J. Earth Syst. Sci. (2022)131 57
https://doi.org/10.1007/s12040-021-01799-5

Measurements of limb-darkening effect and solar radiation during the partial solar eclipse of 21 June 2020 at Varanasi

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MS received 21 December 2020; revised 22 September 2021; accepted 16 October 2021

In this study, we have for the first time discussed the effect of a partial solar eclipse on limb-darkening effect, incoming solar radiation and atmospheric temperature at the surface with the help of a solar telescope with the back-end instrument as the charge-coupled device camera and data of net radiometer installed at the Department of Physics, Banaras Hindu University, Varanasi, India. We have also calculated the eclipse parameters, magnitude and obscuration. A partial eclipse occurred at Varanasi on 21 June 2020 from 10:30:51 am to 02:04:01 pm (IST) for 3 h 33 min. The path of this rare solstice ring of fire was of long duration. Observation of six phases of the partial solar eclipse was recorded and it showed a variation in the intensity over the sun's diameter from one limb to another at different phases of the eclipse. We also estimated the limb-darkening coefficient for six phases of the partial solar eclipse. The average value of the solar limb-darkening coefficient was found to be about 0.61. The observed values of the limb-darkening coefficient; incoming solar radiation and atmospheric temperature at the surface are consistent with earlier studies.

Keywords. Solar eclipse; solar radiation; eclipse obscuration; eclipse magnitude; limb-darkening effect.

1. Introduction

A solar eclipse occurs when the Moon comes along the line of sight of the Sun and the Earth on a new moon day. Eclipses, either solar or lunar, have been interesting topics since ancient times (Anon 1834; Birt 1836). Total solar eclipse events provide a unique opportunity to study several atmospheric processes. The solar flux is progressively decreased as the disc of the Sun is covered by the Moon (Chandra *et al.* 1997). Even in recent times, solar eclipses have been studied extensively by the scientific community (Anderson *et al.* 1972; Founda *et al.* 2007; Tzanis *et al.* 2008; Singh *et al.* 2012; Nayak and Yigit 2018). The first known quantitative eclipse weather observations were reported by Anon (1834) on 30 November 1834. Later, based on the solar eclipse event of 15 May 1836, Birt (1836) reported some qualitative observations from the UK.

During the last century, various environmental studies have shown a correlation to better understand the behaviour of Earth's environment in response to the abrupt and short-period disturbances in the radiation at the time of a solar eclipse. The impact of a solar eclipse on the thermal balance of the atmosphere was also carefully considered. During the solar eclipse, the effect on

Published online: 23 February 2022

the environmental changes can be seen in the meteorological parameters, i.e., relative humidity, temperature, wind and photochemistry by Srivastava *et al.* (1982), cloudiness by Anderson *et al.* (1972), total columnar ozone by Kawabata (1937), boundary layer physics by Antonia *et al.* (1979), ionospheric parameters by Klobuchar and Whitney (1965), gravity waves by Chimonas (1970) and also animals by Zirker (1995) and plants by Deen and Bruner (1933).

The gradual decrease in the brightness from the centre to the edge of the Sun is called limb-darkening effect which is readily apparent in white light images (Pierce *et al.* 1977). Limb-darkening results from the fact that we are looking into hot gas when we look at the Sun and, as a consequence of this, the brightness of the Sun decreases as one looks from the centre of the disc towards the limb. When we look at the centre we see deeper inside the Sun where the gas is hotter and brighter, and when we look at the limb we do not see as deeply and intently into the solar atmosphere where the gas is at a lower temperature (Sánchez-Bajo *et al.* 2002). The Sun's photosphere shows various phenomena that can be observed with a small telescope. The sunspots, granulations, the dark area related to the solar magnetic field can be measured from both the space as well as ground-based observations and are important for space-weather studies (Singh and Singh 2016). However, the limb-darkening effect can be seen from very careful ground-based observations (Tripathi *et al.* 2020). During the total solar eclipse of 21 August 2017, Bernhard and Petkov (2019) showed the limb-darkening effect from the measurements of spectral irradiance for 306 and 1020 nm using the GUVis-3511 multi-channel filter radiometer at Smith Rock State Park, Oregon. Very (1902) studied the absorption of the solar atmosphere and found the variation of the limb-darkening coefficient by varying frequency. The limb-darkening effect is found to be higher at a high frequency (Pierce and Slaughter 1977). Neckel and Labs (1994) discussed two reasons for the limb-darkening effect: (i) the density varies with the distance over the Sun's surface and it decreases from the centre of the sun to the limb and (ii) the temperature decreases with the distance from the centre. Also, when we see along the line of sight at the centre, the solar images look deeper in comparison with the limb due to the thickness of the atmosphere at the limb (Zeilik 1997). Ramanathan (1954) has found the value of the limb-darkening coefficient to be equal to 0.6. The solar telescope that is installed at the Department of Physics, Banaras Hindu University, Varanasi is found to be an excellent facility for the observation and measurements of solar parameters to study the limb-darkening effect during a solar eclipse. The intensity filter mounted at the solar telescope is used to observe the solar disc, also the recorded image and intensity pattern is used to obtain the limb-darkening coefficient and rotational period of the Sun (Tripathi *et al.* 2020).

