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Unique Observation of a Solar Flare by Lunar Occultation During the 2010 Annular Solar Eclipse Through Ionospheric Disturbances of VLF Signals

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Abstract Very Low Frequency (VLF) radio waves propagate through the Earth-ionosphere waveguide. Irregularities caused by excess or deficient extreme ultra-violet and X-rays, which otherwise sustain the ionosphere, change the waveguide properties and hence the signals are modified. We report the results of monitoring of the NWC transmitter (19.8 kHz) by a receiver placed at Khukurdaha (22°27′N, 87°45′E) during the partial solar eclipse (75 %) of 15th January, 2010. The propagation path from the transmitter to the receiver crosses the annular eclipse belt. We got a clear depression in the data during the period of the eclipse. Most interestingly, there was also a X-ray flaring activity in the sun on that day which reached its peak (C-type) right after the time when the eclipse reached its maximum. We saw the effects of the occultation of this flare in our VLF signal since a part of the X-ray active region was clearly blocked by the moon. We quantitatively compared by using analogies with previous observations and found best fitting parameters for the time when the flare was occulted. We then reconstructed the VLF signal in the absence of the occulted flare. To our knowledge, this is the first such incident where the solar flare was observed through lunar occultation and that too during a partial eclipse.

Keywords Solar flares · Eclipses · Radio waves · Ionosphere

1 Introduction

Solar eclipses provide unique opportunities to study the behavior of the ionosphere (Crary and Scheneible 1965; Mitra 1974; Sen Gupta et al. 1980; Lynn 1981; Pant and Mahra,

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1985; Thomson 1993; Clilverd et al. 2001; Kozlov et al. 2007; Karimov et al. 2008; Chernogor 2010; Chakrabarti et al. 2010). During a solar eclipse, the Sun's photosphere is shielded by the Moon thereby decreasing the ionizing radiation from the Sun, causing changes in electron concentration of ionosphere. This causes noticeable effects on VLF radio wave propagation as the wave guide itself changes shape. Not only the solar eclipses, but also the solar flares, sunspot activities, geomagnetic disturbances, meteor showers, nuclear explosions, i.e., any terrestrial or extra-terrestrial event which may affect the electron contents of the ionosphere, will leave its marks on the received VLF signals, since the spherical waveguide formed in the region between the earth's surface and the lower ionosphere (D-layer) changes its shape temporarily.

During solar flares, the X-ray flux received at the Earth increases dramatically, often within a few minutes, and then decays again in times ranging from a few tens of minutes to several hours. These X rays are absorbed before they reach the ground. X-ray detectors on the GOES 14 satellites are monitoring X-ray fluxes from the sun continuously. During the daytime, the propagation paths of VLF/LF waves are largely stable. When a solar flare occurs, the extra ionization generated by the X-rays lowers the effective reflection height of the ionosphere by an amount that depends on the intensity of the X-ray flux (e.g., Mitra, 1974). On 15 January 2010, an annular solar eclipse occurred but the eclipse was partial from Khukurdaha (22° 27′N, 87°45′W), our receiving site (R) (Fig. 1). The receiving station is in a radio quiet zone. It is about 400 km away from the zone of total annularity. During the time of eclipse, a weak flare was in progress and was completely blocked by the moon at the places of total annularity. However, at our receiving station, the maximum coverage of the solar disk was 75 %, and the flare was also blocked partially. Thus what we observed is a combined effect of the eclipse and the partial occultation. This is the first such event that a solar flare was seen through lunar occultation during a partial eclipse (Maji et al. 2010). In Table 1, we present the parameters of eclipse, flare and the receiving station. We present the latitude and the longitude in the first column. In the second column, the coverage in percentage is given. In the next three columns we give the times of the first contact (between the lunar and solar disk), time when the coverage is maximum and the final contact. The last two columns give the beginning and end times when the solar flare remained above C-type (i.e., the flux was higher than 10^{-6}watt/m^2).

