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METRIC RADIO OBSERVATIONS OF THE EVOLUTION OF A “HALO” CORONAL MASS EJECTION CLOSE TO THE SUN

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ABSTRACT

We report direct imaging observations of the propagation of a diffuse thermal radio enhancement in close temporal and spatial association with a “halo” coronal mass ejection from the solar atmosphere, in the metric wavelength regime. The speed and acceleration of the latter in the low corona were estimated in an independent manner from the displacement of the associated radio features, and the average values are 1136 ± 73 km s^{-1} and 157 ± 121 m s^{-2}, respectively. The brightness temperature and electron density of the enhancement were found to be $\approx 1.92 \times 10^5$ K and 2.81×10^7 cm^{-3} at a distance of 2.7 $R_\odot$ from the center of the Sun. We also computed the magnetic field strength of the enhancement at the above height, and the value is ≈ 0.86 G. The mass of the radio enhancement increased by a factor of ~ 2 during our observing period.

Subject headings: solar-terrestrial relations — Sun: activity — Sun: corona — Sun: radio radiation

1. INTRODUCTION

Coronal mass ejections (CMEs) are large-scale magnetoplasma structures that erupt from the Sun and propagate through the interplanetary medium with speeds ranging from only a few kilometers per second to nearly 3000 km s^{-1}. They carry typically 10^{15} g of coronal material. Most of the current observations of CMEs are from coronagraphs that detect them in Thompson scattered sunlight above its occulter. The latter generally covers both the solar disk as well as the low corona (≤ 2 $R_\odot$). Observations from instruments such as the Large Angle and Spectrometric Coronagraph Experiment (LASCO; Brueckner et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*; Fleck, Domingo, & Poland 1995) have now revolutionized our perception and understanding of the solar eruptive events. However, one needs noncoronagraphic data to obtain information on the early evolution of CMEs, in particular for those directed along the Sun-Earth axis that occur far from the plane of the sky. The latter originate on the visible hemisphere of the Sun and appear as a “halo” of expanding circular brightening that completely surrounds or spans a large angle outside the occulting disk of the coronagraph (Howard et al. 1982). The Earthward-moving events are geophysically important, in the context of space-weather related phenomena such as geomagnetic storms (Gosling et al. 1991). Observations of the near-surface onset phase of a CME are vital, since its basic physical state is completely determined there. Its subsequent development during the transit through the heliosphere is just an evolutionary process (Dere et al. 1997). Measurements of CME properties in the lower corona are significant for several reasons. Foremost among them is the general assumption that CMEs have a constant speed behind the occulting disk of a coronagraph. This has often caused controversial results while comparing the CME onset with other solar activity signatures. According to Zhang et al. (2001), the kinematic evolution of a CME can be described in a three-phase scenario: the initiation phase, impulsive acceleration phase, and propagation phase. Among these, the first two phases take place primarily in the low corona. These suggest that a more complete description of the motion of a CME in the lower corona is crucial for a better prediction of its characteristics at higher altitudes. Imaging observations at radio wavelengths play an important role, since they do not have the limitation of an occulting disk and the CMEs can be detected early in their development via the thermal bremsstrahlung radiation that they emit (Sheridan et al. 1978; Gopalswamy and Kundu 1992). Also, one can observe activity at any longitude similar to X-ray and EUV wavelengths (Ramesh 2000). Again, the frontal structure of a CME has a large optical depth at meter wavelengths and can be readily observed (Bastian & Gary 1997; Gopalswamy 1999; Kathiravan, Ramesh, & Subramanian 2002). In this situation, we report the first metric radio observations of the propagation of a diffuse thermal enhancement associated with a halo CME in the lower corona and estimate the speed, acceleration of the latter in an independent manner from the propagation of its radio counterpart.