Several authors studied the impact of a total solar eclipse on the solar irradiance falling on the Earth (e.g., Sharp *et al.* 1971; Silverman and Mullen 1975; Zerefos *et al.* 2000, 2001; Tzanis *et al.* 2008). They aim to study the changes in the spectral solar irradiance at the time of a solar eclipse, the dependency of the limb-darkening effect on the wavelength, the effect on sky brightness due to multiple scattering, as well as to validate the models of radiative transfer. Founda *et al.* (2007) found that the incoming solar radiation varies dramatically at the beginning of the solar eclipse observed at different locations, and is found to have a dependence on the eclipse magnitude. At various places over the globe, i.e., Athens, Greece, it was observed that there is a reduction in the solar ultraviolet radiation up to 97 and 93% at 312 and 365 nm wavelengths. During the solar eclipse of 29 March 2006, Petkov *et al.* (2010) reported ground-level solar irradiance with the use of different radiometric techniques using observations from three Italian stations.

Several authors reported change in stratospheric composition during the solar eclipse (Bojkov 1968; Wuebbles and Chang 1979; Elansky *et al.* 1983; Burnett and Burnett 1985; Mims and Mims 1993). In particular, they found a variation in total ozone content during a solar eclipse which mainly is attributed to the cooling of the atmosphere.

Tzanis *et al.* (2008) observed the relation between temperature, relative humidity and wind speed, i.e., with the decrease in the air temperature, the relative humidity increases and the wind speed decreases. However, various authors found a relatively small variation of surface temperature and surface winds as well as on surface ozone and its precursors during solar eclipse (Srivastava *et al.* 1982; Fernandez *et al.* 1993; Zerefos *et al.* 2001; Kolev *et al.* 2005; Gerasopoulos *et al.* 2008).

Several workers have also reported changes in different meteorological parameters during the solar eclipse period (e.g., Fernandez *et al.* 1996;

Anderson 1999; Krishnan *et al.* 2004; Uddin *et al.* 2007; Kameda *et al.* 2009; Aplin *et al.* 2016). Krishnan *et al.* (2004) reported a decrease of 0.5°C in temperature and also a decrease in wind speed, while the variation in relative humidity was reported within the natural variability of the day during a total solar eclipse effect on 11 August 1999 over Ahmedabad, India. Penaloza-Murillo and Pasachoff (2015) studied air temperature measurements during the first expedition of the total solar eclipse of the 21st century on 21 June 2001 and reported a drop in the air temperature during the event of the eclipse. Hanna (2018) reported the meteorological effects of the solar eclipse on 20 March 2015 over UK showing a decrease in surface temperature and wind speed. Although different meteorological studies show similar patterns of temperature change, the actual drop may vary depending on various factors (e.g., synoptic situation, timing, solar occultation percentage, surrounding environment, etc.). Despite various studies on the effects of a solar eclipse on limb-darkening, solar radiation and meteorological parameters at individual places, a complete study of all the above parameters simultaneously at a place was lacking. To fill this lacuna, this study is based on the effect of the most recent annular solar eclipse on limb-darkening effect and solar radiation that occurred on 21 June 2020 at Varanasi, India.

This paper aims to provide the impact of a solar eclipse on solar limb-darkening effect, solar radiation and atmospheric temperature with the help of a solar telescope and the net radiometer installed at the Department of Physics, Banaras Hindu University, Varanasi (lat. 25°16′05″N, long. 82°59′35″E, alt. 82 m), India. The partial eclipse occurred at Varanasi on 21 June 2020 from 10:30:51 am to 02:04:01 pm (IST) for 3 h 33 min. We have tried to check whether the limb-darkening phenomenon is intrinsic or can be influenced by an object eclipsing Sun. Since we get a sudden drop in the intensity at the eclipse site and no such effect of the gradual decrease in intensity, so we can say that limb darkening is indeed an intrinsic phenomenon. The layout of the paper is as follows: methodologies and instrumentation are presented in section 2, the corresponding results and discussions are presented in section 3 and finally, the conclusions are presented in section 4.

2. Instrumentation and method of analysis

The solar limb-darkening effect can be studied easily if we can measure the intensity of the solar disc from the centre of the Sun towards the limb. For the present purpose, we use a small aperture telescope which is quite sufficient for the study of the limb-darkening effect. We use a charge-coupled device (CCD) detector as a back-end instrument to record the solar images pointed from the telescope. Although photographic emulsion plates can be used as an alternative, CCD provides a better linear response and there is a well-established relationship showing the variation of the intensity of the recorded image and the exposure time. CCDs are also preferred over the other devices because of the easy analysis using simple software in a computer, since CCD records the information in a two-dimensional array of photo-detectors or pixels that provides a digitised image that can be easily displayed, stored and processed in the computer. We have used a refractor telescope with an equatorial mount (with an aperture of 13 cm) with the CCD camera as a back-end instrument. The detector is a commercial low-price 6.1 MP cooled CCD astronomy camera based on the chip SONY ICX413AQ of size 1.8″. The CCD camera provides options to select the exposure time (0.1 ms to 60 min) and to record and store the source image. The exposure can be controlled manually as well as automatically. The size of each pixel of CCD is 7.8 μm × 7.8 μm. The total number of pixels in the CCD is 3032 × 2016. It is a 12-bit CCD with readout noise 5.7 e^{-} and with a dynamic range of 75.8 dB. This CCD can operate in the temperature range of 0–60°C. The maximum fps of the CCD is 2.5 fps (3020 × 2016)/10 fps (720 × 400) region of interest mode. High sensitivity and low dark current are achieved through the adaptation of red, green and blue primary colour mosaic filters and hole-accumulation diode sensors. The spectral band of the blue filter is 400–550 nm having a centre wave length of 460 nm. The spectral band of the green filter is 450–630 nm having a centre wave length of 532 nm and the spectral band of red filter is 570–700 nm having a centre wave length of 620 nm. In this way, we can get a properly focused and unsaturated image of the source (Tripathi *et al.* 2020). Also, a full-aperture solar optical glass filter is used to avoid the saturation on the detector plane, which is made of nickel–chromium that blocks 99.999% of the incoming UV light of the Sun.

