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RADIO OBSERVATIONS OF THE SOLAR CORONA DURING AN ECLIPSE

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ABSTRACT

We carried out radio observations of the solar corona at 170 MHz during the eclipse of 2008 August 1, from the Gauribidanur observatory located about 100 km north of Bangalore in India. The results indicate the presence of a discrete radio source of very small angular dimension ($\approx 15''$) in the corona from where the observed radiation originated.

Key words: eclipses – Sun: corona – Sun: radio radiation – techniques: high angular resolution

1. INTRODUCTION

The solar corona can be routinely imaged from the ground at low radio frequencies ($\sim$30–300 MHz) since the observed emission originates primarily there. The main limitation of the observations is the angular resolution. Lang & Willson (1987) and Zlobec et al. (1992) had shown that radio sources of angular dimension $\sim 30''$–$40''$ exist in the solar corona from where the 327 MHz radiation originates. A similar value ($\approx 49''$) was obtained more recently by Mercier et al. (2006) at the same frequency. The results reported by Kerdraon (1979), Gergely (1986), and Ramesh & Sastry (2000) reveal that there could be similar small angular-sized structures at lower frequencies, i.e., at larger heights in the corona also. It is possible that still smaller structures exist in the corona since the aforementioned angular sizes correspond to nearly the resolution limit of the respective observing instruments. Radio observations of the Sun during an eclipse provide an opportunity to verify this.

During a solar eclipse, the angular extent of the radio source(s) located along the trajectory of the Moon can be identified with high angular resolution using the diffraction effects provided by the Moon's sharp limb similar to the lunar occultation technique (Hazard 1976). The limiting resolution given by the width ($\theta_{\rm f}$) of the first zone of the Fresnel diffraction pattern is

$$\theta_{\rm f} = 2 \times 10^5 (\lambda/2{\rm D})^{1/2}, \qquad (1)$$

where λ is the wavelength of observation and D is the Earth–Moon distance ($\approx 3.8 \times 10^8$m). This advantage has been exploited by several astronomers in the past to obtain data on solar limb brightening (Christiansen & Warburton 1950; Hagen 1956; Krishnan & Labrum 1961), sunspot active regions and plages (Covington 1947; Kundu 1959; Draco 1970; Gary & Hurford 1987; Bagchi et al. 1997), sources of suprathermal microwave emission (Correia et al. 1992; Subramanian et al. 2006), and angular dimension of discrete radio emitting sources at low frequencies (Leftus et al. 1967; Ramesh et al. 1999). In this long history of eclipse observations, the present study at 170 MHz where $\theta_{\rm f} = 10''$ assumes significance since one of the objectives of the proposed large radio antenna arrays such as the Frequency Agile Solar Radiotelescope (FASR), Low Frequency Array (LOFAR), Murchison Widefield Array (MWA), and Long Wavelength Array (LWA) is to image the solar corona at low frequencies with higher angular resolution (see, e.g., White et al. 2003; Bastian & Gary 2005; Kassim et al. 2005; Salah et al. 2005).

