ECLIPSE OBSERVATIONS OF COMPACT SOURCES IN THE OUTER SOLAR CORONA

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Abstract. We report here on high angular resolution observations of solar noise storm sources at a frequency of 75 MHz. The data for the study were obtained at the Gauribidanur Radio Observatory (**l**ong.: 77°26′12″ E, **l**at.: 13°36′12″ N) about 100 km north of Bangalore, India, during the solar eclipse of 24 October 1995. Our main conclusion is that there are structures of angular size $\leq$ 2.5 arc min in the outer solar corona.

1. Introduction

The variation of the spatial structure of noise storm sources has been a subject of investigation for many years. On the basis of multi-frequency observations, McLean (1981) suggested that the storm sources show columnar structure, elongated along open field lines. It is now generally believed that the size of noise storm sources increases with decreasing frequency, from about 2′ at 327 MHz (Lang and Wilson, 1987) to about 21 arc min at 30.9 MHz (Thejappa and Kundu, 1991). But high-resolution studies at 333 MHz with the VLA show that the typical source sizes are in the range 0.5 arc min to 1.5 arc min (Zlobec *et al.*, 1992). At lower frequencies such studies have not been carried out so far because of the lack of radio telescopes with sufficient angular resolution. Eclipse observations of the radio emission from the solar corona can be used to detect discrete sources of radio emission and to check their association with features seen in other frequency bands like white light, X-rays, etc. In addition the source sizes can be measured accurately due to the high spatial resolution that can be obtained. The present observations, carried out with an angular resolution of 14 arc sec, reveal for the first time the existence of small-scale (angular size $\leq$ 2.5 arc min) structures in the outer corona at a height of $\approx 0.4\ R_{\odot}$ above the photosphere, where the 75 MHz plasma level in the quiet Sun is located (Newkirk, 1961).

2. Lunar Occultation Technique

During a solar eclipse, radio observations of the Sun can be carried out with high angular resolution using the diffraction effects provided by the Moon's sharp limb

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(Correia, Kaufmann, and Strauss, 1992). The limiting resolution, given by the angular width (θ_f) of the first zone of the Fresnel diffraction pattern, is

$$\theta_f = 2 \times 10^5 \ (\lambda/2\mathrm{D})^{1/2} \text{ arc sec} , \tag{1}$$

where λ is the wavelength of observation and D is the Earth–Moon distance ($D \approx 3.8 \times 10^8$ m). The duration (T) of the occultation is given by (Hazard, 1976)

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

where s is the semi-diameter of the Moon ($\approx$ 900 arc sec), b is the apparent rate of movement of the Moon in the sky ($\approx$ 0.33 arc sec s^{-1}) and θ is the angle subtended at the center of the Moon by the Moon's path and the source at the time of occultation. According to Drago and Noci (1969), the size of the localized regions on the solar disk can be best estimated by considering the derivative (slope) of their occultation curves. As shown in Figure 2, the covering or uncovering of a discrete source in the corona by the limb of the Moon, coincides with a sharp change in the slope of the occultation curve. If $\phi(t)$ is the observed occultation curve and $\dot{\phi}(t)$, its derivative, then the dimension (d) of the occulted source is given by

$$d = b(t_2 - t_1) \tag{3}$$

where $t_2 - t_1$ is the time interval taken by the limb of the Moon to either fully cover or uncover the source and the term b is the same as in Equation (2).

3. The Instrument

At Gauribidanur the eclipse was partial with a maximum magnitude (eclipse magnitude is defined as the fraction of the Sun's diameter occulted by the Moon) of 0.6123 and an obscuration (eclipse obscuration is a measure of the Sun's surface area occulted by the Moon) of 0.5212. The first contact of the Moon with the Sun took place at 02:02:08 UT with the Moon at PA = 317° (position angle measured counter-clockwise from the north point of the Sun's disk) and the fourth contact at 04:24:26 UT with the Moon at PA = 94° (F. Espenak, personal communication). Observations of the solar corona were carried out using a specially built antenna system. An array of 8 log-periodic dipoles was set-up as a north-south interferometer with a baseline of 28 m. Each arm of the interferometer had 4 antennas with an inter-element spacing of 7 m. The antennas were tilted towards the east in such a way to maximize the response pattern of the array on the Sun at the time of maximum phase of the partial eclipse which occured at 03:08:35 UT as seen from the observatory's longitude. It was not necessary to track the Sun as the beamwidth between the half-power points in the east-west direction was very broad ($\approx$ 6 hr). At $\lambda = 4$ m, the effective collecting area was approximately 64 m^2 and