The raw images obtained with the experimental setup can be used to study the limb-darkening effect. After the calibration, the analysis of the solar images in order to obtain the corresponding limb-darkening coefficients can be performed by a simple method, using an image-processing program. In our case, we have employed Image-J software (https://imagej.nih.gov/ij/). The details of calibration and Image-J software are described in Tripathi *et al.* (2020). More details of the telescope and different instruments were presented elsewhere (e.g., Tripathi *et al.* 2020). A photograph of our experimental set-up of the telescope used to make the observation of the solar eclipse at the observing site of the Department of Physics, Banaras Hindu University, Varanasi (left panel) is shown in figure 1 along with the net radiometer placed on a tripod (right panel).

2.1 *Measurement of limb-darkening effect*

The most basic limb-darkening law is generally referred to as linear limb-darkening law. Since the Sun's intensity is not constant all over the surface, but it shows darkening around the edges. Moon *et al.* (2017) defined an empirical relation to approximate the value of the limb-darkening effect in terms of the specific intensity:

$$I(r) = I(0)\left[1 - u\left(1 - \sqrt{\frac{k^2 - r^2}{k^2}}\right)\right]. \quad (1)$$

In the above equation, k is the solar disc radius, r is the measure of radial distance from the centre of the disc and u represents the limb-darkening coefficient. It can be simplified in terms of μ (=cos θ) as (Moon *et al.* 2017)

$$I = I(0)[1 - u(1 - \cos\theta)] = I(0)[1 - u(1 - \mu)]. \quad (2)$$

Here, $I(0)$ represents the specific intensity value at the disc centre. The specific intensity value near the limb (where $\theta = 90°$ or $r = k$) is given as $I(0)(1 - u)$. Therefore, the limb-darkening coefficient is given by

$$U = \frac{[I(\text{centre}) - I(\text{limb})]}{I(\text{centre})}. \quad (3)$$

The linear limb-darkening coefficient, u determines the shape of the limb-darkening profile. We estimated different parameters at the time of the solar eclipse and try to find out their relationship with the limb-darkening effect.

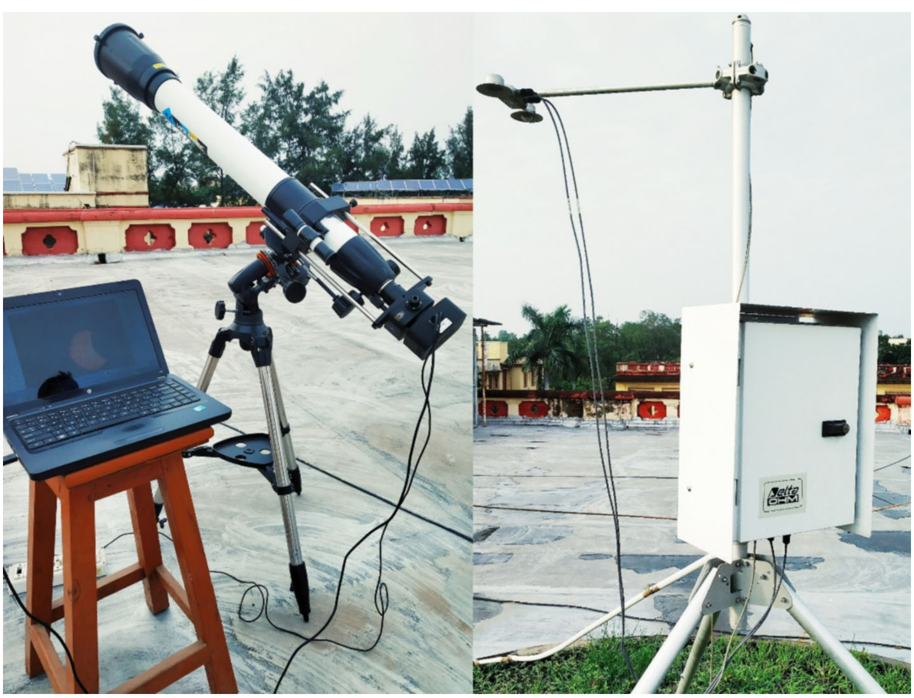

Figure 1. Photograph at the observation site (at the Department of Physics, Banaras Hindu University, Varanasi) showing experimental set-up for the observation of solar eclipse (left panel) and the net radiometer placed on a tripod (right panel).