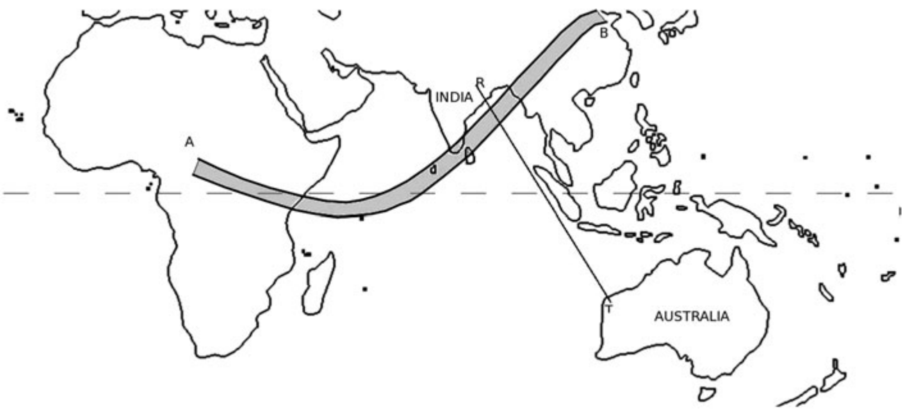

Fig. 1 The propagation path of 19.8 kHz from NWC to Khukurdaha is shown. The *shaded area* from *A* to *B* is the path of total annularity of January 15, 2010. *R* and *T* represent the locations of the receiver

Table 1 Parameters related to the receiving station, eclipse and the flare

Receiver lat, long	Eclipse coverage %	1st contact(IST) altitude (deg)	Maximum (IST) altitude (deg)	2nd contact(IST) altitude (deg)	C 1.0 begins (IST)	C 1.0 ends (IST)
Khukurdaha 22°27′N, 87°45′E	Partial 75.1	12:05:30 +46	13:56:26 +36	15:28:28 +27	13:51:55	14:44:47

In the present work, we examine the combined effects of the solar eclipse of January 15, 2010 on the NWC (19.8 kHz) VLF signals and the effects of the solar flare superposed on it. The receiving station and transmitting station are in opposite sides of the annular solar eclipse zone (AB, Fig. 1). In the next section, we present the details of the eclipse and the flare. In Sect. 3, we present our set up for receiving data. We also present the results. We reconstruct the expected VLF signal in the absence of the solar flare. Finally, in Sect. 4, we discuss our results and make concluding remarks.

2 The Eclipse and The Flare

The annular solar eclipse of January 15, 2010 started at 12:05 IST (=UT+5:30) and continued up to 15:28 IST. This was visible partially (maximum coverage 75 %) from the receiving station. The maximum obscuration was at 13:56:26 IST. Though the transmitter was far away from the eclipse belt, on the way from NWC to Khukurdaha, the Ist, 2nd and 3rd reflection points at the lower boundary of the ionosphere went through an eclipse coverages of 23, 63 and 78 % respectively as measured at 70 km above the ground.

An isolated C1.3 solar flare started at 07:22 UT (12:52 IST) and continued till 10:22 UT (15:52 IST) with a maximum at 08:41 UT (14:11 IST) which is about 15 min after the maximum obscuration of the solar disk. The peak energy flux in 1.5keV to 12.5keV was 1.3×10^{-6}watt/m^2 which is above the detectability limit of our VLF antenna (typically, a C1.0 flare $\sim 10^{-6}$watt/m^2, see Nandi et al. 2010). GOES Satellite was observing the sun unobstructed by the lunar occultation.

In Fig. 2, we superposed the magnetogram data of the sun on the solar disk occulted by the moon taken from web site (http://sec.noaa.gov/). Clearly, visually we can see that a part of the active region (No. 1040) is blocked by the moon. We thus believe that the solar flare was occulted partially by the moon and this is expected to be reflected in the sudden ionospheric disturbance data from this particular solar flare as we will show below.