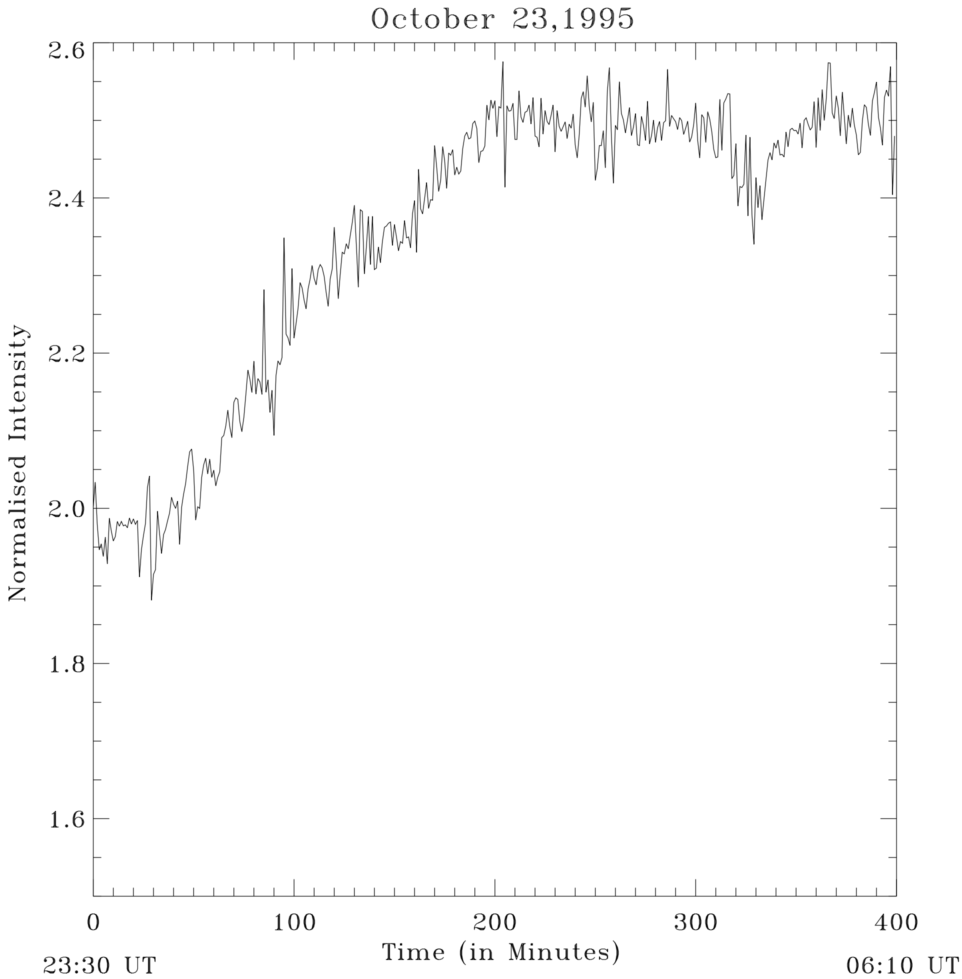

Figure 1. One-dimensional drift scan of the Sun taken on the day before the eclipse.

the minimum detectable flux density was about 100 Jy for an integration time of 2 s. This gave a resolution of approximately 14 arc sec (Equation (1)) in a direction perpendicular to the limb of the Moon.

4. Observations

One-dimensional drift scans of the Sun obtained using the above antenna system on 3 different days are shown in Figures 1–3. On each day, the observations started around 23:30 UT and continued till 06:10 UT. The scan on the eclipse day (24 October 1995) shows the disappearance of 2 discrete sources (A and B) at times 02:06 UT and 03:24 UT. Both the sources reappeared after a duration of

