VERY LARGE ARRAY (VLA) OBSERVATIONS OF SOLAR ACTIVE REGIONS

Kenneth R. Lang and Robert F. Willson
Dept. of Physics, Tufts Univ., Medford, MA 02155, USA

Abstract. Very Large Array (VLA) synthesis maps of the total intensity and the circular polarization of three active regions at 6 cm wavelength are presented. The radiation from each active region is dominated by a few intense cores with angular sizes of $\sim 0.5'$, brightness temperatures of $\sim 10^6$ K, and degrees of circular polarization of 30 to 90%. Some of the core sources within a given active region exhibit opposite senses of circular polarization, suggesting the feet of magnetic dipoles, and the high brightness temperatures suggest that these magnetic structures belong to the low solar corona. We also present comparisons between our VLA maps of circular polarization and Zeeman effect magnetograms of the lower lying photosphere. There is an excellent correlation between the magnetic structures inferred by the two methods, indicating that synthesis maps of circular polarization at 6 cm can be used to delineate magnetic structures in the low solar corona.

1. INTRODUCTION

Interferometric observations of the Sun at 2.8 and 3.7 cm wavelength with angular resolutions of a few seconds of arc (Felli et al., 1974; Kundu et al., 1974; and Lang, 1974, 1977) indicated that solar radiation at these wavelengths and angular resolutions is dominated by intense ($\sim 10^6$ K), small-scale ($< 0.5'$) core sources. The high degree of circular polarization (30 to 90%) of these sources, together with their spatial correlation with solar active regions, suggested that they are intimately related to the magnetic fields of sunspots; and the radio emission was interpreted in terms of the gyromagnetic emission of thermal electrons in strong magnetic fields ($\sim$ 500 gauss) in the lower solar corona.

Except when the Sun is emitting solar flares, the intensity, angular size, and degree of circular polarization of the small scale core sources remain remarkably constant for periods as long as days, and this stability makes them ideal candidates for aperture synthesis techniques. Kundu and Allisandrakis (1975), Alissandrakis (1977), and

M.R. Kundu and T.E. Gergely (eds.), Radio Physics of the Sun, 109-117.

https://doi.org/10.1017/S0074180900036706 Published online by Cambridge University Press

Kundu et al. (1977) obtained the first synthesis maps of solar active regions using the Westerbork Synthesis Radio Telescope (WSRT) at 6 cm wavelength. Their results indicated that the structure of active regions at 6 cm wavelength is mainly determined by the structure and intensity of the solar magnetic field. Moreover, the intense small-scale core sources were shown to be associated with sunspots whose magnetic polarity coincided with the direction of the circular polarization of the 6 cm radio emission. When the WSRT was used to obtain synthesis maps at 21 cm (Chiuderi Drago et al., 1977), however, only extended sources ($\gtrsim$ 2') with low degrees of circular polarization ($\lesssim$ 5%) were found to be associated with active regions.

In this paper we present Very Large Array (VLA) observations of solar active regions which confirm and amplify the 6 cm WSRT results. Each active region was found to contain several intense cores with angular diameters of $\sim$ 0.5',brightness temperatures of $\sim 10^6$ K, and circular polarization of 30 to 90%. Within each active region the core sources are separated by $\sim$ 1' and some of them exhibit opposite senses of circular polarization, suggesting the feet of the magnetic dipoles which are seen as sunspots in the photosphere. In the next section we present the VLA synthesis maps of total intensity and circular polarization at 6 cm wavelength for three active regions. In the following section we compare our VLA maps of circular polarization with magnetograms of the underlying photosphere. A striking correlation between the magnetic structures inferred by the two methods is indicated.

