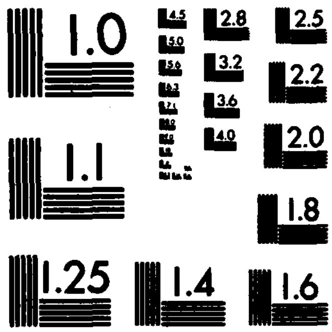
AD-A133 668 THE CIRCULARLY POLARIZED SUN AT 126 CM WAVELENGTH(U) 1/1
TUFTS UNIV MEDFORD MA DEPT OF PHYSICS K R LANG ET AL.
JUN 83 AFOSR-TR-83-0848 AFOSR-83-0019

UNCLASSIFIED FFG 3/2 NL



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THE CIRCULARLY POLARIZED SUN AT 12.6 CM WAVELENGTH

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To appear in Astronomy and Astrophysics

SUMMARY

Circular polarization maps of the Sun with 45" angular resolution at 12 cm wavelength are presented for six continuous days. The polarization corresponds to the extraordinary mode of wave propagation. The maps have degrees of circular polarization up to $\rho_c = 20\%$, and they show an excellent correlation with photospheric magnetograms. A similar correlation exists at 6 cm and 20 cm, and at all three wavelengths the brightness temperatures, T_B, of the circularly polarized emission is $T_B \sim 10^6$ K. This suggests that the emission at all three wavelengths is due to the same hot plasma radiating in the presence of magnetic fields that project radially upwards from the photosphere into the low solar corona. At 6 cm wavelength highly circularly polarized ($\rho_c \gtrsim 50\%$), core sources with angular sizes $\phi \sim 10"$ to 30" occur near sunspots. These core sources are due to gyroresonant emission at the third harmonic of the gyrofrequency, implying longitudinal magnetic field strengths of $H_\ell \sim 580$ gauss at altitudes $h \sim 3 \times 10^9$ cm above the sunspots. In regions near sunspots, the circularly polarized emission at 6 cm, 12 cm and 20 cm could all be due to the gyroemission of hot electrons spiralling in magnetic fields within the low solar corona. If this is the case, longitudinal magnetic fields of strength $H_\ell \sim 280$ gauss and $H_\ell \sim 170$ gauss are inferred from the 12 cm and 20 cm data, respectively. An alternative explanation is polarization by bremsstrahlung propagating in magnetic fields of strength $H_\ell \sim 100$ gauss and 50 gauss, respectively. This mechanism probably applies to extended regions of circularly polarized emission that are not near sunspots.

Key words: Sun: radio radiation - Sun: magnetic fields - Sun: active regions

1. INTRODUCTION

High resolution observations of solar active regions at 6 cm wavelength indicate that bright (brightness temperatures $T_B \sim 10^6$ K), highly polarized (degrees of circular polarization $\rho_c \gtrsim 50\%$) core sources (angular sizes $\phi \sim 10''$ to $30''$) overlie sunspots (Lang and Willson 1979; Alissandrakis, Kundu and Lantos 1980). There is an excellent correlation between the 6 cm maps of circular polarization and Zeeman effect magnetograms of the underlying photosphere (Lang and Willson 1980). The bright, highly polarized 6 cm cores mark the legs of magnetic dipoles that are connected to lower lying sunspots, and angular displacements indicate that the 6 cm emission lies at a height $h \sim 3 \times 10^9$ cm above the photosphere (Lang, Willson and Gaizauskas 1983). The 6 cm maps of circular polarization act as "magnetograms" of the low solar corona, the sense of circular polarization corresponding to the extraordinary mode of wave propagation. The bright, highly polarized core sources at 6 cm have been conclusively shown to radiate by gyroresonant emission in sunspot magnetic fields that project radially upwards into the low solar corona (Lang and Willson 1982). Longitudinal magnetic field strengths of $H_\ell \sim 580$ gauss are inferred from the fact that the detected gyroemission comes mainly from the third harmonic of the gyrofrequency.