2. OBSERVATIONS

The radio data reported were obtained at 109 MHz with the Gauribidanur radioheliograph (GRH; Ramesh et al. 1998) operating near Bangalore in India. The minimum detectable flux limit of the array is ~ 0.02 SFU (1 SFU $= 10^{-22}$ W m^{-2} Hz^{-1}), and the angular resolution is $\sim 7' \times 11'$ (R.A. × decl.), at the above frequency. The field of view is about $3^\circ \times 5^\circ$. The calibration scheme used for processing of the data obtained with the GRH makes use of the available redundancy in the length and orientation of the various baseline vectors and allows us to image sources with a dynamic range of greater than 20 dB (Ramesh 1998; Ramesh, Subramanian, & Sastry 1999). This enables us to detect faint thermal features associated with density enhancements such as streamers, CMEs, etc. in the solar atmosphere. According to the CME list for the year 2000,[4] the LASCO C2 coronagraph observed a full halo CME on 2000 November 24 around 05:30 UT, the time at which it was first noticed in its field of view. The extrapolated lift-off time of the CME was 04:55:52 UT. Its estimated linear speed in the plane of the sky was 994 km s^{-1}. Figure 1 shows a difference image of the event at 05:54 UT by subtracting a preevent image obtained at 05:06 UT. The CME can be clearly noticed as a bright feature above the

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[4] See http://cdaw.gsfc.nasa.gov/CME_list.

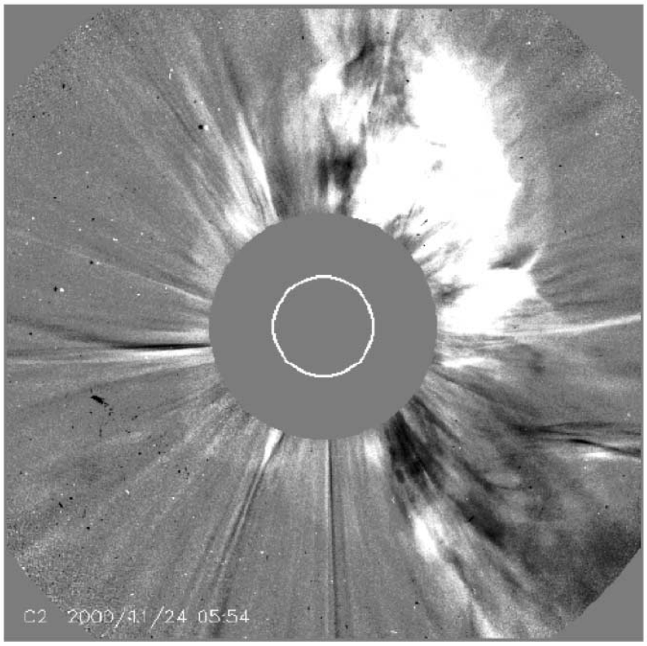

FIG. 1.—Difference image (05:54–05:06 UT) of the CME event observed with the LASCO C2 coronagraph on 2000 November 24. The inner circle indicates the solar limb, and the outer circle is the occulting disk of the coronagraph. It extends approximately up to 2.2 $R_\odot$ from the center of the Sun. Solar north is straight up, and east is to the left. The CME can be clearly noticed as a bright structure above the northwest quadrant of the occulting disk.

northwest quadrant of the occulting disk of the coronagraph. Figure 2 shows the radioheliogram obtained with the GRH at 04:55 UT, the same day. Figures 3, 4, and 5 show the radio difference images corresponding to 05:05, 05:15, and 05:25 UT, with respect to the 04:55 UT image. In addition to the discrete sources on the disk, one can clearly observe enhanced radio emission in close spatial correspondence with the white-light CME described above. Its estimated peak brightness temperature (T_b) was found to be ~10^5 K. A comparison of the LASCO and GRH difference images clearly indicates that the radio enhancement moved in the same direction as the white-light CME. Also, their appearances are closely similar. We therefore conclude that the former is the radio counterpart of the latter. We estimated the velocity of the "radio CME" from the displacement of its centroid in the difference images (Figs. 3, 4, and 5), and the

