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ESTIMATION OF THE ALTITUDE AND ELECTRON DENSITY OF A DISCRETE SOURCE IN THE OUTER SOLAR CORONA THROUGH LOW FREQUENCY RADIO OBSERVATIONS

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One dimensional observations of the Sun during 20–25 February 1995 with the E–W arm of the Gauribidanur radioheliograph at 51 and 77 MHz revealed the presence of a discrete source in the corona whose position shifted everyday with the solar rotation. The measured rate of rotation is used to estimate the altitude of the radio emitting region. The computed spectral index indicates that the source is thermal in nature. A comparison with the optical data shows a close association with an arch filament system on the solar disk.

Keywords: Sun; corona; Hα filaments; streamers; coronal arches; electron density; radio observations

INTRODUCTION

In the solar atmosphere the altitude of the plasma level corresponding to any particular radio frequency is generally estimated using the density models obtained through eclipse and coronagraph observations. The altitude of a discrete emitting region can be calculated from its rate of rotation across the solar disk. Such studies are very

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rare at frequencies < 100 MHz. The one dimensional scans of the Sun obtained with the Nancay E–W interferometer at 169 MHz were used by Moutot and Boischot (1961) to demonstrate that by measuring the rotation rate of the emitting region across the solar disk, it is possible to calculate its height above the photosphere. According to Axisa *et al.* (1971), a discrete source of enhanced emission is best seen for one or two days around its meridian passage. Some sources do persist for a longer duration, but their rotation is often irregular. Sastry *et al.* (1981, 1983) observed that the day-to-day variation of the position of the discrete sources in their maps at 34.5 MHz were irregular. The observations of Sastry *et al.*, were carried out close to the sunspot maximum in 1980. In this paper, we October report observations of the rotation of a discrete source in the solar corona at 51 and 77 MHz using the data obtained with the Gauribidanur radioheliograph (GRH, Ramesh *et al.*, 1998) during February 1995 which was close to sunspot minimum.

OBSERVATIONS

Observations of the Sun were carried out at 51 and 77 MHz using the E–W arm of the GRH during the last solar minimum. On each day, the observing run lasted for about 30 minutes (± 15 minutes around the local noon at 06 : 30 UT). Localised sources of enhanced emission were noticed in our maps on many occasions, but they did not show any regular rotation. However the data obtained during 20–25 February 1995 revealed the presence of a discrete source which rotated with the Sun (Figs. 1 and 2). The location of the discrete source on each day was established by taking the derivative of the observed data close to it and noting where the derivative changes sign. The rotation rate of the source was calculated from this and the least squares fit gives it as $4.4'$/day at 77 MHz and $5.3'$/day at 51 MHz (Figs. 3 and 4). The errors due to the ionospheric effects are considered to be minimal since the observations were made at the local noon. The Sun was relatively 'quiet' and no burst activity was seen in our data. This was also confirmed by reports in the *Solar Geophysical Data* (April, 1995). The radio source Tau A was used for calibrating the solar flux data in the present case. The flux density (S) of the discrete source was estimated after subtracting the contribution of the background 'quiet'

