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Radio observations of a coronal mass ejection induced depletion in the outer solar corona

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Abstract. We report the first low frequency radio observations of a depletion that occurred in the outer solar corona in the aftermath of the CME event of 1986 June 5, with the large E-W one dimensional grating interferometer at the Gauribidanur radio observatory. We estimated the mass loss associated with the depletion and found that it agrees well with the value obtained through white light observations of the event. The radio brightness temperature at the location of the depletion was less by a factor of ≈ 7 compared to the ambient. The angular extent over which the decrease in brightness took place was $\leq 3'$. The electron density variation was found to be proportional to r^{-10}. Since observations at different wavelength bands have different physical origins, the radio method might be useful in independently estimating the characteristics of CME induced coronal depletions.

Key words: Sun: corona – Sun: particle emission – Sun: radio radiation

1. Introduction

It is now well known that transient events in the solar atmosphere like flares, prominence eruptions, CMEs, etc. lead to expulsion of material from the corona. The possible manifestations of the resultant voids are coronal depletions (Hansen et al. 1974; Rust & Hildner 1976), transient coronal holes (Rust 1983; Watanabe et al. 1992; Manoharan et al. 1996; Sterling & Hudson 1997; Hudson et al. 1998) and coronal dimming (Hudson et al. 1996; Gopalswamy & Hanaoka 1998; Zarro et al. 1999). These regions are shortlived and their lifetime varies from less than a day to more than 3 days (Sterling & Hudson 1997). The transient coronal hole reported by Kozuka et al. (1995) had a lifetime of only 17 hrs. Observations of these regions are of interest since transient increases in the solar wind speed in the aftermath of some of the CME events are considered to be closely linked to them (Rust 1983). In this respect, low frequency radio observations play an important role since they provide information on the density and temperature structure in the outer solar corona. The observations reported were carried out at 34.5 MHz with the E-W arm of the large Decameter Wave Radio Telescope (GBDRT) and four small groups of antennas at the Gauribidanur radio observatory (Lat: $13°36'12''$ N and Long: $77°27'07''$ E) near Bangalore in India (Sastry 1995). The entire set-up was operated as a one dimensional grating interferometer along the E-W direction with a total baseline length of 5.6 kms. By correlating the output of each one of the small groups of antennas with the E-W arm of the GBDRT, a fan beam of angular resolution $3'$ in hour angle was synthesized. This is the highest resolution with which observations were ever made on the Sun at this low frequency so far. In this paper, we report the observations of a depletion in the outer solar corona with this instrument in the aftermath of the CME event of 1986 June 5.

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2. Observations

The compound grating interferometer at the Gauribidanur radio observatory was constructed to detect the existence of structures of small angular scale ($\sim$ few arc minutes) in the outer solar atmosphere and angular broadening of radio sources at large distances from the Sun. During June 1986 in the course of our observations on the occultation of the radio source Tau A by the solar corona, we noticed a depletion in the outer corona on June 5. Fig. 1 shows the E-W one dimensional brightness distribution of the Sun obtained on this day at 06:30 UT. One can see that the distribution is markedly asymmetric due to the sudden decrease in the observed brightness immediately after the transit of Sun. This kind of distribution is what one would expect if there is a sharp fall in the electron density in the western hemisphere of the Sun. There was a complete restructuring of the corona in $<$ 24 hrs such that the asymmetry was not there in our scans obtained the next day. The E-W scans of the Sun obtained with the Nancay radioheliograph at 169 MHz on June 5 and 6 at $\sim$ 12:00 UT also showed a similar behaviour. An inspection of the 50 MHz radio heliogram obtained with the Clark lake radioheliograph (CLRH) on June 5 at $\sim$ 20:00 UT revealed the presence of a coronal hole close to the west limb near the equator (Gopalswamy, personal communication). According to Burkepile & St. Cyr (1993), a CME event was observed with the coronagraph/polarimeter on board the Solar Maximum Mission (SMM) satellite on 1986 June 5 from 01:25 UT to 04:41 UT, close to the west limb at position angle = $292°$. (The position angle [PA] is measured counter clockwise from solar north