2. VERY LARGE ARRAY (VLA) OBSERVATIONS OF SOLAR ACTIVE REGIONS

We have used the VLA to observe the following active regions: on March 29, 1978 the active regions AR 1046 (McMath 15205, 24^{o}S 7^{o}W at 12^h UT on March 30); on April 1, 1978 the active region AR 1056 (McMath 15220, 12^{o}N 65^{o}E at 0^h UT on March 31); and on November 4, 1978 the active regions AR 1381 and AR 1374 (McMath 15635, respectively 19^{o}S 14^{o}E and 25^{o}S 22^{o}E at 0^h UT on November 4). The individual antennae of the VLA have a diameter of 25m which provided a beamwidth of 8.6' and an aperature efficiency of 65% at our operating wavelength of 6 cm. In March and April we used 12 antennae with three antennae positioned along the south-east arm at 0.08, 0.09 and 0.15 km from the array center and nine antennae placed along the south-west arm at 0.045, 0.48, 0.71, 0.97, 1.59, 3.19, 5.22, 7.66 and 10.47 km from the array center. In November we also used 12 antennae with four antennae positioned along the south-east arm at 0.08, 0.48, 0.97 and 1.59 km and eight antennae placed along the south-west arm at 0.48, 0.71, 1.59, 3.19, 5.22, 7.66, 10.47, and 13.64 km. Altogether the average correlated flux of 55 interferometer pairs was sampled every 30 s at a signal wavelength of 6 cm for both the left hand circularly polarized (LCP) and right hand circularly polarized (RCP) signals.

For each antenna pair the correlator outputs were calibrated by observing 3C 84, CTA 102, or 3C 273 for 5 min every 20 min, whereas

https://doi.org/10.1017/S0074180900036706 Published online by Cambridge University Press

the solar active region was observed during the remaining 15 min of each 20 min period. The frequent observations of the calibrator lessened the effects of tropospheric refraction variations, and allowed a calibration of the instrumental gain, polarization and phase according to the procedures described by Lang and Willson (1979). The 30 s values of amplitude and phase were then added together to obtain 5 min vector averages with a phase calibration better than 5^o and an amplitude calibration accurate to $< 10\%$. These calibrated averages of the amplitude and phase of each polarization for every antenna pair were then taken to be the amplitude and phase of the source visibility function, and the source intensity distribution was obtained by Fourier transforming the calibrated data. The intensity distributions obtained from the right hand circularly polarized (RCP) and left hand circularly polarized (LCP) signals were then combined to form synthesis maps of the total intensity I = (LCP+RCP)/2 and the circular polarization V = (LCP-RCP)/2.

Our preliminary results indicated that the active regions were all resolved on baselines having fringe spacing $< 15''$, making the longer baseline data at 6 cm unnecessary. Because the visibility function at 21 cm was very similar to that observed at 6 cm, only a few of the shorter VLA baselines produced useful data at 21 cm, and we have omitted an analysis of this data here. The 6 cm data having fringe spacings $< 15''$ were deleted, thereby reducing map noise and the synthesis maps of I and V shown in Figures 1, 2 and 3 were then produced using the "clean" procedure. The maps are in units of Jy per synthesized beam area ($1\ Jy = 10^{-23} erg\ s^{-1} cm^{-2}\ Hz^{-1} = 10^{-26}\ W\ m^{-2}\ Hz^{-1}$) with contour level values denoted in the figure legends. The r.m.s. sensitivity of the VLA system for 12^h of observation of the 10^4 K Sun is estimated to be 0.06 Jy.

Each of the maps shown in the figures contain small-scale core sources with angular diameters of $\sim 0.5'$ and high degrees of circular polarization (peak V/I = 30 to 90%). The most intense components of AR 1046, AR 1056 and AR 1381 have intensity distributions with respective peak values of 70, 90, and 200 Jy per square arc second. Assuming a source size of 30" x 30" and using the Rayleigh-Jeans law with a wavelength of 6 cm these peak brightness values correspond to respective peak brightness temperatures of two to five million degrees. These high values of brightness temperature suggest that the core sources are located in the low solar corona. Under the assumption that the observed radiation is the gyromagnetic emission of thermal electrons radiating at the first few harmonics of the gyrofrequency, magnetic field strengths of a few hundred gauss are inferred (about 890 gauss for the second harmonic radiating at 6 cm wavelength).