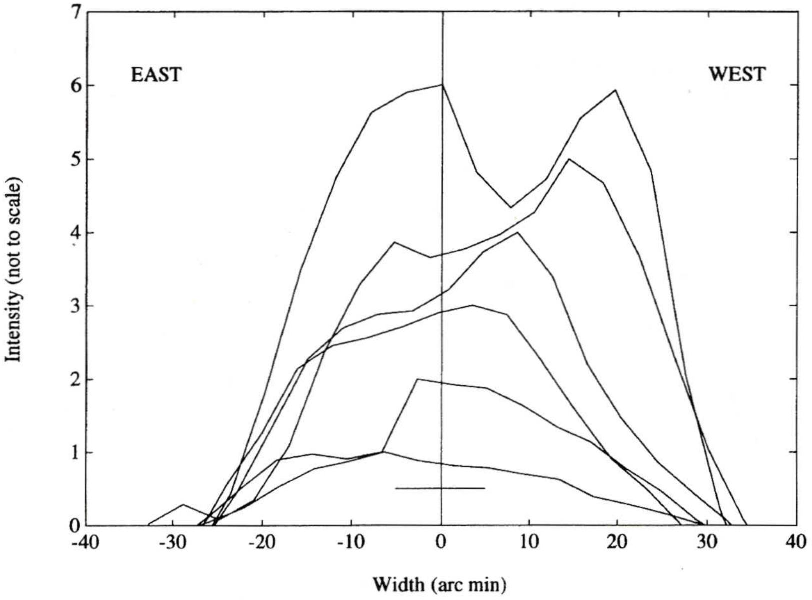

FIGURE 1 Observations of the East – West one-dimensional brightness distribution of the Sun at 51 MHz with the E – W arm of the GRH. The profiles are plotted with increasing intensity (not to scale) from 20 – 25 February 1995. The beam size is indicated by the horizontal bar close to the *abcissa*.

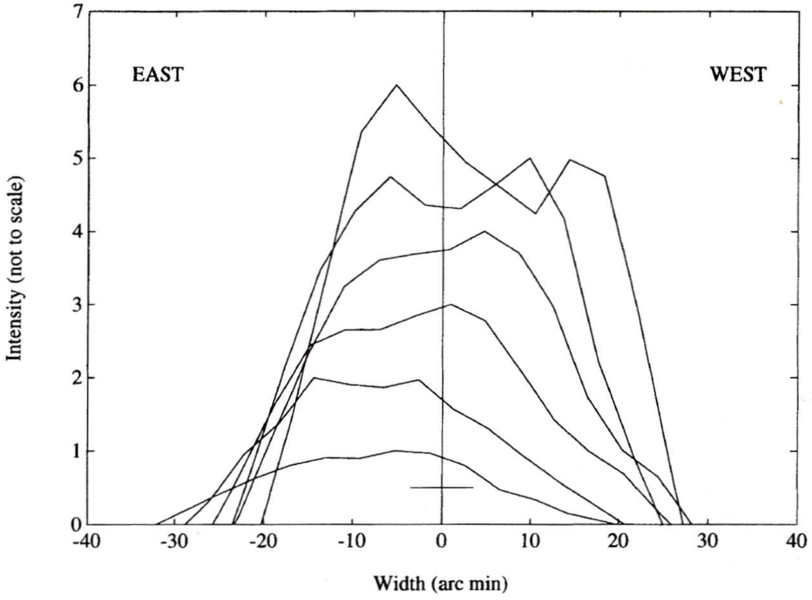

FIGURE 2 Same as Figure 1 but at 77 MHz.