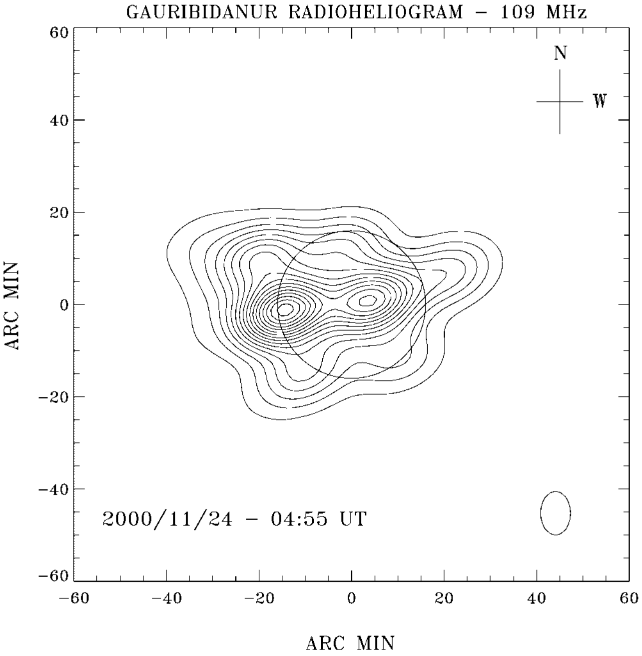

FIG. 2.—Radioheliogram obtained with the GRH on 2000 November 24 around 04:55 UT. The peak T_b is ≈4.18×10^6 K, and the contour interval is 0.27×10^6 K. The open circle at the center is the solar limb. The instrument beam is shown near the bottom right corner.

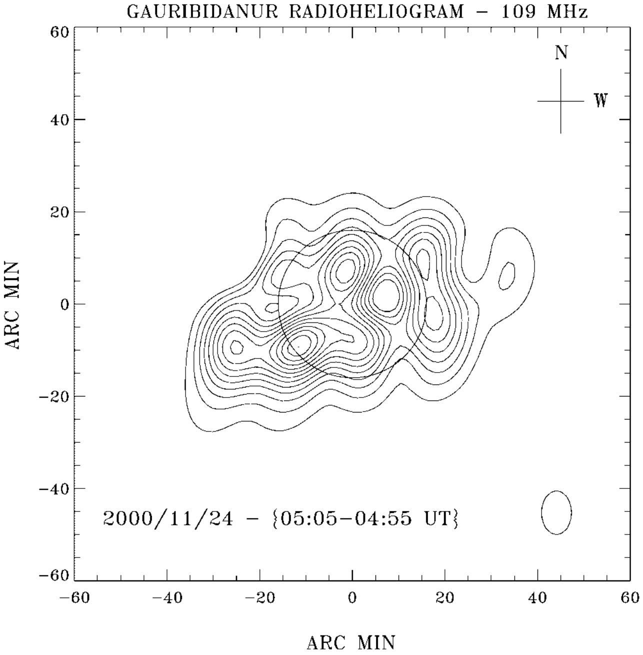

FIG. 3.—Difference image obtained by subtracting the radioheliogram obtained at 04:55 UT from 05:05 UT. The peak T_b is ≈6.08×10^6 K, and the contour interval is 0.34×10^6 K.