3. COMPARISONS WITH MAGNETOGRAMS

The coronal magnetic structures inferred from the 6 cm maps of circular polarization may be compared with the full disk magnetograms taken daily at the Kitt Peak National Observatory (KPNO). Both circular

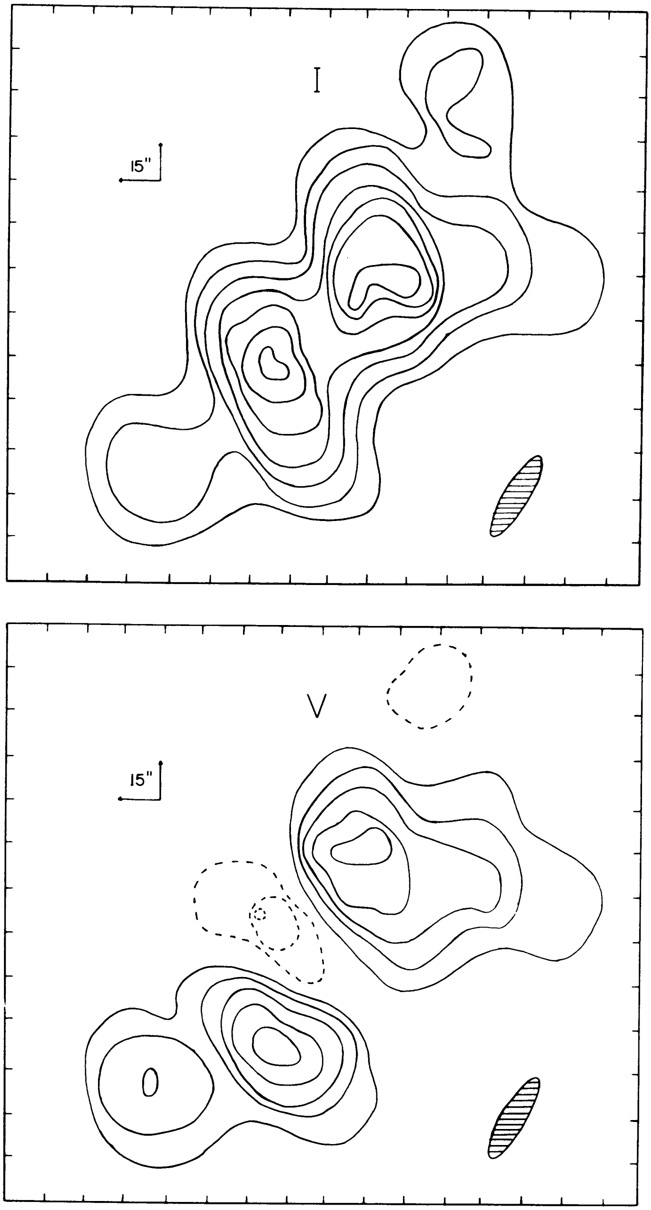

Fig. 1 VLA synthesis maps of the total intensity, I, and the circular polarization, V, at 6 cm wavelength of solar active region 1046 (McMath 15205) for one days observation on March 29, 1978. North is up, west is to the right, dashed lines indicate negative values of V and correspond to right circularly polarized radiation, and solid lines denote positive V values and left circularly polarized radiation. The contours for the I map are at 70, 60, ... 10 Jy per square arc second. The maximum positive and negative values of the V contours are +50 and -30 Jy per square arc second, and the contour levels are also in step of 10.