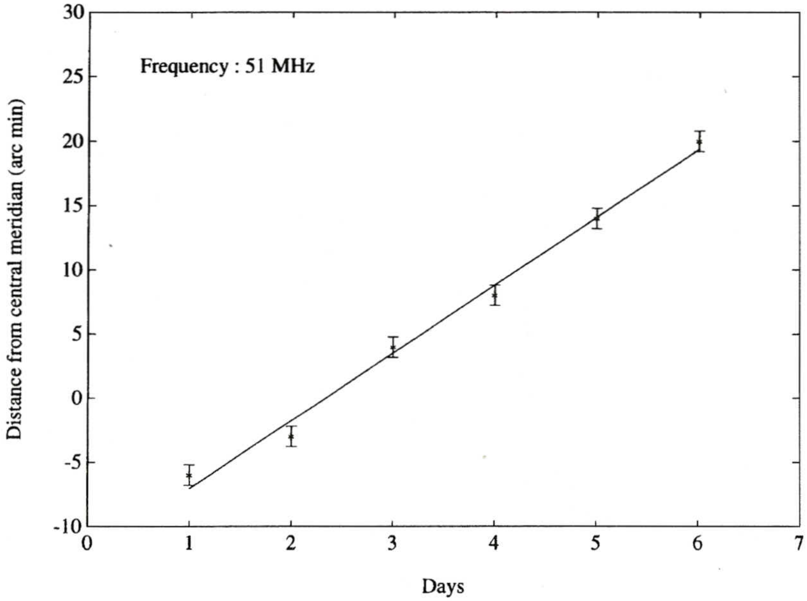

FIGURE 3 Location of the discrete radio source from the central meridian on successive days at 51 MHz. The least squares fit to the observed values and the error bar associated with them is also shown.

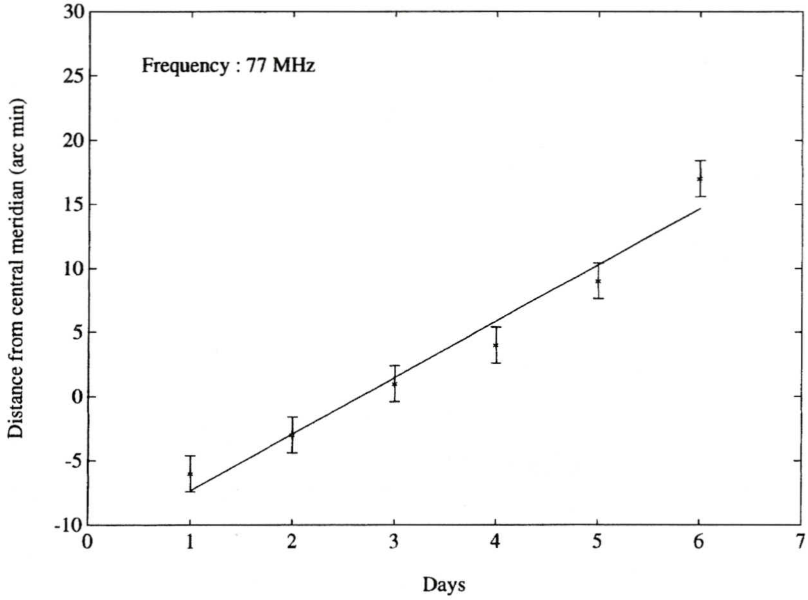

FIGURE 4 Same as Figure 3 but at 77 MHz.

TABLE I Details of the discrete source

Date	$S_{51\,MHz}$ *(in Jy)*	$S_{77\,MHz}$ *(in Jy)*	*Spectral index* γ
20.2.1995	1713	5856	2.98
21.2.1995	1653	4105	2.21
22.2.1995	1908	5666	2.64
23.2.1995	1453	3939	2.42
24.2.1995	1571	3953	2.24
25.2.1995	1018	5004	3.87

Sun from the observed flux. The 'quiet' Sun flux was taken to be ≈ 2837 Jy and 7469 Jy at 51 and 77 MHz respectively (Erickson *et al.*, 1977). Table I gives the flux density of the discrete source for each day at 51 and 77 MHz, and also the spectral index (γ) calculated using them. The errors in the estimation of the flux density are mainly due to: (1) the variation in the antenna gain with zenith angle. In the present case, this error was calculated to be approximately 10% based on the flux density measurements of various point sources at different declinations with the GRH and; (2) the uncertainty in the measurement of flux density of the calibrator which is approximately 5% (Nelson, Sheridan and Suzuki, 1985).