Observations at longer radio wavelengths generally refer to higher levels in the solar atmosphere. For instance, Very Large Array (V.L.A.) observations of solar active regions at 20 cm wavelength delineate loop-like structures that connect lower lying sunspots of opposite magnetic polarity. The most intense 20 cm emission occurs near the apex of the loops, and it has been attributed to optically thick bremsstrahlung of a hot plasma trapped within coronal loops

(Lang, Willson and Rayrole 1982). The 20 cm emission is almost certainly the radio wavelength counterpart of the ubiquitous coronal loops detected at soft X-ray wavelengths. Dulk and Gary (1983) have recently provided supporting evidence for this view by using the V.L.A. to map the entire Sun at 20 cm. They found that intense 20 cm emission comes from bipolar active regions, and that the brightest emission occurs near the line of polarization reversal. They similarly attribute the 20 cm emission to bremmstrahlung from the corona and the upper transition region.

There is no detectable circular polarization at the apex of the 20 cm loops, and this may be attributed to optically thick emission and/or magnetic fields that are transverse to the line of sight (Lang and Willson 1982). Dulk and Gary (1983) have nevertheless reported the detection of circularly polarized 20 cm emission from the legs of dipolar loops. Under the assumption that the circular polarization ($\rho_c \sim 20\%$) is due to effects of bremsstrahlung propagating in a magnetic field, they infer longitudinal mangetic field strengths of $H_\ell \sim 20$ to 70 gauss at altitudes $h \sim 10^9$ to 5×10^9 cm.

In the next section, we present circular polarization maps of the entire Sun at 12 cm wavelength. They are extraordinarily similar to the 20 cm polarization map given by Dulk and Gary. In both cases the sense of circular polarization refers to the extraordinary mode of wave propagation, and there is an excellent correspondence between the polarization maps and photospheric magnetograms. In this respect, the data are also similar to those obtained for the 6 cm core sources. The polarized emission at 12 cm and 20 cm is apparently larger in angular extent and lower in circular polarization than the 6 cm core sources, but this may be in part due to an instrumental effect. For instance, the 1.5' beamwidth of the 12 cm observations would not resolve the core sources and the polarization would be diluted. In any event, we conclude our paper by stating that gyroemission may account for the circular polarization observed near sunspots at both 12 cm and 20 cm wavelength. The magnetic field strengths required by the gryoemission explanation have already been inferred from observations at 6 cm for comparable heights $h \sim 3 \times 10^9$ cm and temperatures $T_B \sim 10^6$ K, but for smaller areas. Extended regions of circularly polarized emission at 12 cm and 20 cm that are not near sunspots probably owe their polarization to the propagation effects of bremsstrahlung in a magnetic field.

2. OBSERVATIONS

We have observed the Sun at 12.6 cm wavelength (or 2,380 MHz) on 24 August through 29 August 1980 at the Arecibo Observatory where the beamwidth is 1.5'. Signals from both the right circularly polarized (RCP) and left circularly polarized (LCP) receivers were simultaneously recorded with a 40 MHz bandwidth and 2 s integration time. An area of 1° in right ascension (α) by 40' in declination (δ) was observed by scanning in α at twice the sidereal rate (or at 1° in 2 m) at intervals of 45" in declination. A complete map of the Sun was made in slightly less than two hours, which is the approximate time that the Sun can be viewed at favorable zenith angles with the Arecibo telescope. Maps of total intensity I = (LCP+RCP)/2 and circular polarization ρ_c = (LCP-RCP)/(LCP+RCP) were constructed with an angular resolution of 45", or half the half-power beamwidth.

The 12.6 cm circular polarization maps are compared with photospheric magnetograms in the accompanying three figures. The contours are drawn at intervals of ρ_c = 0.02, 0.04, 0.06..0.20 with solid contours corresponding to positive ρ_c and dashed contours corresponding to negative ρ_c. The full disk magnetograms are taken daily at the Kitt Peak National Observatory (KPNO) using the Zeeman effect of the 8680 Å line of neutral iron. Both the circular polarization maps and the KPNO magnetograms delineate the structure of the longitudinal component of the magnetic field. There is an excellent correspondence between the photospheric features seen in the magnetograms and the regions of circular polarization seen at 12.6 cm where the brightness temperatures $T_B \sim 10^6$ K. Dark magnetogram regions refer to negative magnetic polarity and correspond to left hand circular polarization; whereas light magnetogram regions refer to regions of positive magnetic polarity and correspond to right hand circular polarization. The sense of circular polarization at 12.6 cm therefore corresponds to the extraordinary mode of wave propagation.