3 The Experimental Setup, Methodology and Results

A loop antenna and Gyrator III type receiver were deployed to monitor VLF data at Khukurdaha. Real time narrow band amplitude data from several transmitters is being recorded automatically in the computer. Detection of a weak flare in NWC data is a very routine activity from our receiver. In Fig. 3a, b, we present the VLF responses (top panel) of two isolated flares (a) C4.0 (on 6th February, 2010) and (b) C1.3 on 12th February, 2012) as seen by the GOES satellite in the 1.5–12.5 keV band (middle panel). The bottom panel gives the ratio of the two data amplitudes (which corresponds to a shift in log scale), when the flare was above B5. A horizontal line at C1.0 has been drawn for a duration when

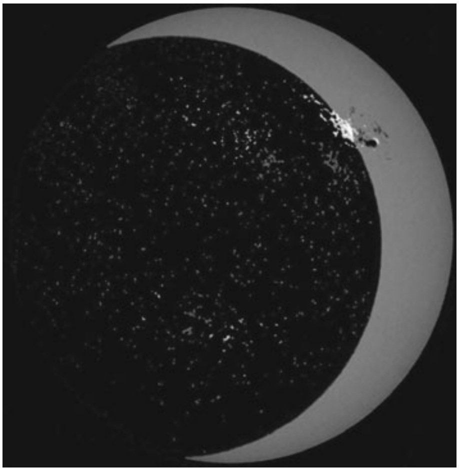

Fig. 2 Magnetogram superposed on the visual Sun. It is clear that the part of the *outer ridges* of the active region is blocked by the moon

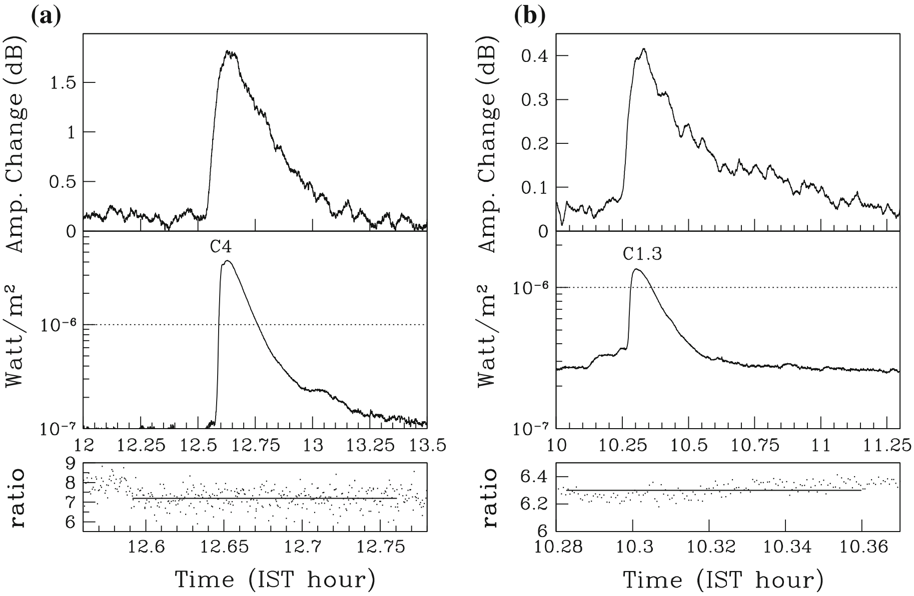

Fig. 3 Examples of a **a** C4.0 flare and a **b** C1.3 flare in GOES 14 data in the *middle panel* and corresponding NWC signal in the *upper panel* (after subtraction from the previous day's data) received at Khukurdaha. The *shape* of the VLF amplitude variation is roughly similar to the solar flare data especially in region above C1.0 as can be seen from near constancy of the ratio of the VLF/GOES amplitudes (*bottom panel*). The *horizontal line* in *bottom panel* (drawn at C1.0) corresponds to time range in which the data is above C1.0

the flare is above C1.0. This is to show that the ratio is nearly constant in this region. We thus use the fact that near the peak, the factor of proportionality is a constant. Given that weak flares could be detected and have features similar to those of the X-ray variation, major dissimilarity between the two shapes could be attributed to occultation of the flare by the moon.