ALTITUDE, ELECTRON DENSITY OF THE EMITTING REGION

It is well known that the apparent movement of a localised source across the solar disk is proportional to its height above the photosphere. In the present case, we estimated the height (h) of the discrete radio source using the relation,

$$h = \left[\left(\frac{\alpha}{\beta}\right) - 1\right] \mathrm{R}_{\odot} \tag{1}$$

where α is the apparent rotation of the radio source in 24 hours as measured by an observer at the Earth, β is the apparent rotation of the associated optical source during the same period, and $\mathrm{R}_{\odot}$ is the radius of the Sun ($\approx 6.96 \times 10^5$ km). It is to be noted here that α is measurable only in the celestial E–W direction. This implies β must be also along the same direction. To calculate the value of β along the celestial E–W direction, one should know the position angle (P) of the Sun's axis of rotation from the celestial North, the heliographic latitude (B_o) and longitude (L_o) of the central point of the solar disk, and the heliographic coordinates (B, L) of the corresponding optical source on the surface of the Sun at the beginning and end of the above period. From these, one can deduce the heliocentric angular distance (ρ) and position angle (θ) of the source from the center of the disk of the Sun as seen from the Earth using the following equations (Smart, 1962),

$$\rho = \cos^{-1}[\sin B_o \sin B + \cos B_o \cos B \cos(L - L_o)] \tag{2}$$

and

$$\theta = P - \sin^{-1}\left[\frac{\cos B \sin(L - L_o)}{\sin \rho}\right] \tag{3}$$

Finally,

$$\beta = \sqrt{\rho_1^2 + \rho_2^2 - 2\rho_1\rho_2 \cos(\theta_1 - \theta_2)} \tag{4}$$

where ρ_1, ρ_2 and θ_1, θ_2 are the heliocentric angular distance and position angle of the optical source from the center of the Sun's disk at the beginning and end of the period. The values of P, B_o and L_o in Eqs. (3) and (4) given above can be found from the *Astronomical Almanac* for any particular day in a year.

An inspection of the *Solar Geophysical Data* (August, 1995) for the period under study indicated a close association between the discrete radio source in our data and an arch filament system (AFS) located close to the equator on the disk. The latter crossed the central meridian on the same day as the radio source, *i.e.*, 22 February 1995 and was not noticed after 25 February 1995, again same as in our case. The heliographic location of the AFS was (N12 E27) at ~06:00 UT on 20 February 1995 and (N12 W50) at ~23:59 UT on 25 February 1995. Substituting these values along with the other in the above set of equations, we get $h \approx 0.19\,R_\odot$ at 77 MHz and $0.44\,R_\odot$ at 51 MHz.

It is well known that for a radio emitting structure to be visible at a particular observing frequency, its electron density (N_e) should not exceed the plasma density at that frequency. Otherwise the radio waves will get reflected and do not penetrate into the region. Thus the maximum of emission is likely to be located close to the critical density level because, (i) the electron density in the solar atmosphere decreases with increasing altitude, and (ii) at any particular observing frequency, most of the emission comes from a very small region close to the corresponding plasma level where the absorption coefficient is maximum. This implies that the densities at heights $0.19\,R_\odot$ and $0.44\,R_\odot$ above the photosphere are $7.32 \times 10^7\,\mathrm{cm}^{-3}$ and $3.21 \times 10^7\,\mathrm{cm}^{-3}$, the critical values at 77 and 51 MHz respectively. The equatorial density model of the background corona (a component of the corona distinct from features like streamers, holes, *etc.*) near solar minimum derived by Saito, Poland and Munro (1977) gives $N_e = 5.31 \times 10^7\,\mathrm{cm}^{-3}$ and $1.78 \times 10^7\,\mathrm{cm}^{-3}$ corresponding to the above two levels. This means that the source has to be ~ 1.5 times denser than the ambient (as given by Saito model) to explain radio emission at 77 and 51 MHz from the above altitude.

