get affected by absorption lines due to disc light, close to the emission lines. Occurrences of total solar eclipses provide very good opportunity to study these variations with time of course for small duration of the totality. Generally intensity oscillations have been studied in the continuum, green (5303 Å) and red (6374 Å) emission lines by taking the images of the solar corona at high frequency to study the existence of high frequency waves in the corona and thereby investigate the heating of plasma to million degrees (Pasachoff et al. 2002; Singh et al. 1997, 2009). New generation detectors have permitted to record the signal even when the light level is too low. In recent times, we therefore, planned to perform high resolution slit spectroscopy around the green and red emission lines simultaneously at a high cadence of 1 frame every 5 seconds. The spectroscopic observations have the advantage to correct the signal for the variation in sky transparency during the observations. Table 1 shows the development of observational techniques over the years which became possible due to improvement in the technology.

Table 1. Summary of observations made during various solar eclipses.

Year	Experiment	Type	Frequency
1980	Image red line intensifier	Multi-slit spectroscopy	Spatial
1983	Image red line intensifier	Multi-slit spectroscopy	Spatial
1994	Image red and green line intensifier	Multi-slit spectroscopy	spatial
1995	PMT continuum	1 location	10 Hz
1998	PMT continuum	4 locations	50 Hz
2006	CCD green and red only one limb	Imaging	0.3 Hz
2009	CCD green and red	Imaging	1.1 Hz
	(all around the sun up to 1.5 $R_\odot$)		
2009	CCD green and red	Spectroscopy	0.2 Hz
2010	CCD green and red	Spectroscopy	0.23 and 0.9 Hz
2010	CCD H_α line as a function of height	Spectroscopy	~7 Hz

The analysis of all these data sets indicates intensity variations at some locations with period of strongest power around 27 sec for the green line and 20 sec for the red line (Singh et al. 2011a). These results confirm earlier findings of variations in the continuum intensity with periods in the range of 5 to 56 sec by Singh et al. (1997). Wavelet analysis has been used to identify significant intensity oscillations at all pixels within our field of view. Significant oscillations with high probability estimates were detected for some locations only. These locations seem to follow boundary of active region and in the neighborhood, rather than within the loops itself. These intensity oscillations may be caused by fast magneto–sonic waves in the solar corona and partly account for heating of the plasma in the corona. Further, we found intensity, velocity, and line width oscillations with periodicity in the range of 25 - 50 sec from the spectroscopic observations made during the 2009 eclipse. These oscillations can be interpreted in terms of the presence of fast magneto-acoustic waves or torsional Alfvén waves (Singh et al. 2011a).

7. The proposed visible emission line coronagraph

The occurrence of total solar eclipses provides observations of solar corona with minimum of scattered light in the visible part and near-IR of the spectrum but for short durations to study the intensity oscillations in the solar corona and the coronal magnetic fields. The varying sky transparency and scattered light introduces a large amount of uncertainty when studying the high frequency oscillations and magnetic fields in the solar corona and thus it becomes difficult to believe the results because of the low amplitude of the variations in intensity and magnetic fields have large uncertainties. Therefore a coronagraph with these instruments in space, above the earth's atmosphere will provide ideal conditions to study the existence of waves and the strength of magnetic fields. Keeping in view of the above mentioned goals we proposed a 20 cm coronagraph to be launched in space by ISRO and take the images of the solar corona in the green (at 5303 Å) and red (6374 Å) emission lines with the following scientific goals. a) To determine the existence and nature of waves in the solar corona by studying the intensity oscillations using emission lines of Fe XIV at 5303 Å and Fe X at 6374 Å in different types of coronal structures. b) The simultaneously obtained images of the brightest part of the corona, which is presumably related to some active regions in the 5303 Å and 6374 Å emission lines, representing plasma at about 1.8 MK and 1.0 MK respectively, will yield clues to the cooling processes involved in the coronal and post-flare loops. Also a clue to the formation of loops by evaporation may be possible. c) High cadence observations will permit to determine the kinematics of CME's (coronal mass ejections) and possibly the origin of solar wind. d) Information about the origin and acceleration of CMEs will help to predict space weather and help the space programs.

The visible emission line internally occulted coronagraph is being developed as a collaborative project by IIA, LEOS, ISAC, SAC and USO and is expected to be put in the orbit in 2014. The data will be available to all the interested scientists.

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