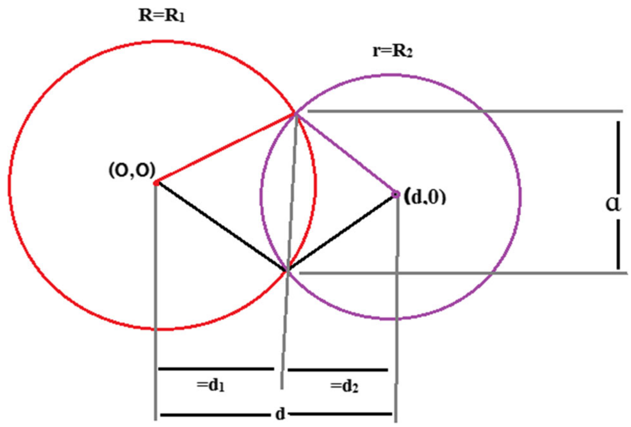

Figure 2. Intersection of two circles used in the calculation of the magnitude of eclipse and eclipse obscuration.

$$\text{Overlapped area} = r^2 \cos^{-1}\left[\frac{d^2 + r^2 + R^2}{2dr}\right] + R^2 \cos^{-1}\left[\frac{d^2 - r^2 + R^2}{2dr}\right] - 0.5\sqrt{\sqrt{(-d + r + R)(d - r + R)(d + r - R)(d + r + R)}}. \tag{7}$$

2.2 *Estimation of solar eclipse magnitude*

The eclipse magnitude is defined as the ratio of the apparent length of the Sun's diameter obscured by the Moon to the measured value of the apparent diameter of the Sun (Harrington 1997). The geometry of the solar eclipse can be visualised as the area enclosed between the two circles, as shown in figure 2. The solar eclipse magnitude is defined as (Sarrvesh *et al.* 2011)

$$\text{Eclipse magnitude} = \frac{\text{Len\_Obs}}{2 \times \text{Sun\_radius}}, \tag{4}$$

where Len_Obs represents the part of the solar diameter obscured by the eclipsing object. Len_Obs is defined as

$$\text{Len\_Obs} = (\text{Sun's radius} - d_1) + (\text{Moon's radius} - d_2), \tag{5}$$

where d_1 and d_2 are distances as shown in figure 2.

2.3 *Estimation of eclipse obscuration*

The eclipse obscuration is given as the fraction of the area of the Sun occulted by the Moon. From a mathematical point of view, it can be given as the area enclosed between the two circles (Harrington 1997). Now, consider the two circles with radii R and r and centred at (0, 0) and (d, 0) intersect in a region with a shape like an asymmetric lens as shown in figure 2. The eclipse obscuration is calculated using the formula (Sarrvesh *et al.* 2011):

$$\text{Eclipse\_Obs} = \frac{\text{Overlapped area}}{\text{Area of Sun}}, \tag{6}$$

where the area of the asymmetric lens shown in figure 2 represents the overlapped area. The formula for the overlapped area is given by (Sarrvesh *et al.* 2011)

At the time of occurrence of a solar eclipse, the apparent diameter of both the Sun and the Moon are approximately equal. Therefore, the formula for the overlapped area is obtained by considering the radius of both the circular regions to be equal and is given by

$$\text{Overlapped area} = \left(2r\cos^{-1}\left(\frac{d}{2r}\right)\right) - d\sqrt{r^2 - \frac{d^2}{4}}. \tag{8}$$

Here, r is the radius of both the circular regions.

2.4 *Measurement of solar radiation and temperature*

To measure the solar radiation, we used a net radiometer installed at the Department of Physics, Banaras Hindu University, Varanasi. There are only two pyranometers (the first one is related to the measurement of the incoming solar radiation and the second one is related to the measurement of the reflected solar radiation) installed on the net radiometer. The net radiometer is also equipped with a temperature sensor that measures the atmospheric temperature. The pyranometers measure the solar radiation for wavelengths between 0.3 and 3.0 μm. The measurement range of solar radiation is 0–2000 W/m^2, the spectral range is 305–2800 nm and the typical sensitivity is 5–15 μV/(W/m^2). The temperature measurement range is −40 to 80°C.

3. Results and discussion

With the help of the solar telescope installed at the Department of Physics, Banaras Hindu University, Varanasi, India, we observed the partial solar eclipse that occurred on 21 June 2020. Since this solar eclipse occurred during the monsoon season in India, there was partial cloudy weather on the day of the eclipse over Varanasi. Due to this cloudy weather, we were not able to record continuous and clear measurements of a solar eclipse. However, we have taken the observations of some phases of the eclipsed Sun with the help of a telescope along with the CCD camera whenever the sky was clear and tried to analyse the different parameters of a solar eclipse and studied the effect of a solar eclipse on limb-darkening effect.