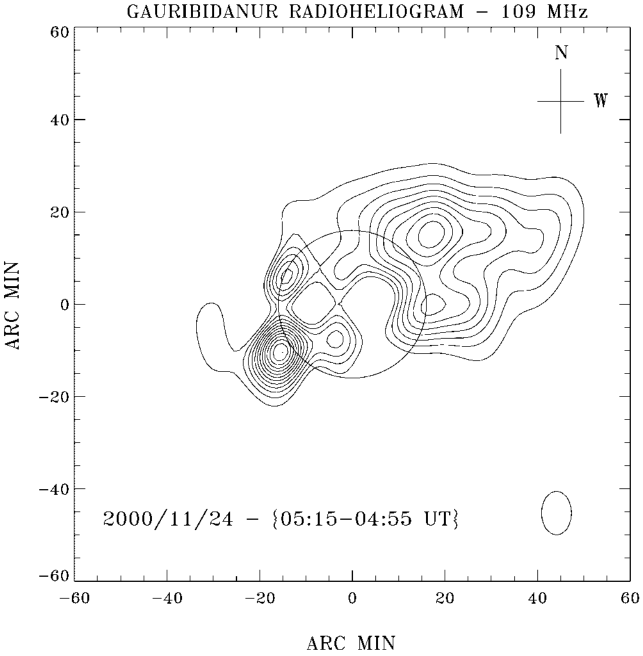

FIG. 4.—Same as in Fig. 3, but the timings are 04:55 and 05:15 UT. The peak T_b is ≈6.1×10^6 K, and the contour interval is 0.39×10^6 K.

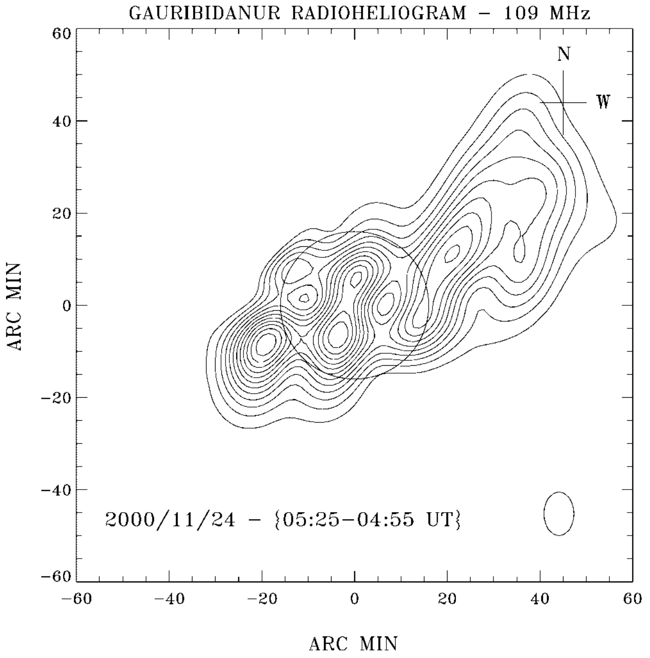

FIG. 5.—Same as in Figs. 3 and 4, but the timings are 04:55 and 05:25 UT. The peak T_b is ≈5.6×10^6 K, and the contour interval is 0.29×10^6 K.

values are 1087 ± 73 and 1185 ± 73 km s^{-1} during the interval 05:05–05:15 UT and 05:15–05:25 UT, respectively. This gives it an effective acceleration of ∼157 ± 121 m s^{-2}.

3. ANALYSIS AND RESULTS

Single frequency observations of CME-associated discrete radio sources traveling outward to large heights (∼2–3 $R_\odot$) in the solar corona are generally attributed to nonthermal continuum emission from moving type IV radio bursts (see Dulk 1980 and references therein), since the observed T_b ($\geq 10^7$ K; Wagner et al. 1981; Stewart et al. 1982; Gopalswamy & Kundu 1989) is usually higher than that because of the emission from the background “quiet” Sun (∼10^6 K), which is purely thermal in nature. But in the present case, the T_b of the enhanced radio emission observed at the location of the white-light CME is less than the electron temperature (T_e) of the solar corona (≈1.4×10^6 K; Fludra et al. 1999). Also, no type IV emission was reported during our observing period on 2000 November 24 (Sol.-Geophys. Data, 2001 January). We would like to point out here that optically thin synchrotron radiation from the nonthermal electrons entrained in the magnetic field of the CME could also give rise to low values of T_b (∼10^4–10^5 K), as shown recently by Bastian et al. (2001) for the event of 1998 April 20. But we could not verify the above (through spectral index estimation) in the present case, since the radio imaging data is available at only one frequency. However, it is to be noted that the CME event described here was not accompanied by any nonthermal continuum emission in the metric range, unlike the event reported by Bastian et al. (2001; see Sol.-Geophys. Data, 1998 June, for details). Therefore, it is possible that the CME-associated enhanced radio emission observed by us in the present case is most likely thermal in nature, and the excess emission observed off the limb in the northwest quadrant of the GRH images is due to bremsstrahlung from the extra electrons associated with the halo CME. Its mass (M) is given by

