RADIO WAVELENGTH OBSERVATIONS: STRUCTURE, STRENGTH AND VARIABILITY OF MAGNETIC FIELDS IN THE TRANSITION REGION AND THE SOLAR CORONA

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ABSTRACT

The 6 cm radiation of solar active regions marks the legs of dipolar loops which have their footpoints in lower-lying sunspots. The temperatures $T \approx 10^6$K and longitudinal magnetic field strengths $H_\ell \approx 600$ Gauss at heights $h \approx 4 \times 10^9$ cm above sunspot umbrae. The circularly polarized emission at 6 cm delineates the magnetic structure above sunspot penumbrae. The 20 cm radiation of solar active regions delineates the ubiquitous coronal loops previously detected at X-ray wavelengths. We infer semilengths $L \approx 5 \times 10^9$cm, maximum electron temperatures $T_e(\max) \approx 3 \times 10^6$K, emission measures $\int N_e^2 d\ell \approx 10^{28}$cm^{-5} and electron densities $N_e \approx 10^9$cm^{-3} for the 20 cm bremsstrahlung. Future V.L.A. observations at 20 cm may be used to determine the magnetic field strength of coronal loops. Changes in temperature and magnetic structure before and during solar bursts are briefly discussed.

THE LEGS OF MAGNETIC DIPOLES CONNECTING SUNSPOT UMBRAE

Enhanced 6 cm emission is often most intense above sunspot umbrae. Lang and Willson (1979,1980) have shown that this sunspot-associated emission has high brightness temperatures of $T_B \approx 2 \times 10^6$K and high degrees of circular polarization of ρ_c = 60 to 80%. The 6 cm emission marks the legs of magnetic dipoles which join sunspots of opposite magnetic polarity. The highly polarized radiation ($\rho_c \approx 70\%$) corresponds to the extraordinary mode of wave propagation in magnetic fields with the same polarity as the underlying sunspots. It is explained as optically thin gyroresonance emission in the low solar corona above sunspots where the temperatures $T \approx 10^6$K and the longitudinal magnetic field strength $H_\ell \approx 600$ Gauss (third harmonic at 6 cm). The observed circular polarization requires resonance at the third harmonic because the second harmonic is optically thick and gyroresonant absorption is an ineffective opacity agent at the fourth harmonic. Polarization by propagation effects requires even higher magnetic field strengths which would make the regions everywhere optically thick to gyroresonant absorption. The two most

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intense components of the 6 cm emission are displaced inwards by about 25". Assuming that the sunspots mark the feet of a circular dipole, we infer a height h $\approx$ 4 x 10^9 cm above the solar photosphere. These maps show no evidence for cool material above sunspot umbrae, but they refer to structures that are stable for hours. Cooler material with lifetimes shorter than a few hours would not be detected. There is no evidence for an abnormally thin transition region above sunspots.

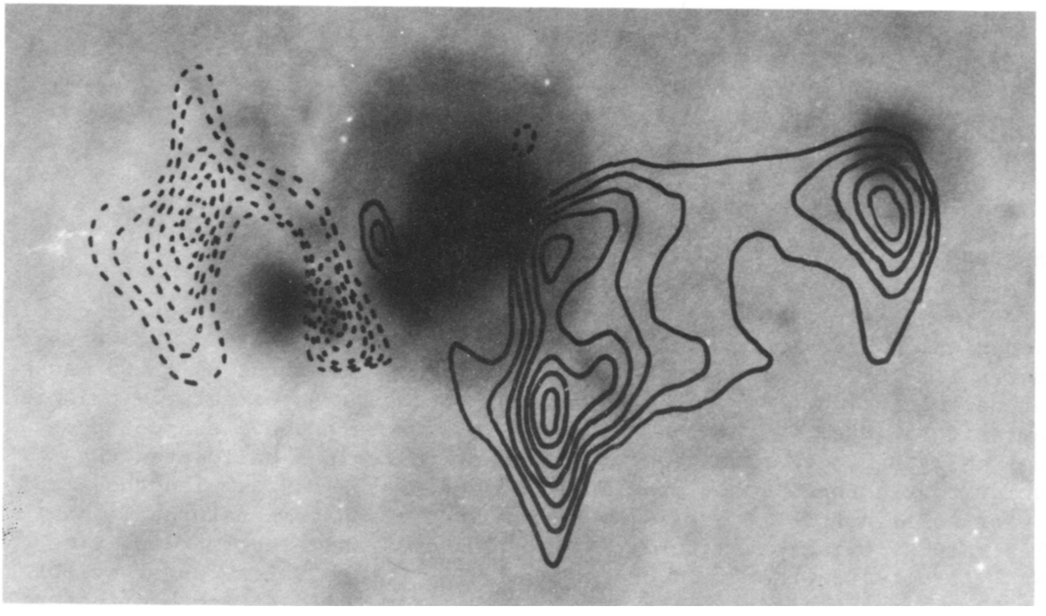

Fig. 1. A 6 cm synthesis map of circular polarization (Stokes parameter V) superimposed upon an offband Hα photograph taken on the same day. The polarized emission is concentrated above the sunspot penumbrae where the magnetic field lines are curved. (Offband Hα courtesy of Frances Tang, Big Bear Solar Observatory.)