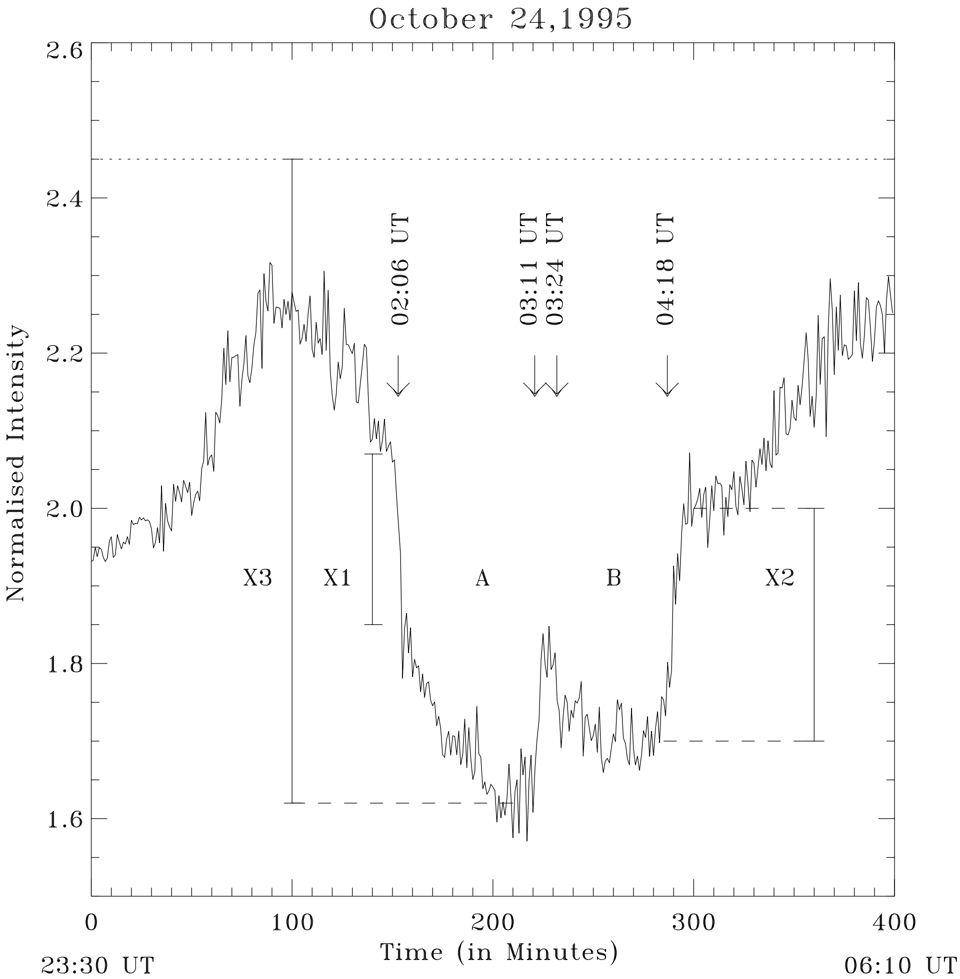

Figure 2. One-dimensional drift scan of the Sun taken on the day of the eclipse. The dotted line (corresponding to normalised intensity = 2.45) represents the average value of the quiet-Sun level observed on the days prior to and after the eclipse. See text for details on the lines X1, X2, and X3.

65 and 54 min at 03:11 UT and 04:18 UT, respectively. The angular sizes of the two sources were estimated using Equation (3) and the derivative of the observed eclipse curve shown in Figure 4: the values are $\leq$ (2.5 arc min$\pm$0.5 arc min). Each point in Figure 4 is given by

$$\phi(t + \Delta t) - \phi(t) , \qquad (4)$$

where $\Delta t = 1$ min. To minimise the contribution due to the noise, this curve has been convolved with a Gaussian of half power width equal to 2 arc min. This is the first time that enhanced density regions of this small dimension have been observed in the outer solar corona. As neither the effective collecting area

