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LOW-FREQUENCY RADIO OBSERVATIONS OF THE ANGULAR BROADENING OF THE CRAB NEBULA DUE TO A CORONAL MASS EJECTION

R. Ramesh, C. Kathiravan, and Ch. V. Sastry
Indian Institute of Astrophysics, Koramangala, Bangalore, 560034, India; ramesh@iiap.ernet.in, kathir@iiap.ernet.in, csastry@iiap.ernet.in
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ABSTRACT

We report two-dimensional, low-frequency radio observations of the angular broadening of the Crab Nebula (Taurus A) due to a coronal mass ejection (CME), at a distance of ∼41 $R_\odot$ from the Sun. The estimated electron density in the CME is about 50 times greater than that of the ambient corona at that location. The calculated mass agrees approximately with that reported earlier for similar events at large distances from the Sun.

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

1. INTRODUCTION

While passing through the solar corona, radio waves from a distant cosmic source get scattered because of the refractive index variations from point to point. Consequently, there is an apparent increase in the angular size of the radio source. Such observations can be used to yield valuable data concerning the structure of the solar corona (Machin & Smith 1951; Hewish 1955; Vitkevich 1958; Erickson 1964; Slee 1966). The amount of coronal scattering depends to a large extent on the relative location of the Sun and radio source. One generally observes a gradual increase/decrease in the angular size of the latter during its ingress/egress. But there are instances when short-term changes in the observed pattern have been noticed, particularly in the case of the Crab Nebula, which lies close to the plane of the ecliptic and passes as near as about 5 $R_\odot$ from the Sun around June 15 every year (Vitkevich 1955; Blum & Boischot 1957; Gorgolewski et al. 1962; Sastry & Subramanian 1974). This could be due to a propagation of streams of charged particles outward from an active area on the Sun's disk (Slee 1959; Vitkevich 1961; Erickson 1964). However, a precise correspondence between an ejection of material from the Sun and a change in the angular dimensions of a radio source due to its occultation by the former has not been reported so far. In this Letter, we report on the two-dimensional radio observations of the angular broadening of the Crab Nebula at a distance of about 41 $R_\odot$ from the Sun, due to its occultation by a slow coronal mass ejection (CME).

2. OBSERVATIONS

The radio data reported were obtained with the Gauribidanur radioheliograph (GRH; Ramesh et al. 1998) during the course of our observations on the occultation of the Crab Nebula (a point source for the GRH) by the solar corona. The observing frequency was 50 MHz, and the integration time used was 4.64 s. Figure 1 shows the radio map of the Crab Nebula obtained on 1997 June 3 at 07:37 UT when it was at a distance of ∼45 $R_\odot$ to the southeast of the Sun. No appreciable angular broadening was noticed on this day. This is consistent with the earlier result that the broadening of the Crab Nebula in the tangential and radial directions, due to scattering by density irregularities in the solar corona, becomes noticeable only when it is approximately 15 $R_\odot$ from the Sun (Harries, Blesing, & Dennison 1970). Figure 2 shows the radio map of the Crab Nebula obtained on 1997 June 4 at 07:33 UT when it was at a distance of ∼41 $R_\odot$ from the Sun. A comparison with Figure 1 shows a clear broadening of the source in either direction on this day. The observed half-power widths were 38′ × 35′. The measured integrated flux density was 1852 ± 200 Jy. This is less compared with the actual flux density of the Crab Nebula at 50 MHz, which is ≈2287 Jy. Our observations were calibrated using the radio source Virgo A, whose flux density at 50 MHz is about 2863 Jy (Nelson, Sheridan, & Suzuki 1985). The radio map of the Crab Nebula obtained on 1997 June 5 when it was at a distance of ∼37 $R_\odot$ from the Sun is shown in Figure 3. Again, no broadening of the source was observed as like in Figure 1. According to the 1997 CME list, the Large-Angle Spectroscopic Coronagraph (LASCO; Brueckner et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*) observed a faint CME on 1997 June 2 at 06:30 UT (the time at which it was first noticed in the field of view of the LASCO C2 coronagraph) in the southeast quadrant of the Sun at a position angle (P.A.) of 106° (Fig. 4). The angular width of the event was ∼80°. Its primary speed was 159 km s^{-1}, and no acceleration was reported. The Sun was "quiet," and no white light or X-ray flare was observed during the above period. Also, this particular CME event was not accompanied by any radio bursts or Hα filament disappearance (Sol.-Geophys. Data 1997a, 1997b). The final height measurement of the event was in the LASCO C3 coronagraph image at 23:25 UT on 1997 June 2 when the leading edge of the CME was at ∼15.1 $R_\odot$ from the Sun at P.A. = 115° (O. C. St. Cyr 2000, private communication). Extrapolating the height-time measurement, we find that the CME should reach a distance of ∼41 $R_\odot$ from the Sun about 31.5 hr later (i.e., on 1997 June 4 at ∼07:30 UT, the time at which the Crab Nebula transited the local meridian at Gauribidanur), and we carried out observations of the source with the GRH. Therefore, it is possible that the observed broadening of the Crab Nebula shown in Figure 2 is probably due to the presence of the CME in the foreground.