2. OBSERVATIONS

The solar eclipse of 2008 August 1 was partial at Gauribidanur observatory (lat: 13°36′ N; long: 77°26′ E)[1] with a magnitude of $\approx$32% and obscuration of $\approx$22%.[2] Note that the solar eclipses are always partial/annular at radio frequencies since the size of the radio Sun is large compared to the Moon. The radiation corresponding to the typical solar radio-observing frequencies originates at or above the associated "critical" level located either in the chromosphere or the corona depending on the frequency of observation. The first contact of the Moon with the "optical" Sun during the eclipse on 2008 August 1 occurred at $\approx$11:11 UT. The position angle (P.A., measured counterclockwise from the north point of the solar disk) of the Moon with respect to the Sun at that time was $\approx 345°$. The corresponding values for the maximum phase of the eclipse were $\approx$11:55 UT and $\approx 31°$, respectively. The fourth contact was at $\approx$12:37 UT with the P.A. at that time being $\approx 77°$. The declination of the Sun was $\approx 18°$ north, which is close to the latitude of the Gauribidanur observatory. We carried out observations of the solar corona at 170 MHz for a few days around 2008 August 1 with two Yagi antennas in the correlation interferometer mode. This scheme was preferred over the total power mode because of the comparatively better sensitivity and the minimal contribution to the correlated output from the galactic background and other large-scale structures in the sky (see, e.g., Kraus 1982). For our routine observations, we keep the antennas fixed vertically pointing at the zenith. But in the present case, we tilted them toward the terrestrial west and kept them fixed pointing at a zenith angle of $\approx 75°$. This was done to maximize the gain because the local time corresponding to the maximum phase of the eclipse was $\approx$5:30 PM (Indian Standard Time, IST $\approx$ UT + 05:30 hr). The baseline between the antennas was $\approx$40 m and was oriented in the east–west direction. The minimum interference fringe width corresponding to the above baseline distance is $\approx 3°$ at the zenith. Due to baseline foreshortening, the fringe width gradually changes with time and attains a maximum close to the period when the source is rising or setting. The response of the interferometer in the north–south direction is the primary beam width of the individual Yagi antennas ($\approx 60°$, between the half-power points) in that direction. These imply that the Sun is a point source, and a plot of the observations should essentially be the east–west response (fringe) pattern of the interferometer as the Sun drifts across the antennas. The minimum detectable flux density of the observing

1 http://www.iiap.res.in/centers/radio
2 http://xjubier.free.fr/en/site_pages/SolarEclipseCalc_Diagram.html

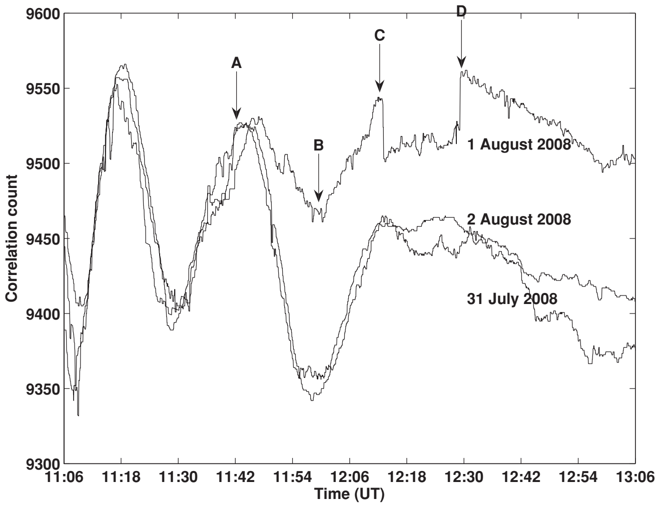

Figure 1. Observations of the solar corona at 170 MHz on 2008 July 31 and August 1 and 2 with a two-element interferometer system at the Gauribidanur observatory. The dip during the time interval ≈12:12–12:29 UT in the observations on 2008 August 1 corresponds to the occultation of a discrete radio source in the solar corona by the Moon. Refer to Section 2 for explanations of the arrow marks A, B, C, and D. The variation in the mean level of the fringes is likely due to the absence of phase switching in our receiver system (see Thompson et al. 1986 for details).

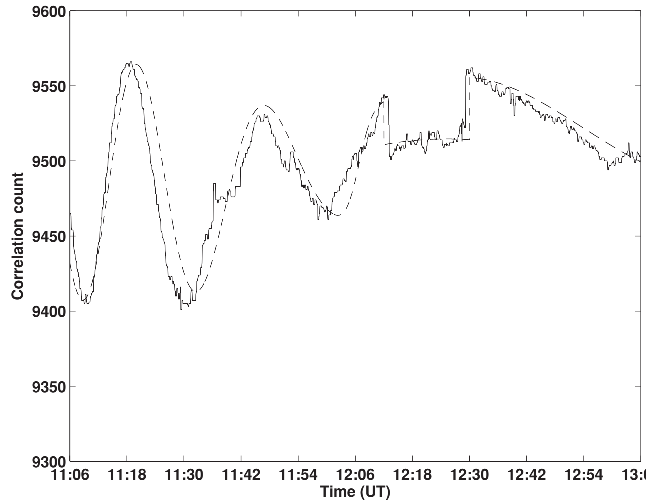

Figure 2. Superposition of our observations on the eclipse day (the solid line profile) in Figure 1 and its simulation (the dotted line profile).