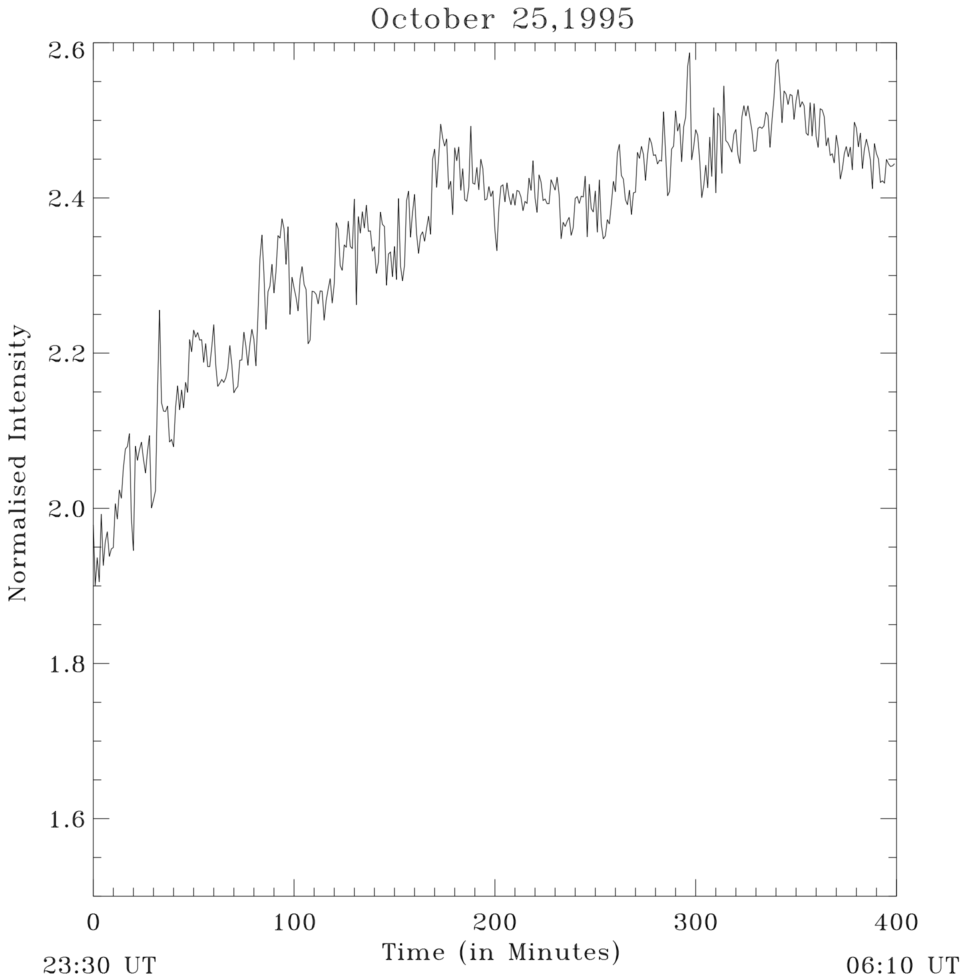

Figure 3. One-dimensional drift scan of the Sun taken the day after the eclipse.

of the antenna system was known observationally nor any sidereal source was observed for a direct calibration of the observed scans, the flux densities of the sources A and B were estimated as follows: In Figure 2, X1 and X2 represent the fall/rise in the observed flux level corresponding to the covering/uncovering of the sources A and B, respectively; X3 represents the fall due to the covering of the source A plus the background quiet Sun. The background quiet-Sun level is the average of those observed on the days prior to and after the eclipse. This level is indicated in Figure 2 by a dotted line. Assuming the value of the quiet-Sun flux density at 75 MHz to be 10 500 Jy (Sheridan and McLean, 1985), the flux density corresponding to an obscuration of 52.12% at the maximum phase of the eclipse turns out to be 5027 Jy. This corresponds to X3–X1 in Figure 2. Using this, the flux densities corresponding to X1 and X2 were estimated to be