$$M = 2 \times 10^{-24} (5 f^2 T_e^{1/2} T_b L^{-1})^{1/2} V \text{ g}, \tag{1}$$

where f (MHz) is the observing frequency and L ($R_\odot$) is the depth of the radio enhancement along the line of sight. The latter is unknown and is taken to be the same as the observed radial width. The volume (V) of the region of enhanced emission was determined by multiplying its radial and lateral width with the depth along the line of sight. We assumed that the coronal plasma is a fully ionized gas of normal solar composition (90% hydrogen and 10% helium by number), and each electron is associated with approximately 2×10^{-24} g of material. In addition to the above, we also derived the magnetic field strength (B) associated with the density enhancement assuming that the plasma $\beta \approx 0.05$, as found by Vourlidas et al. (2000) for some of the LASCO CMEs at about the same height range as the radio CME described here. Table 1 lists the values of the different parameters of the latter mentioned above. It is well known that the distance (s) traveled by a CME in a given time interval (t) can be found, since the initial speed (u) and the acceleration (a) are known. For the values of $u = 1087$ km s^{-1}, $a = 157$ m s^{-2}, and $t = 29$ minutes (time difference between the last and first height measurement using GRH [05:25 UT] and LASCO data [05:54 UT], respectively), we found that the centroid of the radio CME should be located at a height of 5.78 $R_\odot$ from the center of the Sun, at 05:54 UT. According to the LASCO measurements, the leading edge of the CME was located at a height of 5.71 $R_\odot$ at 05:54 UT.

4. CONCLUSIONS

We studied the kinematics of the halo CME event that took place on 2000 November 24 around 05:30 UT using the data obtained with the GRH, close to the Sun. The speed of the CME in the low corona was estimated independently from the observed displacement of the associated thermal radio enhancement, and the average value is ≈1136 ± 73 km s^{-1}. This agrees well with the corresponding speed estimated using white-light observations. There is a good agreement between the extrapolated location of the radio CME and the height-time measurements of the leading edge of the white-light CME obtained using the LASCO data, suggesting that the former corresponds to the frontal loop of the white-light CME. The acceleration of the radio CME (≈157 ± 121 m s^{-2}) estimated by us is consistent with the result published by Zhang et al. (2001), according to whom the CMEs undergo an acceleration of

TABLE 1
CHARACTERISTICS OF THE “RADIO CME”

Time (UT)	Coordinates of Centroid ($R_\odot$)	Position Angle[a] (deg)	Brightness Temperature (K)	Electron Density (cm^{-3})	Mass (g)	Magnetic Field (G)
05:05	0.22N, 1.06W	282	3.34×10^5	1.24×10^8	2.68×10^{16}	2.40
05:15	1.09N, 1.41W	308	2.86×10^5	4.46×10^7	3.82×10^{16}	1.33
05:25	2.03N, 1.81W	318	1.92×10^5	2.81×10^7	4.42×10^{16}	0.86

[a] Measured counterclockwise from the solar north.