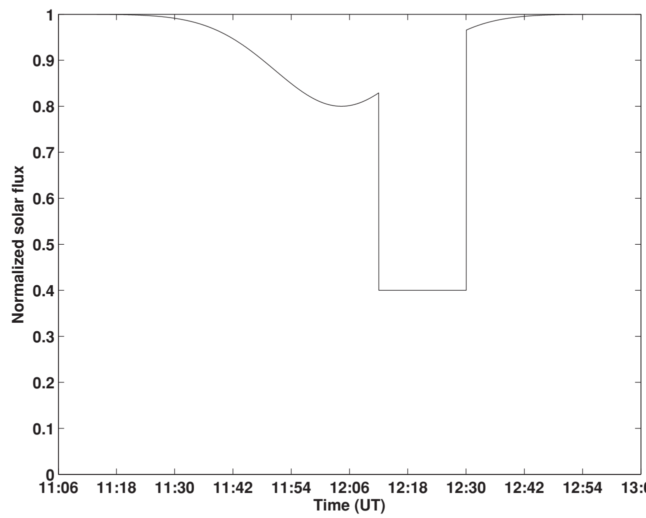

Figure 3. Predicted temporal variation in the solar radio flux density as seen from Gauribidanur on 2008 August 1 during the eclipse period. The gradual decrease and increase centered around the maximum phase of the eclipse at 11:55 UT correspond to the occultation of the background emission from the "whole" Sun. The sharp change during the interval ≈12:12–12:29 UT corresponds to the occultation of the discrete source near the solar limb in the southeast quadrant of the Sun mentioned in Section 2.

setup is ≈0.05 sfu (sfu = solar flux unit = 10^{-22} W m^{-2} Hz^{-1}) for a bandwidth (Δf) of ≈1 MHz and integration time ≈1 s. No delay tracking (τ_i, instrumental delay) was applied to compensate for the geometrical delay (τ_g) between the radio frequency signal incident on the two antennas of the interferometer from directions away from the instrumental zenith/meridian because of the following reason: for a zenith angle of ≈90° and baseline $d = 40$ m, the estimated $\tau_g \approx 0.13$ μs. For our observing bandwidth of 1 MHz, the corresponding decorrelation is ≈1%. This is very minimal and can be neglected. Similarly, we did not use fringe stopping technique to suppress the interference fringes due to the time-varying geometrical phase difference between the signal incident on the two antennas.

Figure 1 shows the result of our observations during the time interval 11:06–13:06 UT on three successive days, viz., 2008 July 31 and August 1 and 2. Due to technical issues, we recorded only the cosine component of the visibility (Kraus 1982). One can notice interference fringes until ≈12:10 UT on all three days. The absence of fringes beyond the above period is most likely due to the low elevation of the Sun. The gradual decrease in the observed correlation count beyond ≈12:30 UT indicates this. Note that the local time corresponding to the observations in Figure 1 is ≈4:30–6:30 PM. The observed profiles in Figure 1 are consistent with each other but for the following: (1) a noticeable reduction in the correlation count during the interval 11:42–12:12 UT (indicated by markers A and C) on the eclipse day as compared to the non-eclipse days. We presume that this must be due to the above period being close to the maximum phase of the eclipse at 11:55 UT mentioned earlier. (2) A sudden reduction ("dip") in the observed correlation count from ≈12:12 UT which continued until ≈12:29 UT (indicated by the arrow marks C and D, respectively). We will describe this in more detail in Section 3.