As shown in figure 3, the trajectory of the rare solstice annular solar eclipse was very narrow and long. The path of the solar eclipse spanned 14 countries and two continents, Africa and Asia, as shown in figure 3. The path of this solar eclipse was passed through some parts of Central and Eastern Africa, southern Arabian Peninsula including Yemen, Oman and Southern Arabia; parts of South Asia including southern Pakistan, northern India and Nepal; parts of East Asia including South China and Taiwan and part of Micronesia including Guam. Also, a partial solar eclipse was seen in the rest of Africa, south-eastern Europe, most of Asia and in New Guinea and Northern Australia just before sunset. In West Africa, the path was about 85 km where annularity lasted only for about 1 min 20 s, which was the widest path. In India, an annular solar eclipse was seen over various places within a narrow corridor of the northern part of the country which was part of Rajasthan, Haryana and Uttarakhand and also it was seen as a partial solar eclipse from the other parts of the country. There

Table 1. *Details of the annular solar eclipse phases on 21 June 2020 and its timing in India.*

Phases of solar eclipse	Time
Partial solar eclipse began	9:15:58 am
The total solar eclipse began	10:17:45 am
Maximum eclipse	12:10:04 pm
The end of the total solar eclipse	14:02:17 pm
The end of the partial eclipse	15:04:01 pm

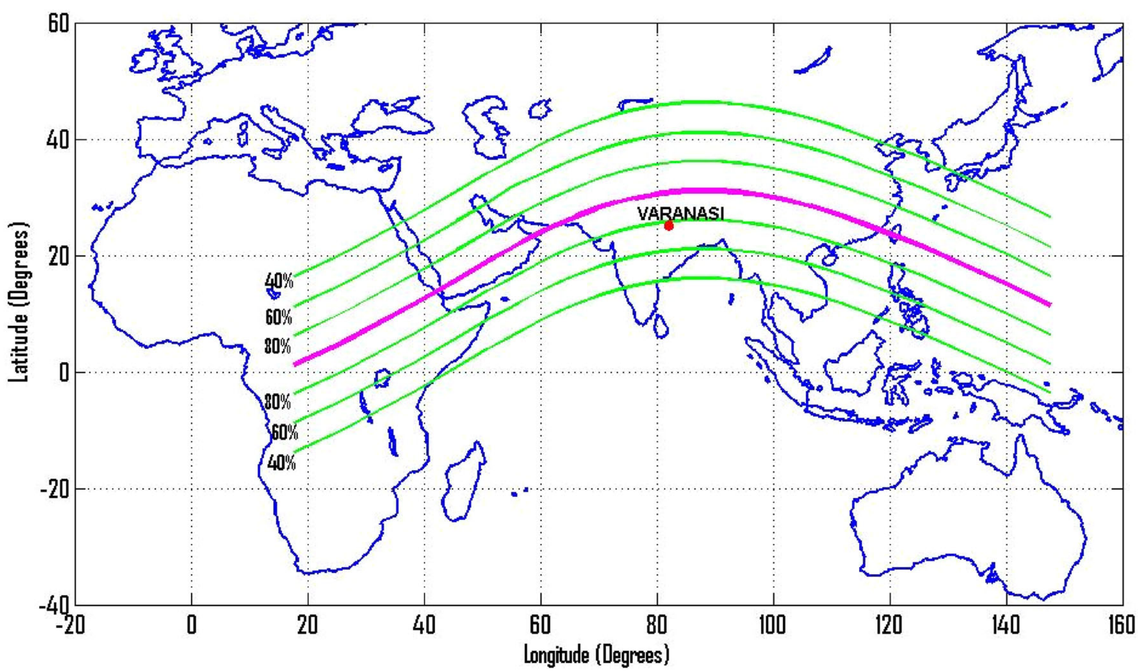

Figure 3. Path of annular solar eclipse traced over India on June 21, 2020, with percentage obscuration. The red dot shows the location of Varanasi (lat. 25°16′05″N, long. 82°59′35″E, alt. 82 m), India.

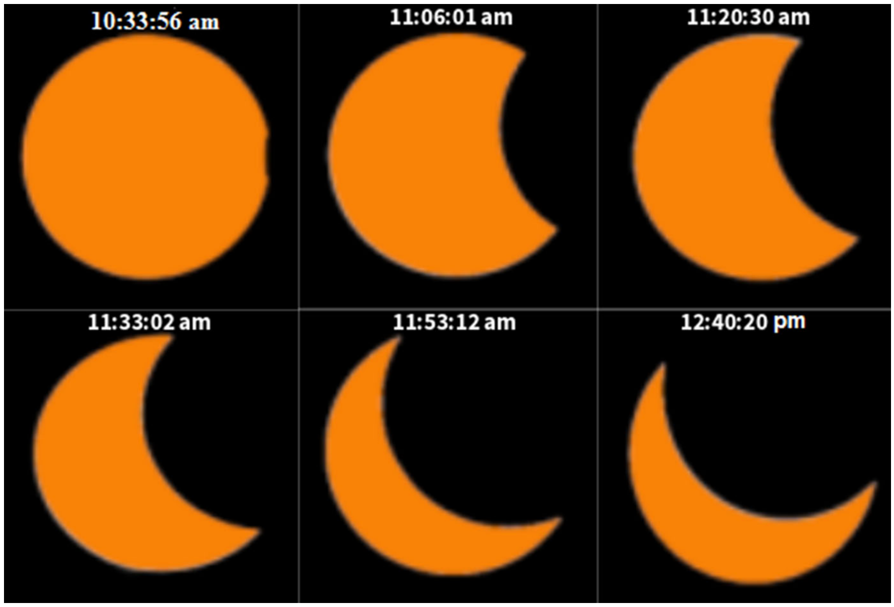

Figure 4. Combined images of different phases of annular solar eclipse at different times (IST) as on 21 June 2020 over Varanasi.