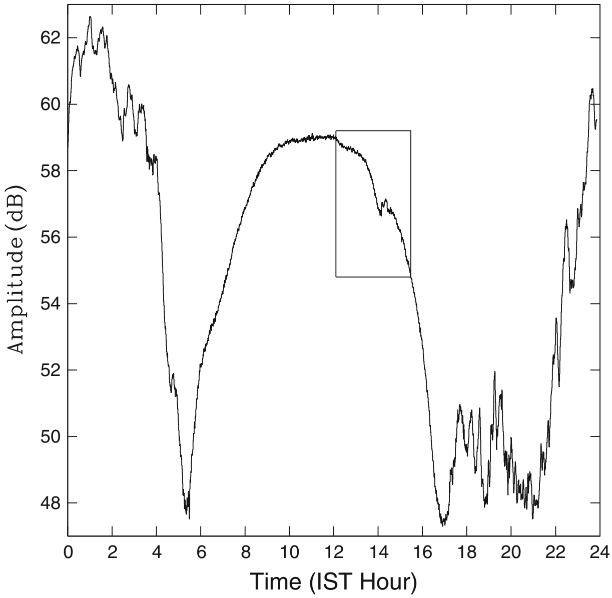

Fig. 4 A full day data from our receiving station on the eclipse day. The *box* highlights the ionospheric disturbances observed due to the joint effects of the eclipse and the flare. *Data* is normalized by LWPC midday value with respect to our receiving station. The time is in IST (UT+5:30)

In Fig. 4, we present the amplitude (dB) variation of the NWC signal as obtained by our receiver on the 15th January. The box highlights the region around the eclipse which clearly shows a dip near the eclipse maximum and a upward rising kink near the flare maximum. For the analysis of the effect of the eclipse we consider the data of 3 days from 14th January to 16th January, 2010. We normalized the data of our receiver with the amplitudes in the midday and midnight as predicted by the LWPC code (Ferguson 1998). The data of the 3 days (marked) are plotted in Fig. 5. The data of the 14th and the 16th January are smoother as compared to that of the 15th January. The effects of the eclipse and the flare are now analyzed in the following way.

In Fig. 6, we present three panels—in the top panel, we show the GOES data of the solar flare in soft X-rays (upper curve) and hard X-rays (lower curve) of the 15th January, 2011 during the time of the eclipse. On the 14th and the 16th January, the solar disk was X-ray quiet at around B 1.1. Thus we could subtract the average of the VLF data of the 14th and 16th from the data of the 15th to obtain the combined effects of the flare and the eclipse. The subtracted result is shown in the middle panel. The net deviation from ‘0’ is by about -1dB is due to the combined effect: a reduction of electron number density at the lower ionosphere due to the solar eclipse, and an enhancement of the electron density due to the solar flare. In the lower panel, we present the fraction of the exposed disk of the sun as a function of time. This is to show that the VLF signal remains almost normal till the solar disk is covered by about 25 %. Note that the observed minimum of the VLF signal is about 7 min after the maximum obscuration. This is on the larger side as compared to what is observed for eclipse (without any flare) at a distance of 6,000 km (see, Clilverd et al. 2001 for delay in the midrange of 1,000–10,000 km). They however see a similar delay (again, without any flare) in the short path length (<1,000 km). In Chakrabarti et al. 2010,