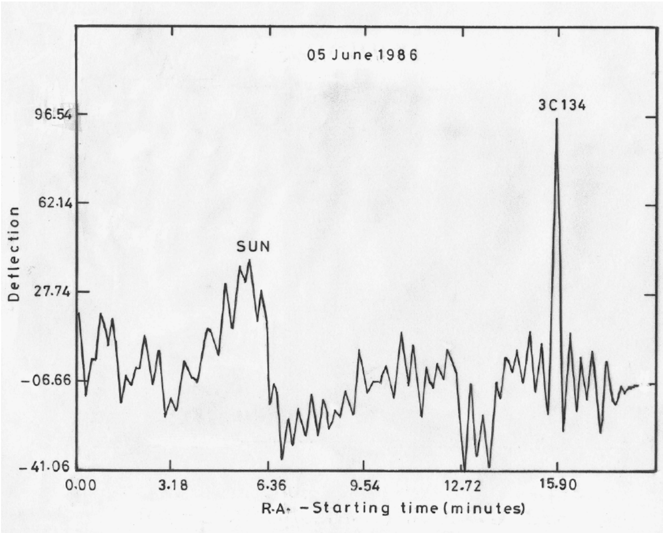

Fig. 1. E-W one dimensional brightness distribution of the Sun at 34.5 MHz obtained using the compound grating interferometer at the Gauribidanur radio observatory. The synthesized beam on the radio source 3C134 (a point source for the instrument) is also shown. The solar east is on the left.

through east). The angular width of the event was $\sim 45°$, and the estimated speed was ≈ 227 km/s. The coronal mass expelled was about 1.3×10^{15} gm. The encircled portion in Fig. 2 shows the ejected material. Fig. 3 shows the region of the corona where material depletion was observed in association with this event as compared to the pre-event time. The mass loss corresponding to this depletion was about 4.761×10^{13} gm (Stanger, personal communication). The Sun was 'quiet' and no non-thermal radio bursts were reported. This particular event was also not accompanied by filament disappearance (*Solar Geophysical Data* [August 1986; December 1986]). Our observations were calibrated using the radio source 3C134 (Fig. 1). The angular width of the region across which the decrease in the solar brightness took place was estimated from the observed response on the above calibrator source, and the value is $\leq 3'$. Assuming circular symmetry, we calculated the peak brightness temperature (T_b) of the 'quiet' Sun and the depletion region, and the values are 0.83×10^6 K and 0.12×10^6 K respectively. The latter is approximately same as that reported for a long lived coronal hole observed with the CLRH at 30.9 MHz by Wang et al. (1987). The estimated T_b of the hole was in the range $0.11 - 0.15 \times 10^6$ K.

3. Analysis and results

In order to simulate the observed radio brightness distribution profile of 1986 June 5, and quantitatively estimate the properties of the coronal hole the following procedure was adopted: We carried out ray tracing calculations using the method described in Sastry et al. (1983) for different values of coronal temperature and electron density. The coronal model used was based on the one determined by Newkirk (1961) for a streamer in an otherwise symmetrical corona. The electron density at any point

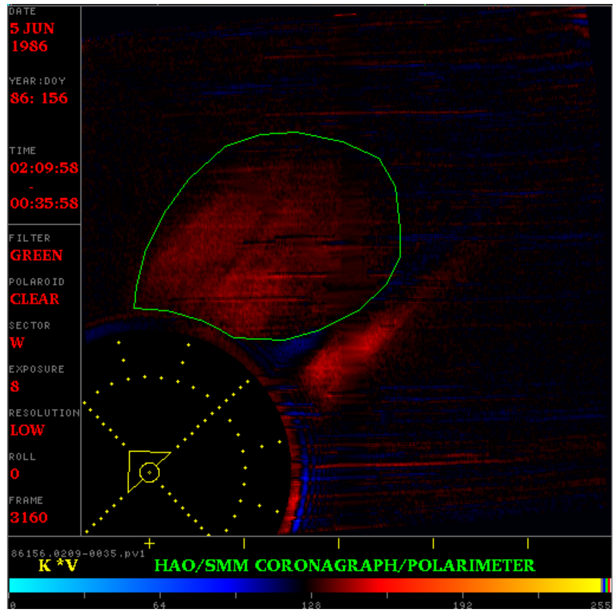

Fig. 2. Difference image (02:09:58 UT - 00:35:58 UT) of the CME event of 1986 June 5 observed with the coronagraph/polarimeter onboard the SMM satellite. The occulting disk is at a height of 0.6 $R_\odot$ above the solar limb. The solar north is indicated by the arrow at the center of the dotted circle (solar limb) at the bottom left corner of the image. One can clearly notice the the ejection (encircled portion) in the N-W quadrant at PA = $292°$.