Table 2. *Solar eclipse magnitudes and eclipse obscuration for different phases of solar eclipse of images taken over Varanasi which is shown in figure 3.*

Sl. no.	Partial solar eclipse images over Varanasi	Time (IST)	Eclipse magnitude	Eclipse obscuration
1	Image 1	10:33:56 am	0.027	1.983
2	Image 2	11:06:01 am	0.184	5.180
3	Image 3	11:20:30 am	0.434	8.460
4	Image 4	11:33:02 am	0.551	9.811
5	Image 5	11:53:12 am	0.711	11.580
6	Image 6	12:40:20 pm	0.714	13.490

were few striking places such as Dehradun, Kurukshetra, Chamoli, Joshimath, Sirsa, Suratgarh, etc. where a ring of fire was visible for at least 1 min. At the maximum eclipse, the Moon covered up to 98.8% of the Sun which made it the deepest annual solar eclipse of the century. The timings of the solar eclipse in India are shown in table 1. In Uttarakhand, India, a maximum eclipse was observed with a magnitude of 0.996 and with a trajectory width of 21 km. However, the annularity lasted only for 38 s. The red dot in figure 3 shows the location of Varanasi (at Banaras Hindu University, lat. 25°16′05″N, long. 82°59′35″E, alt. 82 m), India. The partial eclipse occurred at Varanasi on 21 June 2020 from 10:30:51 am to 02:04:01 pm (IST) for 3 h 33 min.

The images of the six different phases of a partial solar eclipse that we have taken for the analysis are shown in figure 4. We have used GNU image manipulation program (https://www.gimp.org/) for different colour coding of the solar images of the CCD measurements. The images taken from the CCD camera are well resolved and are ideal for solar eclipse studies. With the help of equations (4 and 6), we measured the eclipse magnitude, as well as eclipse obscuration for the different images of figure 4 which is tabulated in table 2.

Using the CCD camera and Image-J software (https://imagej.nih.gov/ij/) we have analysed the observed data and have obtained the limb-darkening effect which is shown in figure 5. We also estimated the solar limb-darkening coefficient for all the different six eclipse phases shown in figure 4 and is tabulated in table 3. The average value of the solar limb-darkening coefficient was found to be about 0.61. Tripathi *et al.* (2020) estimated the value of limb-darkening coefficient using the same telescope and analysed the intensity variation of

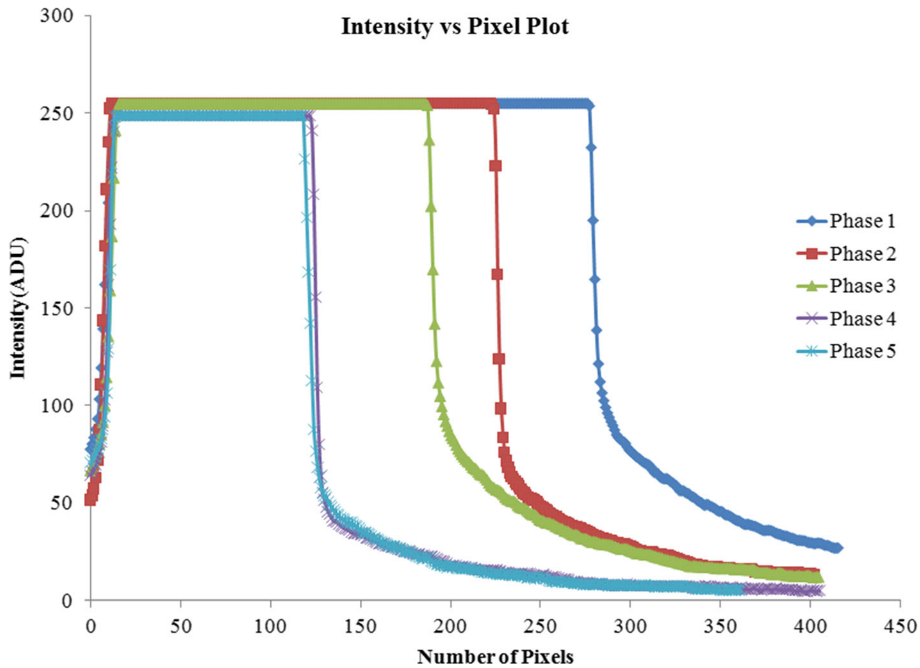

Figure 5. Intensity variations from one limb to another limb of a Sun's diameter of different phases of solar eclipse observed on 21 June 2020 over Varanasi.