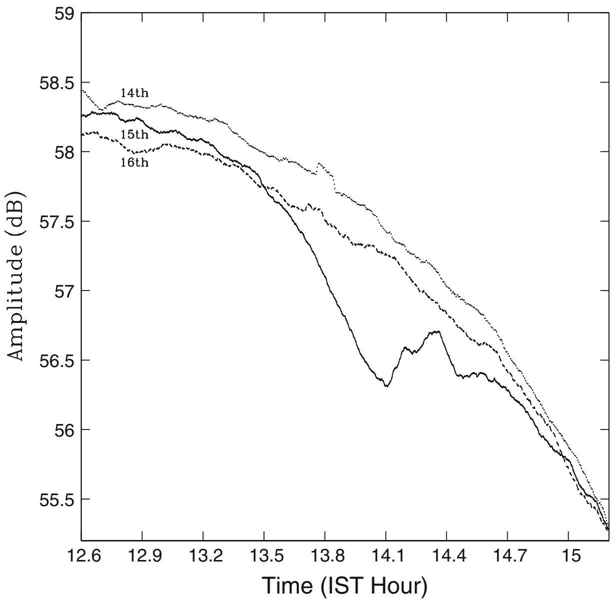

Fig. 5 Comparison of the VLF data of the 15th January with those of the 14th and the 16th (*marked*). The deviation from normal, smoother data in the 15th January, 2010 is clear. The noise is less than 0.05 dB

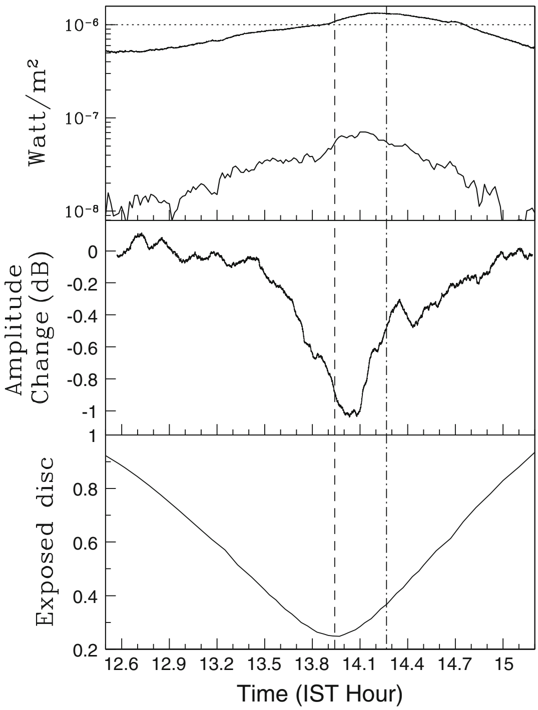

Fig. 6 *Upper panel*: GOES data of the solar flares in soft X-rays (*upper curve*) and hard X-rays (*lower curve*) of 15th January, 2011. Middle panel: Difference of the average of the 14th and the 16th data from that of the eclipse day. The net deviation from normal, which is due to a reduction due to eclipse and enhancement due to the flare is about −1dB. *Lower panel*: Fraction of the unobstructed solar disk as a function of time (IST) on the eclipse day. The *dashed vertical line* indicates the time of the maximum eclipse and the *dot-dashed vertical line* indicates the time of the peak flare

a delay of 2–3 min was noted for shorter paths (<3,000 km). The unusual shift of ~7 min, along with bumps in the signal profile in the recovery phase, is already an indication that the solar flare has modified the result expected from the eclipse alone. We split the signal for the eclipse effect using a procedure described below.

Separation of the effects of the eclipse and the flare is tricky, since the flare could have been occulted partially by the moon and thus could affect the net signal variation differently than what would be expected from the unobstructed flare. However, there are several clues: (a) Fig. 3a shows that a C4.0 flare enhanced the signal by about 0.5dB (when it was above 10^{-6} W/m^2) and by the time it was down to C1.3, the enhancement is about 0.3dB. Exactly same enhancement is also seen in Fig. 3b. Here too, the difference in VLF signal amplitude is about 0.3dB between the time the signal crosses 10^{-6} W/m^2 and the peak at 1.3×10^{-6} W/m^2. (b) The enhancement of the VLF signal intensity by the flare is roughly proportional to the flux. This could be seen in the bottom panels of Fig. 3a, b, which is simply the difference in the upper panel (which is already in log scale) and the middle panel value in log scale. (c) The sudden minimum of the VLF signal at ~14.43 IST indicates that an obscuration could be centered around this point. (d) Given that the X-ray emitting region is very small, it is easier to block and expose faster and thus a time symmetric function of blocking, such as an inverse Gaussian, $-Ae^{-(t-t_0)^2/(2\tau^2)}$ (where A is the amplitude, t is the time in hours and τ is the half-width of the Gaussian) could be adequate to model the occultation.