In nearly every case, a dipolar feature in the magnetograms corresponds to a dipolar feature in the 12.6 cm maps of circular polarization. (The westernmost region on August 25, 26, and 27 was so intense that it saturated the 12.6 cm receiver, and it is therefore absent from the maps.) The close correspondence between the longitudinal magnetic field structure seen in the photosphere and the low solar corona (12.6 cm when $T_B \sim 10^6$ K) indicates that the magnetic fields project radially outwards from the photosphere into the low solar corona. Our maps of total intensity, which we do not present here, indicate that the maximum brightness occurs between the 12.6 cm dipolar features where there is no detectable circular polarization. This suggests that the intense 12.6cm emission may be bremsstrahlung from coronal loops. As we shall next see, the circularly polarized emission may have an alternative explanation.

3. DISCUSSION

Maps of circular polarization observed at 6 cm, 12 cm and 20 cm all show bright ($T_B \sim 10^6$ K) features that are strongly correlated with the longitudinal magnetic field structure delineated by photospheric magnetograms. This suggests that the circularly polarized emission at all three wavelengths is due to the same hot plasma radiating in the presence of magnetic fields that project radially upwards from the photosphere into the low solar corona. In fact, the bright ($T_B \sim 10^6$ K), highly polarized emission ($\rho_c \gtrsim 50\%$), core sources (angular sizes $\phi \sim 10''$ to $30''$) that lie near sunspots at 6 cm wavelength must be due to gyroemission at the third harmonic of the gyrofrequency, and this means that the longitudinal magnetic field strength $H_\ell \sim 580$ gauss at heights $h \sim 3 \times 10^9$ cm above sunspots (Lang and Willson 1982; Lang, Willson and Gaizauskas 1983). Although the circularly polarized emission at both 12 cm and 20 cm is apparently larger in angular extent and lower in circular polarization than the 6 cm core sources, this could be due to the larger beamwidths at the longer wavelengths that do not resolve the core sources and therefore detect a lower polarization. As shown by Lang (1974), angular resolutions of $\sim 10''$ are required to resolve the highly polarized core sources.

The circularly polarized emission at 12 cm and 20 cm wavelength that lies near sunspots may also be due to gyroemission. Observations at X-ray wavelengths have shown that the free-free optical depth is relatively low near sunspots, and that bremsstrahlung only becomes detectable near the apex of coronal loops. That is, the bremsstrahlung from regions overlying sunspots is at least two orders of magnitude weaker than the bremsstrahlung from the coronal loops that join sunspots of opposite magnetic polarity (Pallavicini, Sakurai and Vaiana 1981). We therefore believe that gyroemission is at least a plausible explanation for the circularly polarized emission of active regions at 12 cm and 20 cm wavelength near sunspots. Of course, the gyroresonance emission at 20 cm could be absorbed by free-free processes, thereby becoming trapped before it can be detected; but this is less likely to be the case at 12 cm for the free-free optical depth scales as ν^{-2}, or as the inverse square of the observing frequency ν and the optical depth for gyroresonant absorption scales as ν^{-1}. In any event, longitudinal magnetic field strengths of $H_{\ell} \sim 280$ and 170 gauss are required if gyroemission explains the 20% circular polarization observed at 12 cm and 20 cm, respectively whereas $H_{\ell} \sim 100$ and 50 gauss if the polarization is caused by bremsstrahlung propagating in a magnetic field. The higher magnetic fields for regions near sunspots have already been inferred from the 6 cm measurements at comparable altitudes and temperatures.

In the cases where broader circularly polarized emission with angular sizes $\phi \gtrsim 45''$ exist in regions that are not near sunspots, the circularly polarized emission at 12 cm and 20 cm is probably due to propagation effects. The magnetic field strengths are probably weaker in these regions, and the optical depth due to bremsstrahlung larger.

ACKNOWLEDGEMENTS

We gratefully acknowledge Dr. William Livingston of the Kitt Peak National Observatory for providing us with photospheric magnetograms. Radio wavelength observations of solar active regions at Tufts University are supported under grant AFOSR-83-0019 with the Air Force Office of Scientific Research. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center which is operated by Cornell University under contract with the N.S.F.. We also thank our referee, Professor George A. Dulk for useful and constructive suggestions.