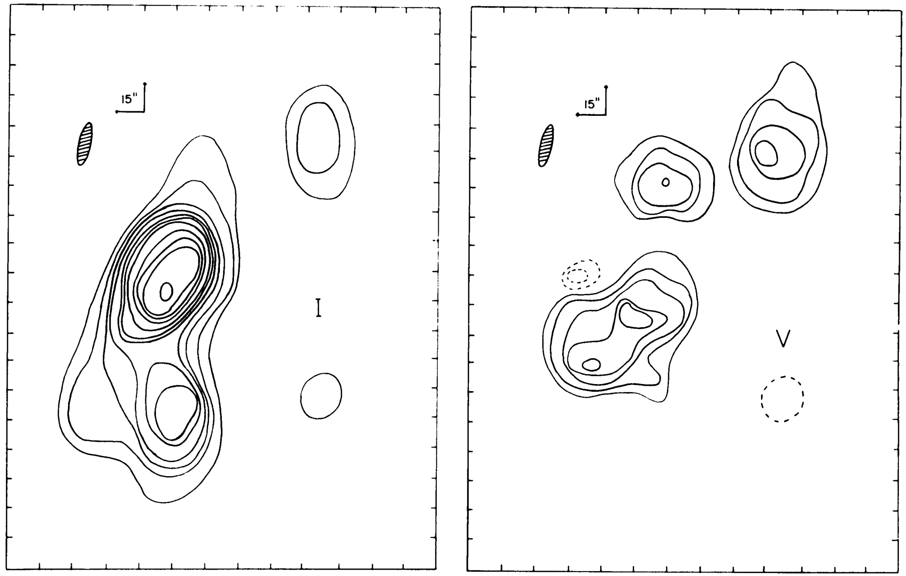

Fig. 2. VLA synthesis maps of the total intensity, I, and the circular polarization, V, at 6 cm wavelength of solar active region 1381 (McMath 15635) for one days observation on November 4, 1978. North is up, west is to the right, dashed lines indicate negative values of V and correspond to right circularly polarized radiation, and solid lines denote positive V values and left circularly polarized radiation. The contours for the I map are at 200, 180, ..10 Jy per square arc second. The maximum positive and negative values of the V contours are +60 and −20 Jy per square arc second, and the contour levels are in steps of 10.