In Fig. 7, we show the result assuming, $A = 0.2$, $\tau = 0.041$, $t_0 = 14.43$. The curve (a) is the hard X-ray flux (Curve b in Fig. 7) suitably multiplied by a factor obtained from previous flares (see, Fig. 3) so as to have ~0.3 dB enhancement at the flare peak. The curve (b) is the observed VLF signal (same as in the middle panel of Fig. 6). Curve (c) is

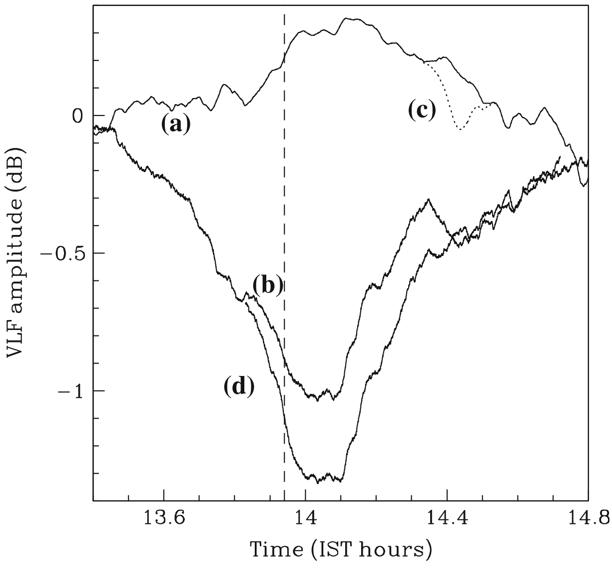

Fig. 7 Expected VLF signal of the eclipse after removing the effects of the flare which was partly occulted by the moon. **a** GOES flux (in log scale) in hard X-ray channel suitably shifted to produce ~0.3 dB at the peak; **b**. The observed VLF signal with a combined effects of the eclipse and the flare; **c**. The model flare profile at the VLF receiving station after symmetric occultation by the lunar disk is included; **d**. The expected VLF amplitude variation due to the partial eclipse alone, obtained from **b**–**c**

the flare signal received by the earth after lunar occultation centered at $t = 14.43$. The (d) is resultant (=b–c) VLF amplitude which would have been expected if the flare was absent.

The resultant curve is more symmetric, became minimum only about 4 min after the maximum obscuration. Moreover, the net reduction is about -1.4 db which is more close to reality. We have drawn the resultant during which the flux is above 10^{-6} W/m^2, (C-type), since our receiver is weakly sensitive below this flux. Notice that the signal corrected for the flare matches with the observed flare after $t = 14.4$.

4 Discussion and Conclusions

In this paper, we have presented the results of a unique cosmic coincidence when a solar flare occurred during an annular solar eclipse and the flare was occulted by the lunar disk as seen by the VLF receiving station at Khukurdaha, INDIA. Since it is difficult to point to the boundary of a flaring region, we have taken resort to modeling the occultation of the flare and computed the expected VLF signal in the absence of the flare which seems to be sufficiently reasonable. Our result, corrected for the flare, indicates that the VLF signal became minimum at 4 min after the maximum obscuration of the sun. The error could be about a minute as the delay of the response of the ionosphere due to a weak X-ray flare around noon has been found to be of this order. The deviation of the signal was highest of about -1.4dB and it returned back to normal value almost symmetrically. We computed the correction term using the solar flux in the hard X-ray channel, as the region is expected to be smaller and is liable to be quickly occulted in a symmetric way.

Of course, several satellites such as Hinode and RHESSI were also observing the sun on this date. An independent X-ray imaging (in one dimension) of the flaring region could be done using our VLF data through numerical simulation of the atmospheric response of the flare exposed after occultation of the moon. This is beyond the scope of the present paper and would be dealt with elsewhere.

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