DISCUSSIONS

The discrete sources in the low frequency radio maps of the Sun are generally attributed to weak noise storms which are non-thermal in nature (Sheridan, 1970; Alissandrakis, Lantos and Nicolaidis, 1985; Lantos *et al.*, 1987). This can be ruled out in the present case because: (1) the noise storm emission is considered to be highly variable (Shevgaonkar, Kundu and Jackson, 1988; Alissandrakis and Lantos, 1996). Sastry (1994) pointed out that the observed flux density of the 'quiet' Sun should vary significantly in the presence of weak noise storm sources; (2) no type I radio bursts were reported during our observational period in the *Solar Geophysical Data* (April, 1995); and (3) the non-thermal spectral index is generally < 0 and can be < -3 for some process like the plasma emission (Kaplan and Tystovitch, 1968) which is widely considered to be responsible for noise storm radiation. According to Subramanian and Sastry (1988), the observed spectral index is not likely to attain large ($> +2$) positive values even if the thermal and non-thermal contributions are mixed along the line of sight. However the situation might be different if the non-thermal emission is confined to a narrow bandwidth.

In the case of emission being thermal, the radio sources were widely assumed to be streamers above Hα filaments (Dulk and Sheridan, 1974; Shevgaonkar, Kundu and Jackson, 1988; Lang and Willson, 1989). But, systematic studies with the Nancay radioheliograph during solar minimum indicate that the radio sources of thermal origin are best associated with 'neutral' lines of the longitudinal photospheric magnetic field and the emission comes from moderately dense loops spanning the 'neutral' line (Alissandrakis, Lantos and Nicolaidis, 1985; Lantos *et al.*, 1987; Lantos, Alissandrakis and Rigaud, 1992). According to Alissandrakis and Lantos (1996), any association of the radio sources with the filaments does not imply a physical connection between the two, but should be considered as an association with the underlying 'neutral' line. This suggests a possible link between meterwave sources and arch filament systems (AFS) since the latter connect opposite magnetic polarities and bridge the 'neutral' line (Bruzek, 1967). Therefore it is possible that the discrete radio source observed in the present case might be associated with the arch filament system described in the previous section. Another point we would like to mention here is regarding the density variation inside the discrete source as compared to that of a streamer, since regions of closed magnetic field lines in the solar corona are supposed to have a flatter density gradient compared to regions of open field lines (Athay, 1973). From the observations with the Coronal Diagnostic Spectrometer onboard the *Solar and Heliospheric Observatory* (SoHO) during the recent solar minimum period, Li *et al.* (1998) measured the density of a coronal streamer at heights $0.15\,R_\odot$ and $0.5\,R_\odot$ above the photosphere to be $1.23 \times 10^8\,\mathrm{cm}^{-3}$ and $1.26 \times 10^7\,\mathrm{cm}^{-3}$ respectively. This gives $N_e \propto R_\odot^{-8.6}$ between the above two levels in the corona. Compared to this, we have $N_e \propto R_\odot^{-1.8}$ between $0.19\,R_\odot$ and $0.44\,R_\odot$ from the present observations. We would like to point here that the latter estimate must be treated with caution since low frequency radio radiation is generally believed to undergo scattering by small scale (~ 100 km) density inhomogeneities in the solar corona. This could possibly extend the 50 MHz discrete source to a greater height (compared to the 77 MHz source) than that given by pure free–free emission (Kundu *et al.*, 1987). It is clear from the above that further observations are necessary to establish the properties of the discrete sources of thermal emission in the low frequency radio maps of the Sun, and interpret the origin of their emission.

CONCLUSIONS

We have observed the radio emission from the 'quiet' Sun during the declining phase of the last solar cycle with the E–W arm of the GRH at 51 and 77 MHz. The observations during the period 20–25 February 1995 showed the presence of a discrete source at the above two frequencies whose position shifted everyday with the solar rotation. Our main results are:

1. The sources were thermal in nature.
2. The altitude (above the photosphere) of the sources is $\approx 0.44\,\mathrm{R}_\odot$ and $0.19\,\mathrm{R}_\odot$ respectively at the above two frequencies.
3. The density variation in the discrete source between the above two levels in the corona is $N_e \propto \mathrm{R}_\odot^{-1.8}$.
4. The radio source was closely associated with an arch filament system on the solar disk.

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