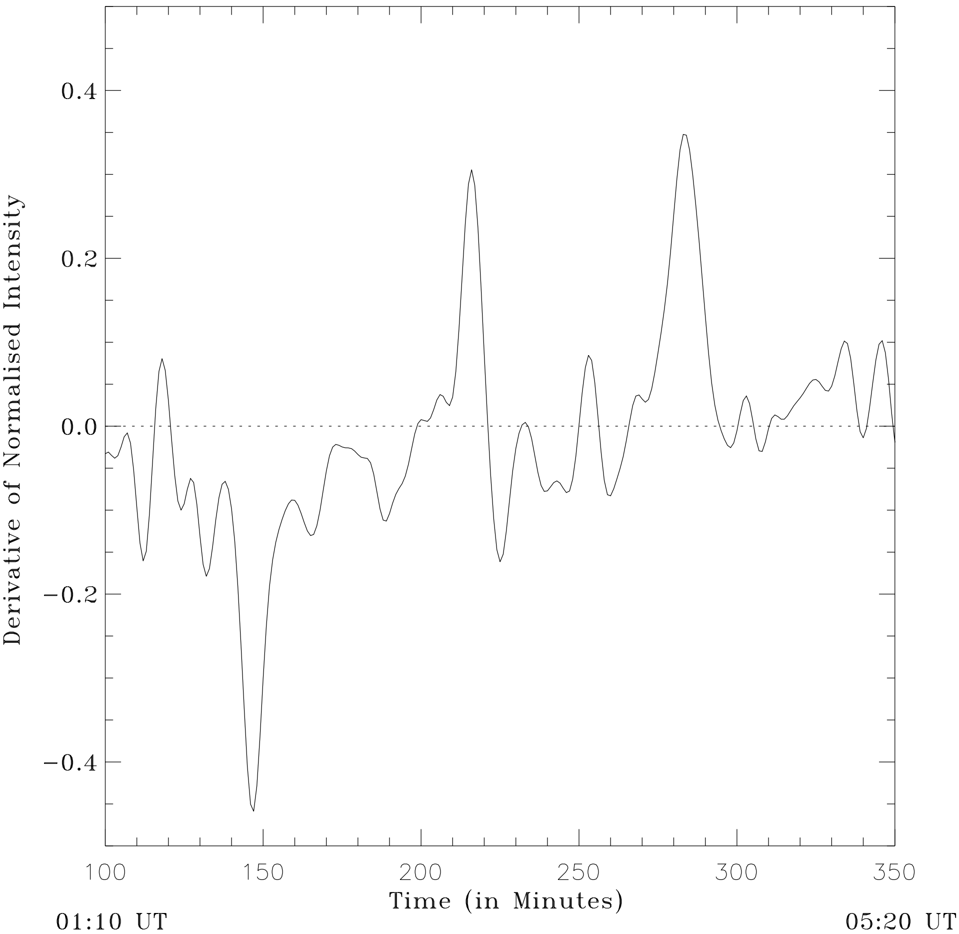

Figure 4. The derivative of the observed eclipse curve.

about 1753 ± 100 Jy and 2479 ± 100 Jy, respectively. Obviously, the above flux densities quoted for the sources A and B are approximate. By assuming circular symmetry, the brightness temperature (T_b) of the sources A and B were estimated to be $\approx 1.92 \times 10^7$ K and 2.72×10^7 K, respectively. These values are consistent with earlier measurements of Kundu and Gopalswamy (1990) for similar sources. Also, since it is widely believed that emission from noise storm sources occurs at or near the local plasma frequency (McLean, 1981), the alitude of the sources observed by us must be approximately 0.4 $R_\odot$ above the photosphere, the location from where the 75 MHz radiation originates.

Figure 5 shows the soft X-ray picture of the Sun taken at 03:14:04 UT by the *Yohkoh* satellite. From the contact timings of the Moon with the Sun and the position angle of the Moon at various times, the path of the Moon's shadow as seen from our observatory's location was established (Figure 5). Combining this