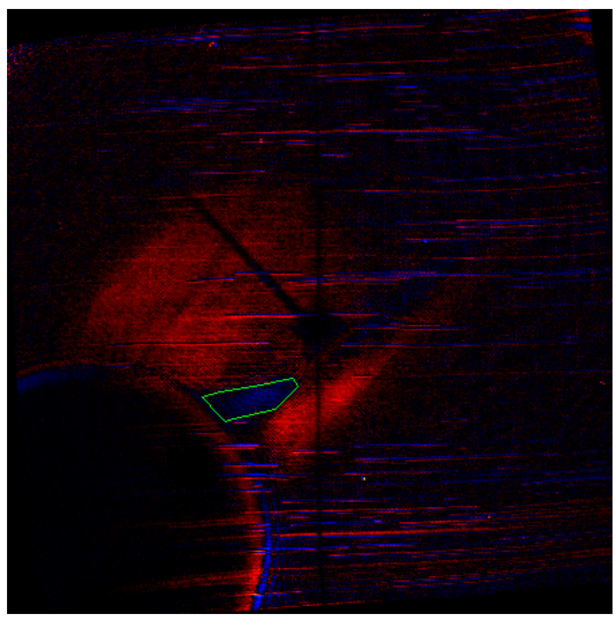

Fig. 3. Same image as in Fig. 2 with the region of depletion (PA $\approx 270°$) shown separately inside a box. The vertical bar in the center and the diagonal line to the upper left corner are artifacts.

in the corona was assumed to be half of that given by the above model since the present observations were carried out during solar minimum period (Thejappa & Kundu 1994), i.e.

$$N_e(\rho) = N_0 \left[1 + C_N \exp(-\beta^2/2\,\sigma^2)\right] \quad \mathrm{cm}^{-3} \tag{1}$$

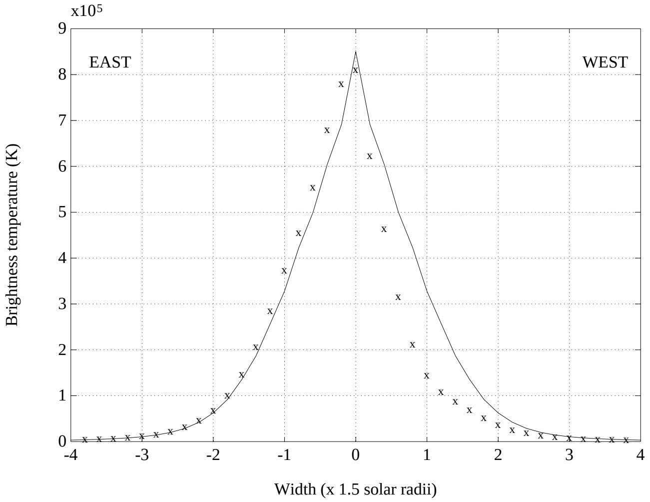

Fig. 4. One dimenisonal E-W brightness distribution of the Sun at 34.5 MHz obtained using ray tracing calculations based on the density model of Newkirk (1961). The solid line profile represents the brightness distribution without the coronal hole and the profile drawn using x's is with the coronal hole.

where $N_0 = 2.1 \times 10^{4.32/\rho}$, ρ is the distance from the center of the Sun, β is the distance from the axis of the region of density enhancement/depletion and, σ is the width of the region. All distances are in units of solar radii. The constant C_N determines the density enhancement/depletion factor. We first estimated the profile of the brightness distribution assuming the coronal hole was not present on that day. We then introduced a coronal hole, and varied its strength and position to obtain the best fit of the observed profile. The results are shown in Fig. 4. We assumed a coronal electron temperature of 10^6 K for our calculation. The brightness distribution would have been like the solid line profile in Fig. 4 if the coronal hole were not present on that day. The profile is symmetric with a full width at half maximum (FWHM) of $\approx 2.5\ \mathrm{R}_\odot$ and a peak brightness temperature of about 0.85×10^6 K. The FWHM is twice the width of the observed profile (to the east of the meridian) on 1986 June 5 shown in Fig. 1. This should be the case since the 'quiet' Sun is generally symmetric in the absence of condensations and/or holes. The peak brightness temperature of the profile shown in Fig. 4 agrees well with that observed on 1986 June 5 of 0.83×10^6 K. We then simulated the brightness distribution with the coronal hole present. For this purpose we again assumed an electron temperature of 10^6 K for the corona, and varied the parameters C_N, σ, and the angle with respect to the line of sight. We obtained a best fit (profile drawn using x's in Fig. 4) with values of $C_N = -0.7$, $\sigma = 0.2\ \mathrm{R}_\odot$, and an angle to the line of sight of $100°$. We were able to account for the decrease in the observed T_b by decreasing the density alone and no decrease in temperature was required. We also calculated the change in the optical depth (τ) of the medium corresponding to the fall in the observed T_b in Fig. 1 (from 0.83×10^6 K to 0.12×10^6 K), and found that τ should decrease by a factor of ≈ 14 to cause the above variation in T_b. This large change in τ is expected since a coronal dimming in the aftermath of a CME is more likely caused by a density depletion (and/or) volume expansion rather than a temperature variation in the coronal plasma (Zarro et al. 1999), and τ is more sensitive to variations in density than temperature, i.e.

$$\tau \propto N_e^2 T_e^{-3/2} \qquad (2)$$

The corresponding change in electron density (ΔN_e) was estimated to be $\approx 1.07 \times 10^7\ \mathrm{cm}^{-3}$. The plasma density corresponding to 34.5 MHz is $1.47 \times 10^7\ \mathrm{cm}^{-3}$.