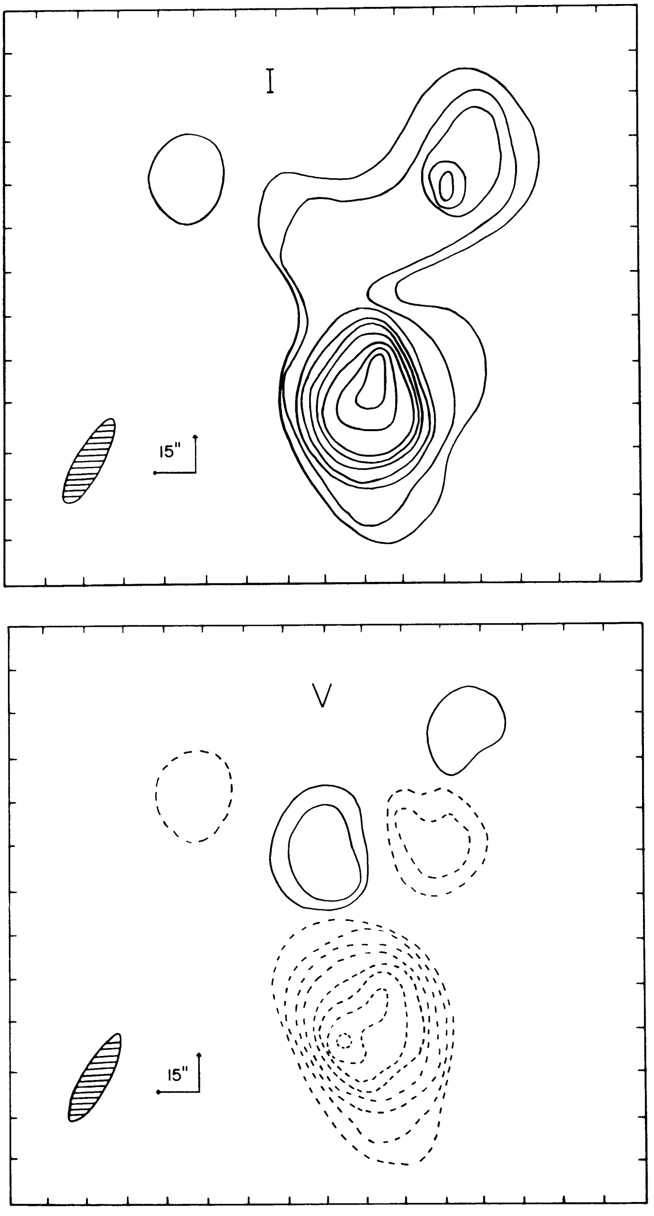

Fig. 3 VLA synthesis maps of the total intensity, I, and the circular polarization, V, at 6 cm wavelength of solar active region 1381 (McMath 15635) for one days observation on April 1, 1978. North is up, west is to the right, dashed lines indicate negative values of V and correspond to right circularly polarized radiation and solid lines denote positive V values and left circularly polarized radiation. The contours for the I map are at 90, 80, 70, ... 10 Jy per square arc second. The maximum positive and negative values of the V contours are +20 and -80 Jy per square arc second, and the contour levels are in steps of 10.