MAGNETIC FIELDS ABOVE SUNSPOT PENUMBRAE

The intense magnetic fields of sunspot umbrae probably project radially upwards into the low solar corona with little loss of strength. This enables the third harmonic of the gyrofrequency to occur at higher, hotter levels of the solar atmosphere where the temperature gradient is small. The situation is different for the curved magnetic fields of the sunspot penumbrae. In this case, the resonance levels corresponding to the third harmonic occur in the lower-lying cooler regions of the solar atmosphere where the temperature gradients are large. In Figure 1 we show that the circular polarized emission (Stokes parameter V) at 6 cm wavelength lies above sunspot penumbrae. The high degrees of circular polarization ($\rho_c \approx$ 95%) of the peaks of the horseshoe structure requires gyroresonant emission with a longitudinal magnetic field strength $H_\ell \approx$ 600 Gauss at lower temperatures T $\approx$ 10^5K above penumbrae. The

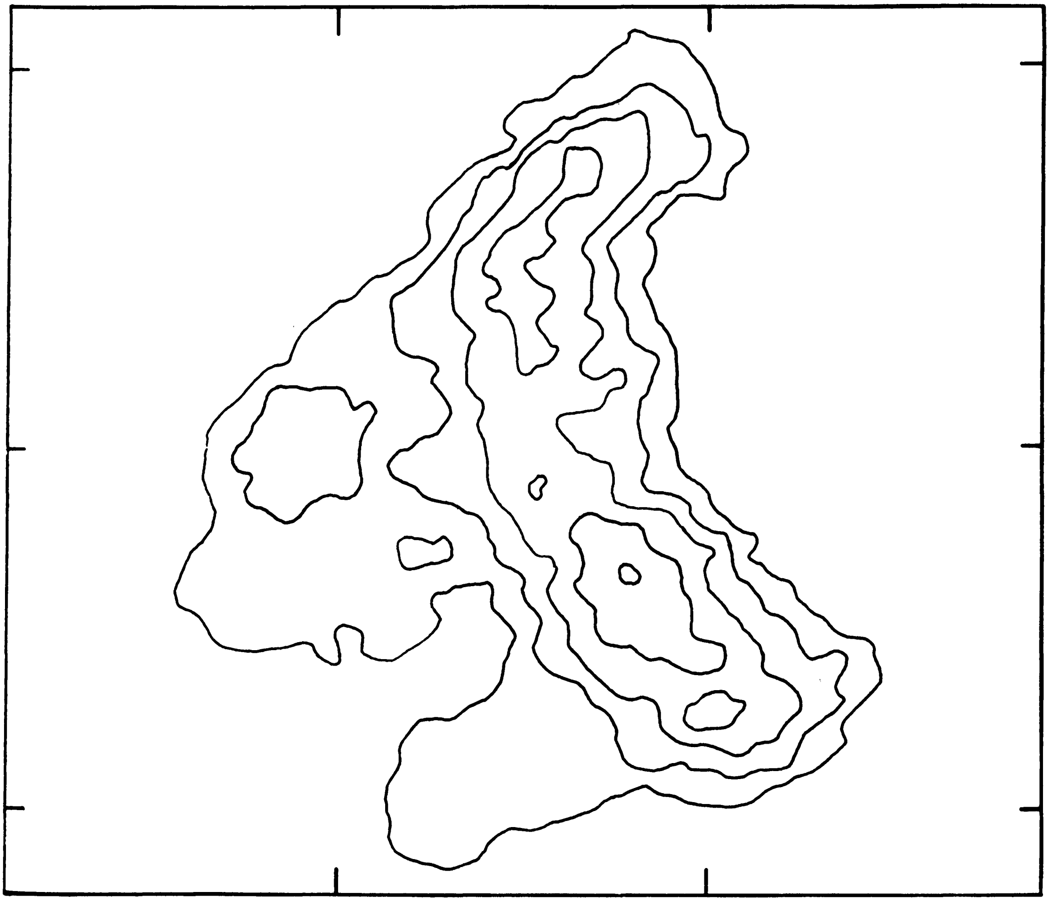

Fig. 2: A 20 cm synthesis map of total intensity delineating a coronal loop connecting two sunspots which lie just to the right of the top and bottom-most extensions of the loop. Here the contours mark levels of equal brightness temperature corresponding to 0.2, 0.4, 0.6 and 0.8 times the maximum brightness temperature of 2 x 10^6K. The angular scale may be inferred from the 60" spacing between fiducial marks. The solar active region is about 20° across the solar surface from the eastern limb, and for this reason we see the coronal loop bending towards the east (left).