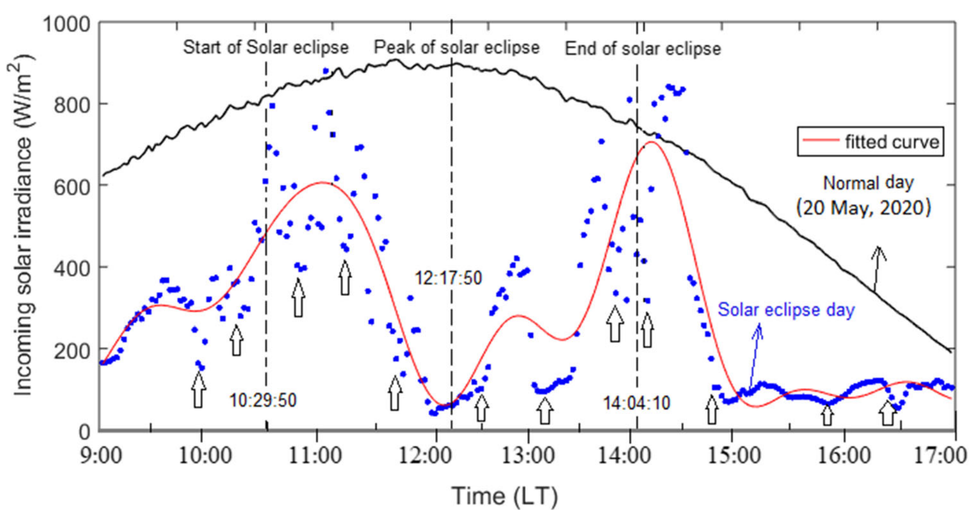

Figure 6. Variation of incoming solar radiation with the different phases of the solar eclipse observed on 21 June 2020 as well as on a normal day (20 May 2020) over Varanasi (the arrow shows the phases of passing clouds).

Table 3. *Measured values of limb-darkening coefficient (u) for different phases of solar eclipse of images taken over Varanasi which is shown in figures 3 and 4.*

Sl. no.	Different partial solar eclipse images over Varanasi	Time (IST)	Limb-darkening coefficient (u)
1	Image 1	10:33:56 am	0.6270
2	Image 2	11:06:01 am	0.6117
3	Image 3	11:20:30 am	0.6156
4	Image 4	11:33:02 am	0.6000
5	Image 5	11:53:12 am	0.6048
6	Image 6	12:40:20 pm	0.6088

the Sun using full solar disc images. Their values were found to be similar to our estimates. Also, Moon *et al.* (2017) estimated the limb-darkening coefficient to be around 0.6–0.7 using satellite data. To obtain the metal element at the star's surface and atmospheric gaseous composition, a limb-darkening study is considered to be important.

We have plotted the variation of incoming solar radiation measurements at annular solar eclipse day along with the normal day (20 May 2020, when there was no such perturbation like cloud and solar eclipse) before, during and after the solar eclipse of 21 June 2020 at Varanasi which is shown in figure 6. A substantial reduction in solar radiance is evident with the increase in solar eclipse and obscuration. The decrease in the measured values was maximum at the peak of the solar eclipse, where we can see a clear dip in these observed values. The solar radiation as well as temperature is expected to continuously decrease during the rise of the eclipse and increase during the decay of the eclipse. However, on the day of the eclipse, it was partially cloudy. Because of which there were some sub-peaks in the irradiance and as well as in the temperature before and after the maximum eclipse, i.e., at ∼11:10 UT, after 14:06 UT, between 12:38 and 13:22 UT. A similar study was seen by Uddin *et al.* (2007) during the study of the total solar eclipse of 29 March 2006. They found that the solar radiation started decreasing from the first contact onwards till the eclipse is maximum. However, with the progress of the eclipse phenomenon clouds appeared that led to dips in the solar radiation curve. We have plotted a curve fitting of the fluctuations in the solar radiation data and computed the change compared to a normal day. Calculated percentage decrease in solar radiation at the time of maximum obscuration compared to normal day and solar eclipse day is found to be 93.6%. Similar behaviour has been reported by Founda *et al.* (2007) over Thessaloniki and Kastelorizo showing 89 and 100% reduced solar radiation, respectively. Subrahamanyam *et al.* (2011) reported a reduction of about 87% solar radiation during the peak period of the annular solar eclipse that occurred on 15 January 2010 at Thiruvananthapuram in India. Aplin *et al.* (2016) have pointed out that there is greater cooling during solar eclipses when the Sun is higher in the sky, i.e., at noon-time. The solar eclipse observed on 21 June 2020 was also visible at various places in India at noon and a significant variation in the solar radiation was recorded. During the eclipse that occurred on 20 July 1963, Pruitt *et al.* (1965) found significant decrease in the incoming solar irradiance reaching the surface at about 5–6 min before the start of the eclipse using the measured value of the incoming solar irradiance at Davis (USA).

The variation of atmospheric temperature at the surface during the annular solar eclipse day along with the normal day before, during and after the solar eclipse of 21 June 2020 at Varanasi is shown in figure 7. Gerasopoulos *et al.* (2008) found that in general, there is a precise drop in the temperature at the time of the eclipse but they also suggested that the temperature changes may also depend on