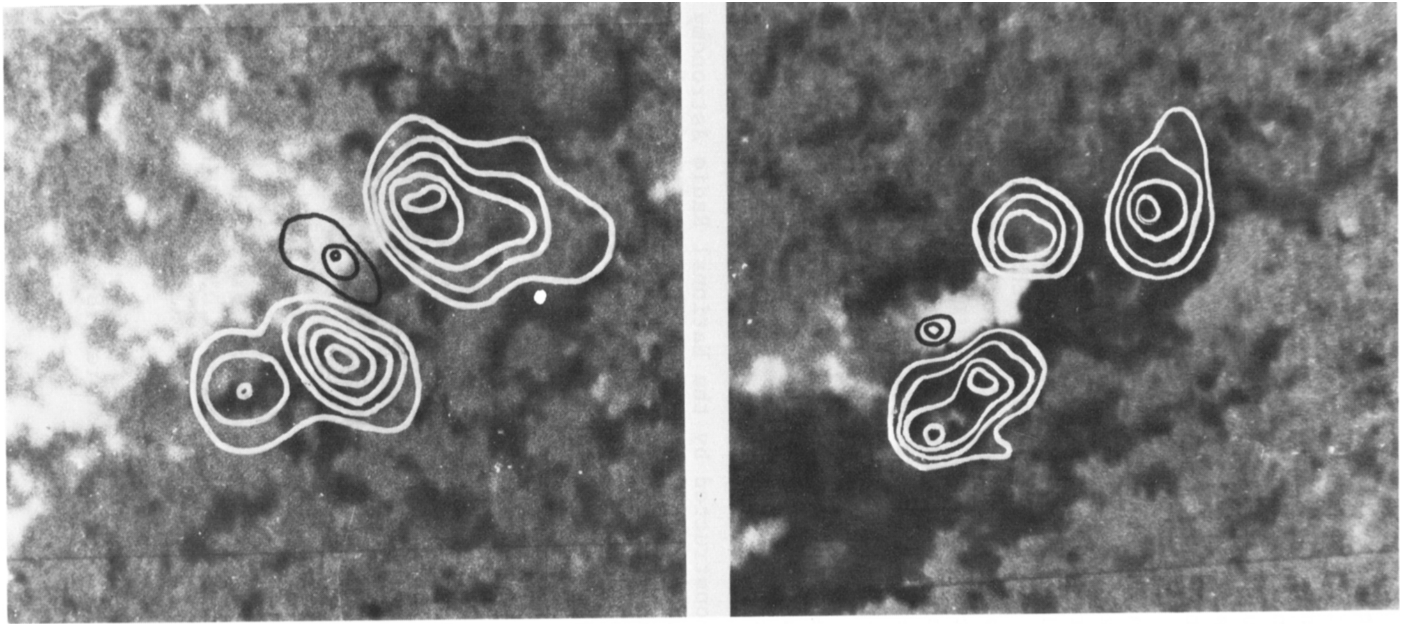

Fig. 4 A comparison of VLA synthesis maps of circular polarization, V, at 6 cm wavelength (see Figures 1 and 3) with KPNO magnetograms taken on the same day. North is up, west is to the right, and the left and right maps respectively refer to AR 1046 (McMath 15205 on March 29, 1978) and AR 1381 (McMath 15635 on November 4, 1978). The dark regions of the magnetograms refer to regions of negative magnetic polarity and correspond to positive V values (solid white contours) and left circularly polarized radiation at 6 cm. The light regions of the magnetograms refer to regions of positive magnetic polarity and correspond to negative V values (solid black contours) and right hand circularly polarized radiation at 6 cm. The magnetograms are enlargements of the appropriate sections of the KPNO full disk magnetograms.

polarization maps and the magnetograms describe the structure of the longitudinal component of the magnetic field, but the magnetograms refer to the lower lying photosphere. In Figure 4 we compare the circular polarization maps of Figures 1 and 3 with KPNO magnetograms taken on the same day (due to inclement weather no magnetogram was available for April 1). The magnetograms were taken using the Zeeman effect of the 8,680 A line of neutral iron, and they are limited to 2" to 3" angular resolution by atmospheric scintillation. In Figure 4 we have enlarged the appropriate section of the magnetograms and compared them with VLA maps with the same angular scale. Here dark magnetogram regions refer to regions of negative magnetic polarity and correspond to positive, left handed circular polarization (solid white lines); whereas light magnetogram regions refer to regions of positive magnetic polarity and correspond to negative, right handed circular polarization (dashed black lines). Figure 4 demonstrates that the circularly polarized structure of active regions at 6 cm wavelength is determined by the intensity and structure of the solar magnetic field, and that the magnetic field inferred from magnetograms for the photosphere is very similar to that inferred from the 6 cm maps for the low solar corona. The shape, orientation, and dipolar structure of the 6 cm maps of AR 1046 are, for example, similar to those of the magnetogram; but note that the spacings between the magnetic flux tubes of the dipoles are smaller in the 6 cm maps - as would be expected if these maps refer to a higher level in the solar atmosphere.

The VLA is being constructed by the National Radio Astronomy Observatory which is operated by Associated Universities under contract with the NSF. Radio interferometric studies of the Sun at Tufts University are supported under contract F 19628-79-C-0010 with the Air Force Geophysics Laboratory.

REFERENCES

Alissandrakis, C.E.: 1977, "Six Centimeter Wavelength Observations of Solar Active Regions and Bursts with Six Arc-Seconds Resolution", University of Michigan (Ph.D. Thesis).
Chiuderi-Drago, F., Felli, M., and Tofani, G.: 1977, Astron. Astrophys. 61, 79.
Felli, M., Pampaloni, P. and Tofani, G.: 1974, Solar Phys. 37, 395.
Kundu, M.R. and Alissandrakis, C.E.: 1975, Nature 257, 465.
Kundu, M.R., Becker, R.H. and Velusamy, T.: 1974, Solar Phys. 34, 185.
Kundu, M.R., Alissandrakis, C.E., Bregman, J.D., and Hin, A.C.: 1977, Astrophys. J. 213, 278.
Lang, K.R.: 1974, Solar Phys. 36, 351.
Lang, K.R.: 1977, Solar Phys. 52, 63.
Lang, K.R. and Willson, R.F.: 1979, Nature 278, 24.

DISCUSSION

Alissandrakis: What is the brightness temperature of the sources? Are the sources sunspot-associated?

Lang: The brightness temperatures range between two and five million degrees for the flux values and angular sizes specified in the text of the paper (about 30" x 36" and 100 Jy per square second of arc). The black features on the magnetograms correspond to sunspots, and Hα pictures will specify whether or not the white regions on magnetograms correspond to the bipolar spot or plage. At any rate, the bipolar structures seen in the magnetograms are reproduced in the VLA.