If the corona consists of fully ionized hydrogen and helium with the latter being 10% as abundant as the former, one finds that each electron is associated with approximately 2×10^{-24} gm of material. Therefore the mass loss associated with the depletion is,

$$M = 2 \times 10^{-24}\ \Delta N_e\ V\ \ \mathrm{gm} \qquad (3)$$

where $V\ (\mathrm{cm}^3)$ is the volume of the depletion region. The main uncertainty in calculating the volume comes from the lack of knowledge of the depth of the depletion region along the line of sight. In the present case, we assumed that the depth and the lateral width of the region are the same as the observed radial width. The volume thus calculated is $2.22 \times 10^{30}\ \mathrm{cm}^3$. Substituting all the values in Eq. (3), we get the mass corresponding to the density depletion as $\approx 4 \times 10^{13}$ gm. This agrees well with the mass of the coronal depletion estimated using the white light pictures of the event.

The form of the electron density distribution in the corona changes with the altitude of the plasma level from where the emission originates. Gergely et al. (1985) derived a distribution of the type $N_e \sim r^{-6} - r^{-8}$ (r is the radial distance from the center of the Sun) for the electron density in the middle corona from their measurements of solar diameter in the frequency range 30-74 MHz. In the present case, the decrease in density over a region of width $\leq 3'$ ($\approx 0.2\ \mathrm{R}_\odot$) implies that the density distribution is of the form r^{-10}. Following Eq. (1), we assumed that the 34.5 MHz plasma level in the background equatorial corona is located at a distance of $1.52\ \mathrm{R}_\odot$ from the center of the Sun for the above calculation.

4. Discussions and conclusions

Using low frequency radio observations we have independently estimated the mass loss associated with a depletion that occurred in the outer solar corona in the aftermath of a CME and found that it agrees well with the value estimated through white light observations of the event. The angular size of the depletion region was $\approx 3'$. The mass loss associated with the depletion was less compared to the mass of the material ejected during the main CME event by two orders of magnitude. It is to be noted here that the CME event of 1986 June 5 was not associated with any other form of activity on the solar atmosphere like prominence eruption, flare and non-thermal radio bursts. The mass estimates of the dimming events reported earlier (Sterling & Hudson 1997; Gopalswamy & Hanaoka 1998) were accompanied by a prominence eruption and a flare (X-ray + white light) respectively. The latter event was also accompanied by Type II and IV non-thermal radio bursts (Hudson et al. 1998).

According to Zarro et al. (1999), the dimming in the extreme ultraviolet (EUV) pictures taken with the instrument EIT onboard SOHO in the aftermath of the halo CME of 1997 April 7 showed a factor of ~ 4 decrease in average intensity with respect to the ambient. Compared to this, the estimated T_b of the depletion region in the present case was less than the 'quiet' corona by a factor of ≈ 7. However the above ratio should be regarded as an upper limit, since it is possible that the actual size of the region might be less than the angular resolution of our instrument. This should give a higher value for the T_b of the depletion region. In this connection we would also like to add that the sizes of the dimming regions seen in the *Yohkoh* soft X-ray images are only $\sim 1.5'$ (Sterling & Hudson 1997). This corresponds to a volume of $\sim 10^{29}\ \mathrm{cm}^3$ which is lesser than that of the depletion observed in the present case by about an order of magnitude.

Our experience with observations on the 'quiet' Sun with the grating interferometer has shown that the angular sizes of the localised emissive regions on the 'quiet' Sun are generally $\geq\ 6'$ at these frequencies. The smaller spatial width of the region over which the temperature decrease has taken place in the present case has important bearing on the theories of scattering of radio radiation by density inhomogeneities in the 'quiet' solar corona. 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 34.5 MHz is about $3'$. This is consistent with our earlier result that there are discrete sources of angular size $\leq 2.5'$ in the outer solar corona from where the decameter wavelength radiation originates (Ramesh et al. 1999).

Doyle et al. (1999) recently reported that the electron density above a long lived polar coronal hole varies as r^{-8} in the height range $1 - 2\ \mathrm{R}_{\odot}$. This is two orders of magnitude lesser than the present estimate which varies as r^{-10}. But the latter must be treated with caution since low frequency ($<$ 100 MHz) radio radiation from the solar corona undergoes scattering (by density irregularities of sizes $\sim 100\ \mathrm{km}$), and refraction effects.

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