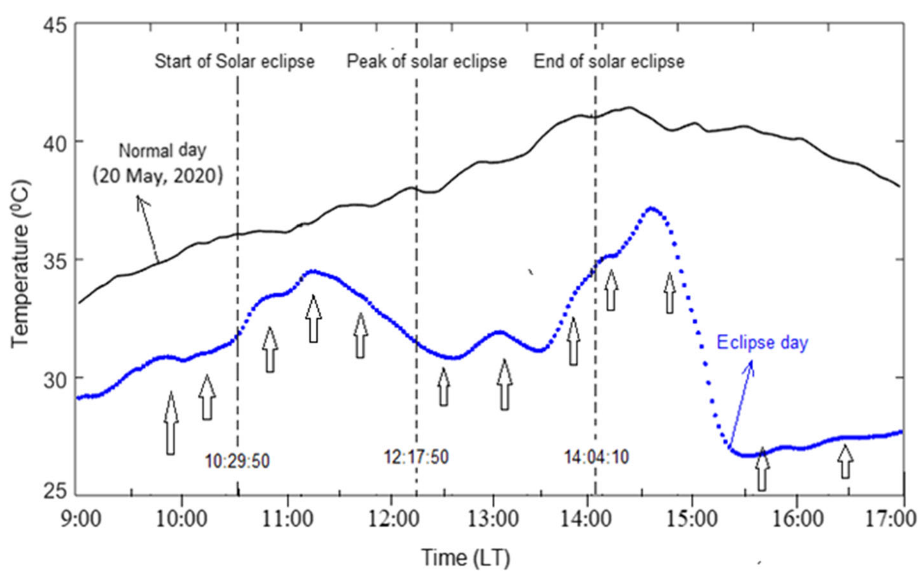

Figure 7. Variation of temperature with the different phases of the solar eclipse observed on 21 June 2020 as well as on a normal day (20 May 2020) over Varanasi (the arrow shows the phases of passing clouds).

various other factors (i.e., synoptic situation, timing, percentage of sun occultation, surrounding environment, etc.). In general, the temperature started decreasing as the eclipse progressed and continued to fall till 10–15 min later the eclipse maximum and then starts tending to achieve its normal trend. Calculated maximum percentage decrease in temperature compared to normal day and solar eclipse day is found to be 20% at 12:37 noon nearly after 20 min of the time of maximum obscuration. Anderson (1999) found that the minimum temperature reached between 5 and 20 min after mid-eclipse when the Sun's limb starts to reappear on the west side of the Moon. They also reported that there is a noticeable amount of cooling that starts when the Sun is approximately half-covered. Burt (2018) in their study over the US during the solar eclipse of 21 August 2017 observed a decrease of 8.2°C with a lag of 15 min from peak totality. Kameda *et al.* (2009) reported a time lag between totality and minimum of the temperature of about 6–30 min, as observed in our case. Girach *et al.* (2012) reported a decrease in temperature by 1.2°C over Thumba, India during the annular eclipse of 15 January 2010 with the time lag of 13 min from the maximum phase of the eclipse. Aplin and Harrison (2003) found that the thermal inertia of the surface layer to be responsible for the time lag. Subrahamanyam *et al.* (2011) reported a temperature reduction of ∼2–8°C in the troposphere and lower stratosphere with ∼4°C cooling around the tropopause and ∼6–8°C in the lower stratosphere during the maximum phase of eclipse using balloon-based measurements during the annular solar eclipse of 15 July 2010 over Thumba, India. Earlier studies in India showed that there is a decrease in air temperature by about 0.5–1.2°C (Dolas *et al.* 2002; Krishnan *et al.* 2004; Bhattacharya *et al.* 2010).

Due to cloudy weather, it was not possible to measure at all the eclipse obscuration but we still were successful to obtain the limb-darkening effect over six eclipse obscurations since the duration of the solar eclipse was the longest ever measured at about 3 h 33 min in Varanasi. Our results of the solar limb darkening, solar radiation and the atmospheric temperature at the surface are in good agreement with the studies previously reported by several authors. Our results also showed that the solar telescope along with a CCD camera mounted at Banaras Hindu University, Varanasi can provide a wonderful opportunity to study and monitor these rare astronomical events and to study the variation of limb darkening over various eclipse phases. All the above results using different measurements simultaneous should be taken into account for the development of various types of models such as radiative transfer, meteorological, etc. for better study of the effects of a solar eclipse in the environment.

4. Summary and conclusion

We presented the effect of a solar eclipse on limb-darkening and solar radiation by using a solar telescope along with auxiliary instruments such as CCD camera and with the data of net radiometer installed at the Department of Physics, Banaras Hindu University, Varanasi. The important findings of this analysis are as follows:

(1) We have estimated the eclipse magnitude and obscuration for six phases of a partial solar eclipse. Due to cloudy weather, we were restricted with limited eclipse phases. Since the duration of the solar eclipse was the longest ever, therefore, we could study the limb-darkening effect for various eclipse phases.
(2) We showed the variations of intensity over the Sun's diameter from one limb to another at different phases of a solar eclipse and have estimated the limb-darkening coefficient for six phases of a partial solar eclipse and our results are consistent with the previous studies.
(3) The variation of incoming solar radiation with the different phases of the partial solar eclipse showed a maximum of 93.6% decrease in solar radiation at the time of maximum obscuration compared to a normal day and a solar eclipse day.
(4) The variation of atmospheric temperature and the surface temperature for an annular solar eclipse day along with a normal day showed a 20% decrease in temperature nearly after 20 min of the time of maximum obscuration.
(5) Our results showed that the solar telescope along with a CCD camera mounted at the Banaras Hindu University, Varanasi provided a wonderful opportunity to study and monitor these rare astronomical events and also to study the variation of limb-darkening effect over various eclipse phases.

Acknowledgements

The study is partially supported by SERB, New Delhi for the CRG project (file no. CRG/2019/

000573) and also partially by the Institute of Eminence (IoE) (scheme no. 6031) to BHU, Varanasi. We are thankful to the referee for the thoughtful comments and suggestions that helped us to improve the quality of the manuscript.

Author statement

Shivam Chaubey: Writing – original draft preparation, software. Gaurav Singh: Methodology, conceptualisation, data curation, plotting and editing. Abhay Kumar Singh: Writing – reviewing, supervision and editing.

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Corresponding editor: Suresh Babu