Figure 2 shows our observations on the eclipse day (2008 August 1) superposed on the simulation of the same. The latter was generated by convolving the interferometer response pattern with the one-dimensional distribution of the solar flux shown in Figure 3. We used the following inputs to model the distribution: (1) gradual decrease/increase in the flux density during the eclipse period 11:11–12:37 UT. The reduction during the maximum phase of the eclipse at 11:55 UT was taken to be ≈20%. Note that the predicted obscuration of the optical Sun was ≈22%. For the radio Sun at 170 MHz whose radius is typically 1.2 $R_\odot$ (see, e.g., Leblanc & Le Squeren 1969), we calculated the obscuration to be ≈20%. (2) An additional, sudden decrease/increase of ≈40% in the flux density for a duration of ≈17 minutes (12:12–12:29 UT) to accommodate the flux density reduction in the observations during the corresponding period (see Section 3 for details). A small offset was added to the convolved output (the simulation), particularly for the interval 11:42–13:06 UT, to match the observed fringes beyond 11:42 UT.

Figure 4 shows the composite of the white-light picture of the solar corona observed around 13:06 UT on 2008 August 1

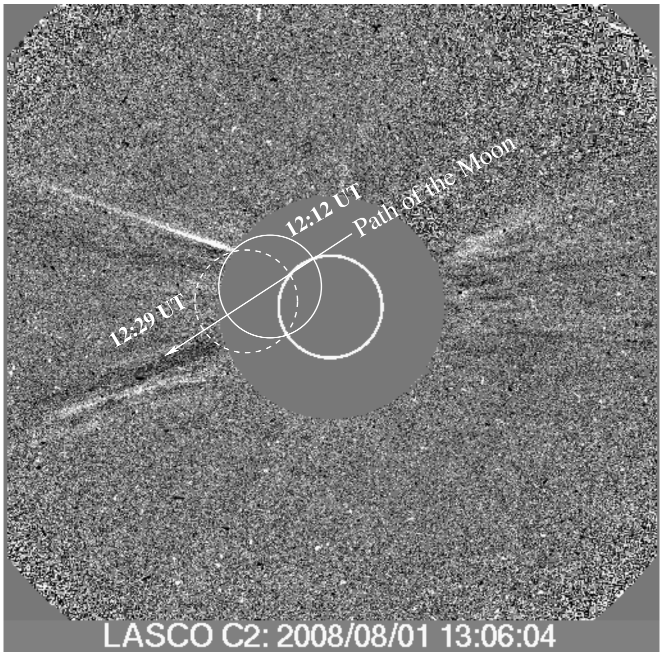

Figure 4. Composite of the white-light difference image of the solar corona observed around 13:06 UT on 2008 August 1 with the *SOHO*–LASCO C2 coronagraph, and the position of the Moon at 12:12 and 12:29 UT on the same day (indicated by the two circles in the northeast quadrant with the corresponding labels). Solar north is straight up, and east is to the left. The above two positions of the Moon correspond respectively to the onset and end of the sudden intensity reduction in the observed profile on 2008 August 1 (see Figure 1). The inner open, thick white circle (in the LASCO image representing the solar limb; $r = 1\,R_\odot$), and outer filled circle correspond to the size of the occulting disk of the coronagraph (radius $\approx 2.2\,R_\odot$).

with the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*), and the position of the Moon corresponding to the dip timings 12:12 and 12:29 UT mentioned above. The bright "ray"-like structure in the northeast quadrant above the coronagraph occulting disk is a coronal mass ejection (CME) whose estimated lift-off time was ≈12:04 UT.[3] The central P.A. of the CME is ≈58°, and its angular width is ≈5°. The linear speed of the CME is ≈387 km s^{-1}. The second-order fit to the height-time measurements of the CME indicates an acceleration of ≈3.4 m s^{-2}. The faint feature above the occulting disk in the northwest quadrant is another CME with central P.A. ≈293°, angular width ≈10°, and linear speed ≈319 km s^{-1} (S. Yashiro 2010, private communication). The first appearance of both the above-mentioned events in the LASCO field of view was at ≈13:06 UT. Other than the above, the Sun was "undisturbed." No Hα and/or soft X-ray flares were reported.[4] The position of the Moon at 12:12 and 12:29 UT in Figure 4 was obtained using the time and P.A. information for the contact of the Moon with the optical Sun at various stages of the eclipse, and the average apparent rate of movement of the Moon ($b \approx 0\farcs5$ s^{-1}) against the stellar background (see, e.g., Kraus 1982).