100–500 m s^{-2} up to a distance of 4 $R_\odot$, and also is in the range of acceleration rates obtained by St. Cyr et al. (1999), who combined Mauna Loa Mark III coronameter and *Solar Maximum Mission* coronagraph/polarimeter measurements for CMEs in the low corona. Akmal et al. (2001) recently made an estimate of the density and temperature of a CME event at a distance of 3.5 $R_\odot$ using the data obtained with the Ultraviolet Coronagraph Spectrometer (Kohl et al. 1995) on board *SOHO*, and the values are 3.13×10^6 cm^{-3} and 2.23×10^5 K, respectively. From an inspection of Table 1, one can note that the present measurements are in good agreement with the above. We also found that the mass of the radio CME increased by a factor of ∼2 during our observing period. This agrees well with the previous reports on the change in CME mass with height (see Gopalswamy 1999 and the references therein). Also, the individual values are in the range of the mass of the CMEs observed with the LASCO coronagraph (Vourlidas et al. 2000). We evaluated the magnetic field strength associated with radio CME from the quoted values of plasma β for some of the LASCO CMEs, and it is ≈0.86 G at a height of about 2.7 $R_\odot$ from the center of the Sun. This agrees with the result obtained by Bastian et al. (2001) for the radio-emitting loops associated with the CME event of 1998 April 20 in the similar height range. The lift-off time of a CME from the solar surface and its subsequent propagation through the coronal medium below the occulter of a coronagraph are traditionally calculated by the back-projection of the CME height. The EUV and X-ray instruments also often fail to identify global changes prior to the appearance of CMEs in the field of view of the existing coronagraphs, as for example in this particular event (Nitta & Hudson 2001). It is therefore suggested that radio imaging observations at low frequencies (≤100 MHz) can be used to study the near-Sun kinematics of CMEs, from the ground. This is important, since the initial speed of a CME close to the Sun is vital to accurately predict its arrival at 1 AU for space weather forecasting (Gopalswamy et al. 2001).

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REFERENCES

Akmal, A., et al. 2001, ApJ, 553, 922
Bastian, T. S., & Gary, D. E. 1997, J. Geophys. Res., 102, 14,031
Bastian, T. S., et al. 2001, ApJ, 558, L65
Brueckner, G. E., et al. 1995, Sol. Phys., 162, 357
Dere, K. P., et al. 1997, Sol. Phys., 175, 601
Dulk, G. A. 1980, in IAU Symp. 86, Radio Physics of the Sun, ed. M. R. Kundu & T. E. Gergely (Dordrecht: Reidel), 419
Fleck, B., Domingo, V., & Poland, A. I., eds. 1995, The *SOHO* Mission (Dordrecht: Kluwer)
Fludra, A., et al. 1999, J. Geophys. Res., 104, 9709
Gopalswamy, N. 1999, in Solar Physics with Radio Observations, ed. T. Bastian, N. Gopalswamy, & K. Shibasaki (NRO Rep. 479; Kiyosato: Nobeyama Radio Obs.), 141
Gopalswamy, N., & Kundu, M. R. 1989, Sol. Phys., 122, 145
———. 1992, ApJ, 390, L37
Gopalswamy, N., et al. 2001, J. Geophys. Res., 106, 29,207
Gosling, J. T., et al. 1991, J. Geophys. Res., 96, 7831
Howard, R. A., et al. 1982, ApJ, 263, L101
Kathiravan, C., Ramesh, R., & Subramanian, K. R. 2002, ApJ, 567, L93
Kohl, J. L., et al. 1995, Sol. Phys., 162, 316
Nitta, N. V., & Hudson, H. S. 2001, Geophys. Res. Lett., 28, 3801
Ramesh, R. 1998, Ph.D. thesis, Bangalore Univ.
———. 2000, Sol. Phys., 196, 213
Ramesh, R., Subramanian, K. R., & Sastry, Ch. V. 1999, A&AS, 139, 179
Ramesh, R., et al. 1998, Sol. Phys., 181, 439
Sheridan, K. V., et al. 1978, Proc. Astron. Soc. Australia, 3(4), 249
Sol.-Geophys. Data 1998, 646, Part I (Boulder: NGDC)
———. 2001, 677, Part I (Boulder: NGDC)
St. Cyr, O. C., et al. 1999, J. Geophys. Res., 104, 12,493
Stewart, R. T., et al. 1982, A&A, 116, 217
Vourlidas, A., et al. 2000, ApJ, 534, 456
Wagner, W. J., et al. 1981, ApJ, 244, L123
Zhang, J., et al. 2001, ApJ, 559, 452