3. ANALYSIS AND RESULTS

If the observed angular broadening of the Crab Nebula in the present case is due to scattering effects by the CME, then one can calculate the electron density N_e of the latter using the following equation (Hewish 1955):

$$\phi = 4.5 \times 10^{-10}\lambda^2 N_e \left(\frac{z}{l}\right)^{1/2} \text{ radians}, \qquad (1)$$

where ϕ is the scattering angle, λ is the wavelength of obser-

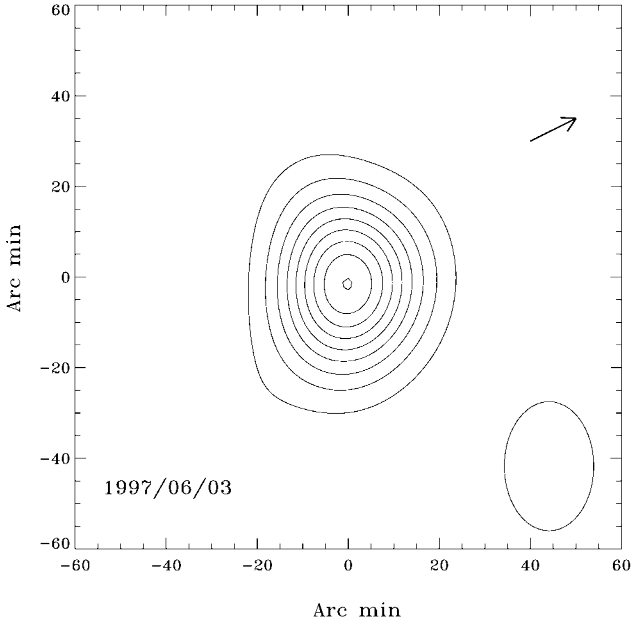

FIG. 1.—Radio map of the Crab Nebula obtained on 1997 June 3 at 50 MHz. The arrow indicates the direction of the center of the Sun. The peak flux is 2287 ± 200 Jy, and the contour levels are 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, and 0.85 times the peak flux. North is straight up, and east is to the left. The instrumental beam is shown in the bottom right-hand corner.

vation, *z* is the depth of the scattering region along the line of sight, and *l* is the scale of the individual irregularities within the scattering region. In applying equation (1) to the present case, we made the following assumptions:

1. The radial width of the CME close to the Sun is ∼1 $R_\odot$ (Gopalswamy 1999), and its value at a distance of 41 $R_\odot$ is $\approx 5.34 \times 10^6$ km. The latter was arrived at by extrapolating the radial width close to the Sun using a typical expansion value of 5 $R_\odot$ day^{-1} (St. Cyr et al. 2000).

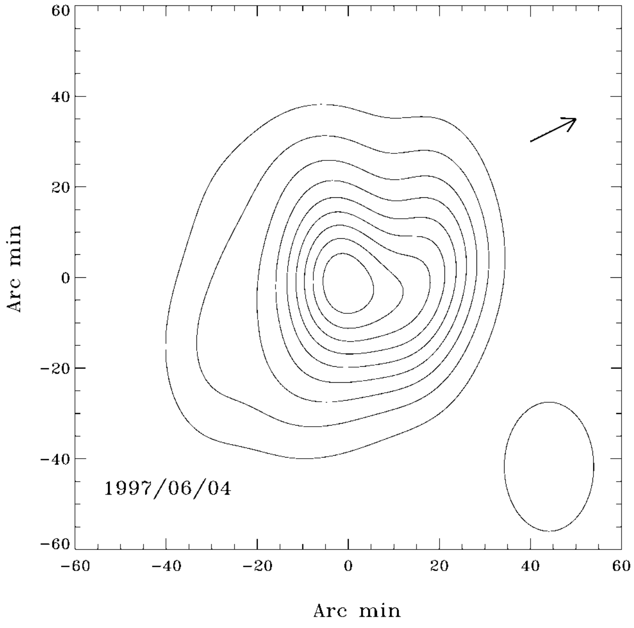

FIG. 2.—Radio map of the Crab Nebula obtained on 1997 June 4 with the CME in the foreground. The peak flux is 1852 ± 200 Jy, and the contour levels are 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9 times the peak flux.