Figure 5 shows the composite of the white-light image of the solar corona observed around 10:30 UT on 2008 August 1 with the *SOHO*–LASCO C2 coronagraph and the radio image obtained with the Gauribidanur radioheliograph (GRH; Ramesh et al. 1998) at 77 MHz on the same day around 09:00 UT. There is a good correspondence between the enhanced radio emission

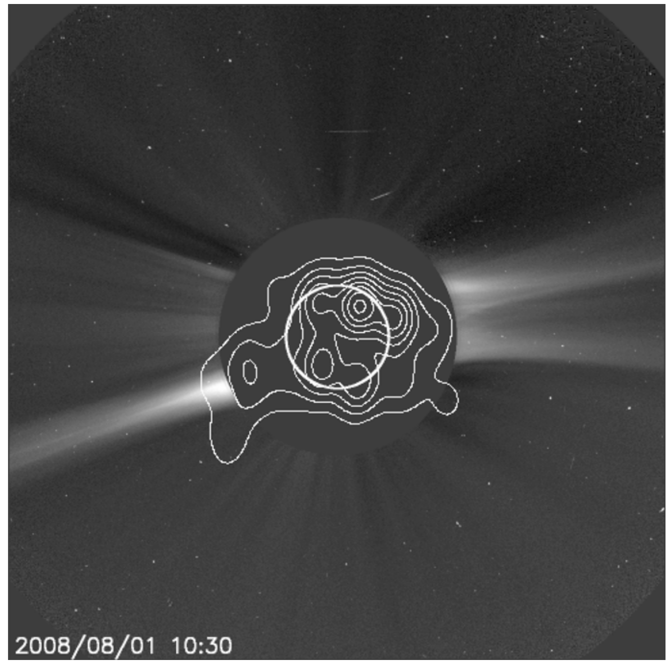

Figure 5. Composite of the white-light image of the solar corona observed around 10:30 UT on 2008 August 1 with the *SOHO*–LASCO C2 coronagraph, and the radioheliogram obtained with the GRH at 77 MHz on the same day around 09:00 UT. One can notice that there is a good correspondence between the enhanced radio emission off the solar limb and the bright structures in the LASCO image, particularly in the southeast quadrant.

off the limb particularly in the southeast quadrant and the bright structures in the *SOHO*–LASCO C2 field of view. A comparison with the white-light pictures of the solar corona obtained during the eclipse period from Mongolia and Russia (Pasachoff et al. 2009; Habbal et al. 2010) shows a good correlation between the radio and white-light emission in the low corona close to the solar limb also. Note that we were not in a position to carry out observations with the GRH during the eclipse period since the Sun was outside the field of view of the antenna.

3. ANALYSIS

The sudden changes in the radio emission from the Sun during an eclipse correspond to the covering (ingress) and/or uncovering (egress) of small areas of enhanced radio brightness in the solar atmosphere by the Moon's limb (Christiansen et al. 1949). At a frequency like 170 MHz, the angular dimension of such regions can be estimated to an accuracy of ≈10″ (see Equation (1)) due to the diffraction effects at the Moon's limb as mentioned above. This indicates that the dip during the time interval ≈12:12–12:29 UT in the observed profile on 2008 August 1 in Figure 1 corresponds most likely to the occultation of one such discrete radio source in the solar atmosphere by the Moon. The points of intersection between the circles representing the position of the Moon at 12:12 and 12:29 UT in Figure 4 indicate the two probable positions for the occulted source (Hazard 1976). We measured the occultation angle (θ) subtended by the above two intersection points at the center of the Moon at 12:12 and 12:29 UT and found it to be ≈74°. Substituting this in the following relation for the duration (T) of the occultation (Hazard 1976),