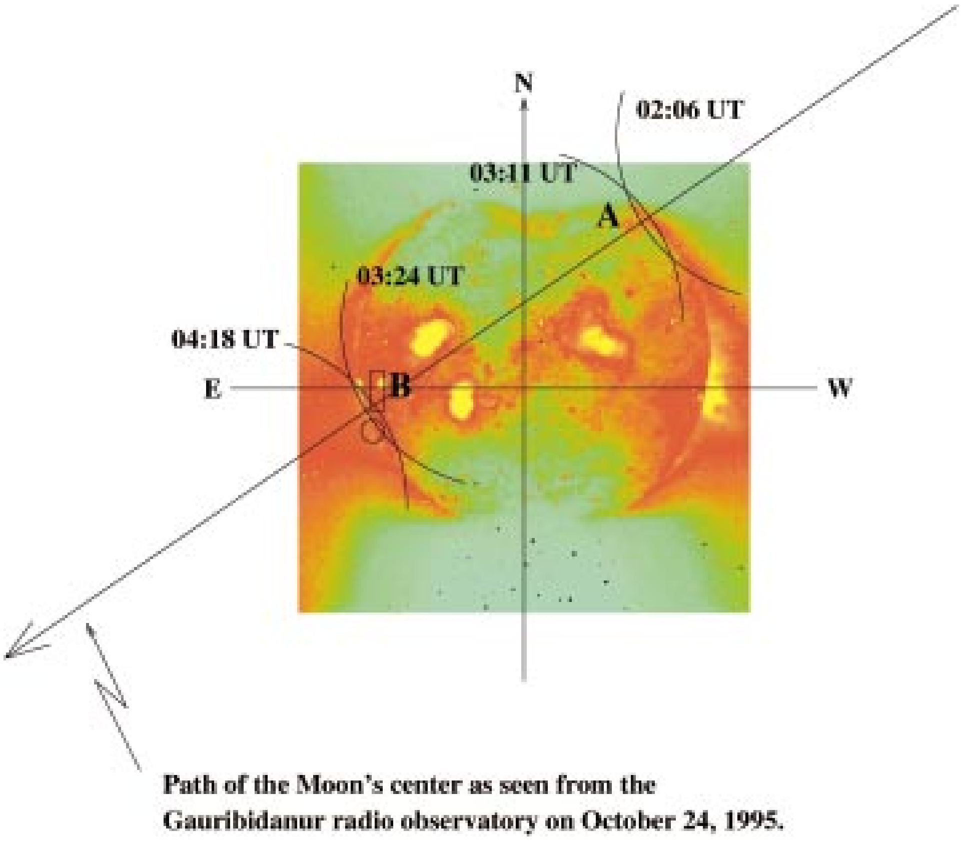

Figure 5. X-ray image of the Sun obtained with the SXT on board *Yohkoh* on 24 October 1995 at 03:14:04 UT (see text for the details).

data with the duration of occultation, we believe that the sources A and B observed by us must have been located in the regions marked A and B respectively in the *Yohkoh* image. According to the *Solar Geophysical Data* (December 1995), a noise storm source was observed with the Nançay radioheliograph (NRH) at 164 MHz on 23 October 1995. The location of this source is indicated by the rectangular box in Figure 5. The dimensions of this box approximately correspond to the resolution of the NRH at 164 MHz. This source remained active even after the observations were over at 15:00 UT on that day at Nançay. It is possible that the source B observed by us is an extension of the same noise storm source into the outer corona. It must be also noted that a prominence eruption was observed by the Hα prominence monitor at the Mauna Loa Solar Observatory (MLSO) around 21:17 UT on 23 October 1995. The circle near the east limb in Figure 5 shows the site of the prominence eruption. So it is not clear to which of these two sources, i.e., the noise storm or the prominence eruption, the source B observed by us corresponds. On the other hand, there is no counterpart, either in the Hα picture or the Nançay one-dimensional scans, for the source A observed by us. This may be due to the fact that the observations were not made at the same time and the source A observed by us might be transient.

5. Discussions

It has been suggested that scattering of the radio radiation by density irregularities increases the apparent sizes of coronal sources and this hypothesis is usually invoked by several authors (Riddle, 1974; Thejappa and Kundu, 1992) to explain the observed low brightness temperature of the outer solar corona. McLean and Melrose (1985) had pointed out that there is no unambiguous evidence to show that scattering is important in any of the burst sources that exhibit fine structure. It is well known that the smallest source size observed gives an upper limit to the scatter broadened image of a point source. The present observations show that the upper limit at 75 MHz is about 2.5 arc min. The 75 MHz system recently installed on the VLA can be used to check if still small size sources exist on the Sun. Sastry (1994) pointed out that the variations in the flux densities of the quiet Sun observed by him at 34.5 MHz might not be due to scattering alone and it is possible that the presence of weak noise storm sources on the Sun (Alissandrakis, Lantos, and Nicolaidis, 1985) could also play a role. The present observations also reveal that weak noise storm sources occassionally exist on the Sun.

In the metric range, the sources of noise storms can have motions of several arc min over time scales of tens of minutes, and close association with the erupting filaments (McLean, 1973; Lantos *et al.*, 1981; Raulin *et al.*, 1991). The lifetime of noise storm sources can vary from hours to days (Malik and Mercier, 1996). Therefore, the prominence eruption observed at the MLSO, the noise storm source observed with the NRH and the discrete source (source B) seen in our eclipse observations may be related to one another.

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