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gyroresonant interpretation is fully confirmed by the theoretical work of Gel'freikh and Lubyshev (1979) which predicted the existence of the circularly polarized horseshoes which we have observed. They are essentially a consequence of the fact that gyroresonant absorption increases with increasing angle between the line of sight and the direction of the magnetic field, as well as the fact that the magnetic fields above sunspot umbrae are intense enough to make these regions optically thick to both modes of wave propagation.

CORONAL LOOPS AT 20 CM WAVELENGTH

Lang, Willson and Rayrole (1982) have reported the existence of two looplike structures at 20 cm wavelength which join regions of opposite magnetic polarity in the underlying photosphere. We subsequently examined the observation tapes and found a total of 15 coronal loops associated with 3 active regions on 5 days. The 20 cm loops are therefore truly ubiquitous features of the solar atmosphere (see Figure 2 for an example). The maximum electron temperatures, T_e(max), are characteristic of those found in the X-ray coronal loops with T_e(max) = 2 to 4 x 10^6K. The total extents of the 20 cm loops range between 4 x 10^9cm and 4 x 10^{10}cm (where 1" $\approx$ 725 km on the solar surface), and these are also comparable to the X-ray coronal loops which have semilengths L of 10^9cm to 10^{10}cm. We can use the scaling relationship of Rosner, Tucker and Vaiana (1978): $T_e(\max) = 1.4 \times 10^3 \, (pL)^{1/3}$ to obtain the loop pressure, p. Choosing $T_e(\max) = 3 \times 10^6$K and $L = 5 \times 10^9$ cm, we obtain a pressure of p = 1.96 dyn cm^{-2}, which is again characteristic of the X-ray coronal loops. The inferred electron density of $N_e = 2.5 \times 10^9$ cm^{-3} can be used together with an average electron temperature of $T_e = 10^6$K to obtain the optical depth, τ, of thermal bremsstrahlung (τ = 2.5), or a brightness temperature of $T_B = 0.92\, T_e$.

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REFERENCES

Gel'freikh, G.B. and Lubyshev, B.I.: 1979, Soviet. Astron.A.J.23,pp.316-322.
Lang, K.R. and Willson, R.F.: 1979, Nature 278, pp.24-28.
Lang, K.R. and Willson, R.F.: 1980, in I.A.U. Symposium 86, Radio Physics of the Sun, eds. M.R.Kundu and T.Gergeley (Dordrecht: Reidel), pp.109-117.
Lang, K.R. and Willson, R.F.: 1982, Astrophys. J.(Lett.)255,pp.L111-L117.
Lang, K.R., Willson, R.F. and Rayrole, J.: 1982, Astrophys. J., July.
Rosner,R., Tucker,W.H. and Vaiana,G.S.:1978, Astrophys.J. 220,pp.643-665.

DISCUSSION

KOUTCHMY: Do you see anything far from active regions, for example at the supergranulation boundaries of the quiet sun?

LANG: This is potentially measurable during quiet sun periods. We have only observed active regions, which dominate the signal when the sun is active.

SPICER: Can you give a physical interpretation of the observed polarization reversals during the flare you have discussed?

LANG: There are two possibilities. One is that we are observing sequential emission from the feet of a small coronal loop about 5 sec of arc in extent. The other is that the first burst emits a plasma cloud, and subsequent bursts propagate through this cloud. The polarization change is then a propagation effect.

LINSKY: Since the radio observations provide a means of measuring magnetic fields in the corona, and as it is possible to measure photospheric fields for the same active regions, could you comment on how the magnetic field varies with height?

LANG: For our published observations the longitudinal magnetic field strength $H_l \approx 1$ - 2 kG at the photospheric level in sunspots. Above sunspots at heights $h \approx 4 \times 10^9$ cm, we measure $H_l \approx 600$ G where the electron temperature $T_e \approx 2 \times 10^6$ K. This refers to the 6 cm emission, which marks the legs of magnetic dipoles. The 20 cm emission delineates the apex regions of coronal loops, and it can potentially measure H_l at these heights. The Russians using the Ratan 600 telescope obtain $H_l \approx 1$ kG at about 3 cm wavelength where $T_e \approx 10^5$ K. Collaborative Soviet-American observations (Ratan 600 – VLA) taken in July 1982 will lead to more detailed values of H_l as a function of height.

SPRUIT: Concerning the polarization reversals: Is not the most obvious and simple explanation that you have fields of both polarities within your field of view, which you do not resolve?

LANG: This is a good explanation. It requires polarization changes of $\sim 100\ \%$ and complete reversal in the sense of polarization at the feet of magnetic dipoles separated by about 5 seconds of arc. Apparently X-ray flares have been observed from small loops of this size.