$$T = (2s/b) \times \cos(\theta), \tag{2}$$

[3] http://cdaw.gsfc.nasa.gov
[4] http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp

we get $T \approx 17$ m. This is equal to the observed occultation duration in the present case. The term s in the above equation is the semi-diameter of the Moon and is $\approx 900''$.

We calculated the angular size of the occulted source (i.e., its linear extent in the direction of movement of the Moon) from the average of the time taken by the received solar flux to reach the minimum value (from the pre-occultation level) during the ingress at ≈12:12 UT (marker C in Figure 1) and subsequently to reach the pre-occultation level from the minimum value during the egress at ≈12:29 UT (marker D in Figure 1). The value is $\approx 15''$.

For the position of the occulted source, we can rule out the intersection point above the path of the Moon in Figure 4 since it is at a large radial distance ($r \gtrsim 2.2\,R_\odot$, the edge of the occulting disk in the *SOHO*–LASCO C2 coronagraph) compared to the 170 MHz plasma level in the background solar corona ($r \approx 1.2\,R_\odot$). This implies that the lower of the aforementioned two intersection points between the circles labeled 12:12 UT and 12:29 UT in Figure 4, located close to the solar limb in the southeast quadrant, is the most likely position of the occulted source. The possibility of a discrete radio emitting source at 170 MHz present there is likely because of the following. (1) The two-dimensional radio image obtained at 77 MHz with the GRH (Ramesh et al. 1998) on 2008 August 1 around 09:00 UT indicates the presence of a weak discrete source close to the aforementioned position (Figure 5). (2) The radio images obtained with the Nancay radioheliograph[5] (NRH) on 2008 August 2 also indicate the presence of a discrete source near the same location. Note that no NRH images were available for 2008 August 1. (3) White-light pictures of the corona obtained during the eclipse reveal activity in the streamer close to the limb in the southeast quadrant (see Figure 6 in Pasachoff et al. 2009). A close-up view of the base of the streamer indicates an arch-like configuration extending up to $r \approx 1.3\,R_\odot$. The arch overlies a chain of filaments on the disk near the limb (see Figures 3 and 7 in Habbal et al. 2010).

We also estimated the flux density of the occulted source, but in an indirect manner as follows: in Figure 3, we had reduced the flux density during the interval 12:12–12:29 UT by ≈40% in order to get a good match between the observations and the simulations in Figure 2 during the corresponding period. We tried different values of flux reduction in the one-dimensional distribution in Figure 3. The best match was only for the above case. This implies that the flux density of the discrete source mentioned in the previous paragraph should be ≈40% of the radio emission from the background solar corona at 170 MHz. If we assume the flux density corresponding to the latter during solar minimum period to be ≈7 sfu (Alissandrakis & Lantos 1996), the flux density of the occulted discrete source turns out to be ≈2.8 sfu. Using this, and assuming circular symmetry, we then estimated the peak brightness temperature (T_b) of the discrete source to be $\approx 6 \times 10^9$ K. The flux density and T_b derived above are in the range of the corresponding values for noise storms at 169 MHz reported in the literature (Kerdraon & Mercier 1983).

4. SUMMARY

The eclipse observations reported indicate the presence of a discrete radio source of very small angular extent ($\approx 15''$) in the solar corona from where the observed 170 MHz radiation originated. This is about a factor of two lower than the sizes of the smallest discrete sources in the solar corona reported earlier (see Section 1). Similar observations in two dimensions might be useful to infer the limiting sizes of the discrete radio wave emitting solar sources at low frequencies (see, e.g., Bastian 2004; Subramanian & Cairns 2011).

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[5] http://bass2000.obspm.fr