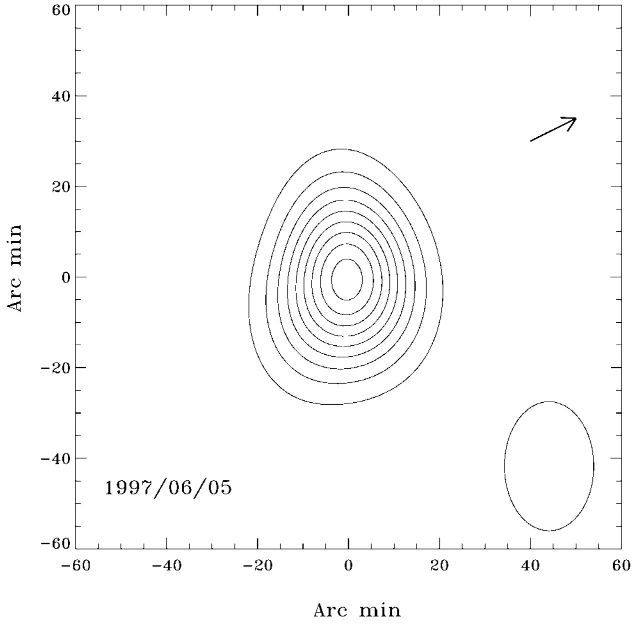

FIG. 3.—Radio map of the Crab Nebula obtained on 1997 June 5 at 50 MHz. The peak flux is 2287 ± 200 Jy, and the contour levels are 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, and 0.85 times the peak flux.

2. The depth of the CME along the line of sight is the same as its radial width.
3. The scale *l* of the scattering irregularities is ∼1000 km (Slee 1966).

Substituting $\phi = 38'$ (the width of the observed scattered dis-

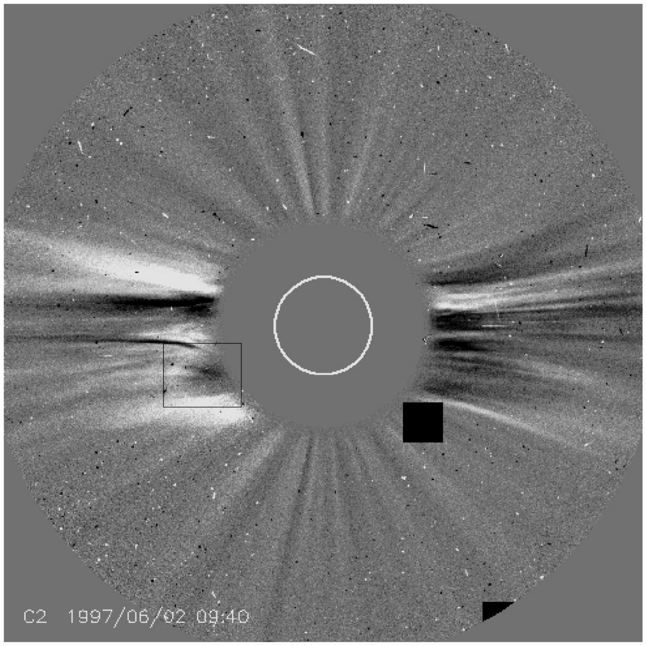

FIG. 4.—Difference image (09:40–02:40 UT) of the CME event observed on 1997 June 2 with the LASCO C2 coronagraph on board *SOHO*. The occulting disk is at a distance of 1.5 $R_\odot$ from the center of the Sun. The location of the CME is indicated by the open rectangular box. North is straight up, and east is to the left.

tribution) and the other values in equation (1), we get $N_e = 9.34 \times 10^3\ \mathrm{cm^{-3}}$. We also calculated the volume V of the CME assuming that it does not undergo any significant latitudinal expansion (Funsten et al. 1999); its lateral width is equal to half of the observed angular span of the white-light CME mentioned earlier ($\approx 7.29 \times 10^5$ km), and the value is about $2.08 \times 10^{34}\ \mathrm{cm^3}$. Since the material comprising a CME is mostly coronal in origin (Hildner et al. 1975) and 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} g of material. Therefore, the mass of the CME is given by

$$M = 2 \times 10^{-24} N_e V \text{ g}. \qquad (2)$$

Substituting the different values in equation (2), we get the mass as $\approx 3.88 \times 10^{14}$ g.

4. CONCLUSIONS

We used the low-frequency radio observations of the occultation of the Crab Nebula by the slow CME event of 1997 June 2 in order to estimate the physical parameters of the latter at a distance of 41 $R_\odot$ from the Sun, assuming that the angular broadening of the radio source is due to scattering effects by the CME. The estimated electron density of the CME is about 50 times greater than that of the ambient corona at that location, which is $\approx 200\ \mathrm{cm^{-3}}$ (Leblanc, Dulk, & Bougeret 1998). The calculated mass agrees approximately with that reported recently for some of the white-light CMEs at large distances from the Sun, using LASCO data (Vourlidas et al. 2000). Also, it is consistent with the scenario that slow CMEs have smaller masses (Gothoskar & Rao 1999). It is suggested that further observations of this type might be useful in understanding the association between the energetic events in the Sun's atmosphere and the related disturbances in the interplanetary medium, in an independent way.

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