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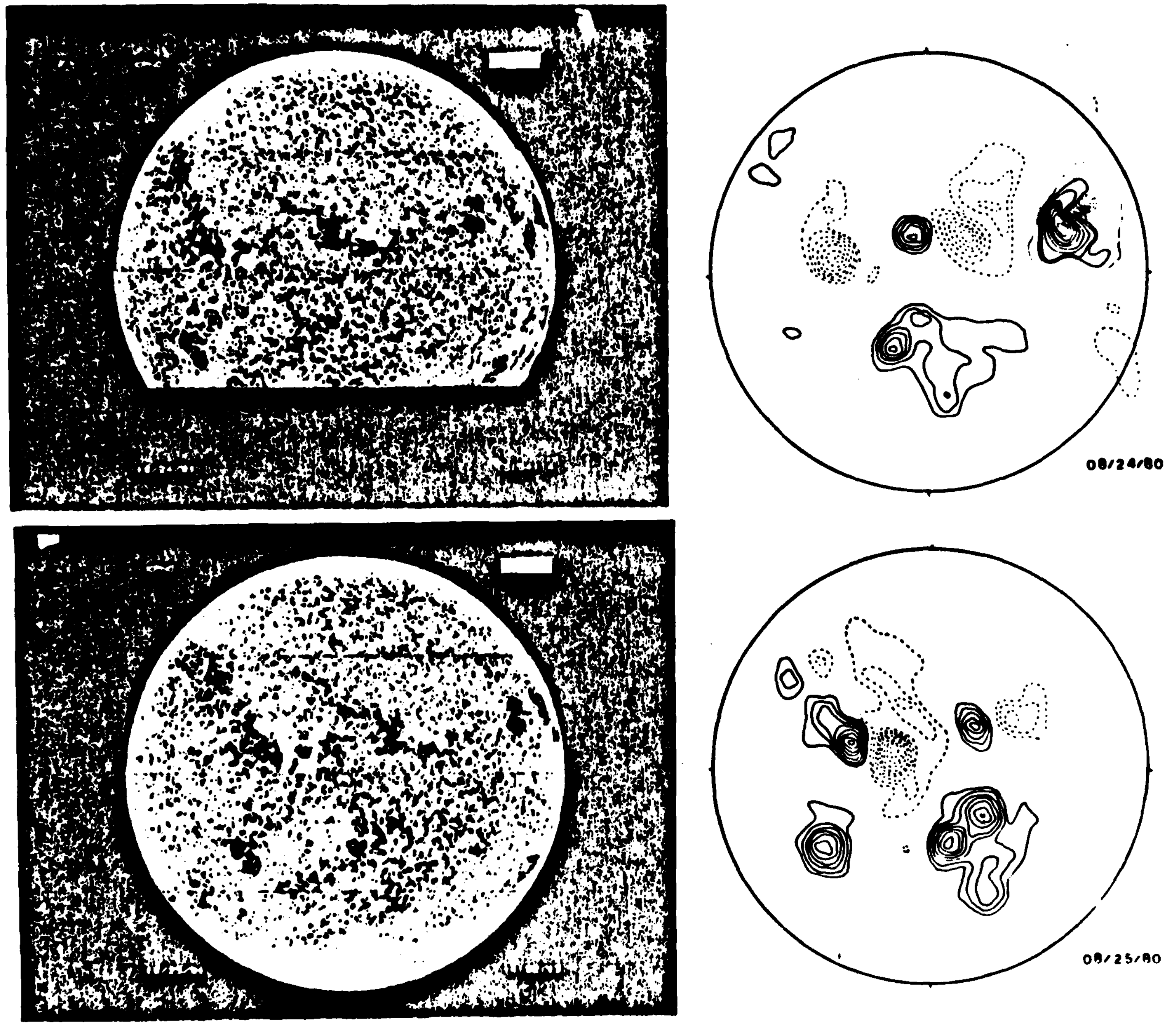
FIGURE LEGENDS

Photospheric magnetograms (left) and circular polarization maps at 12.6 cm (right). There is a good correlation between the dipolar structures in the photosphere and low solar corona (at 12.6 cm where $T_B \sim 10^6$ K).

(Editor's note: This can be used below each of the three figures).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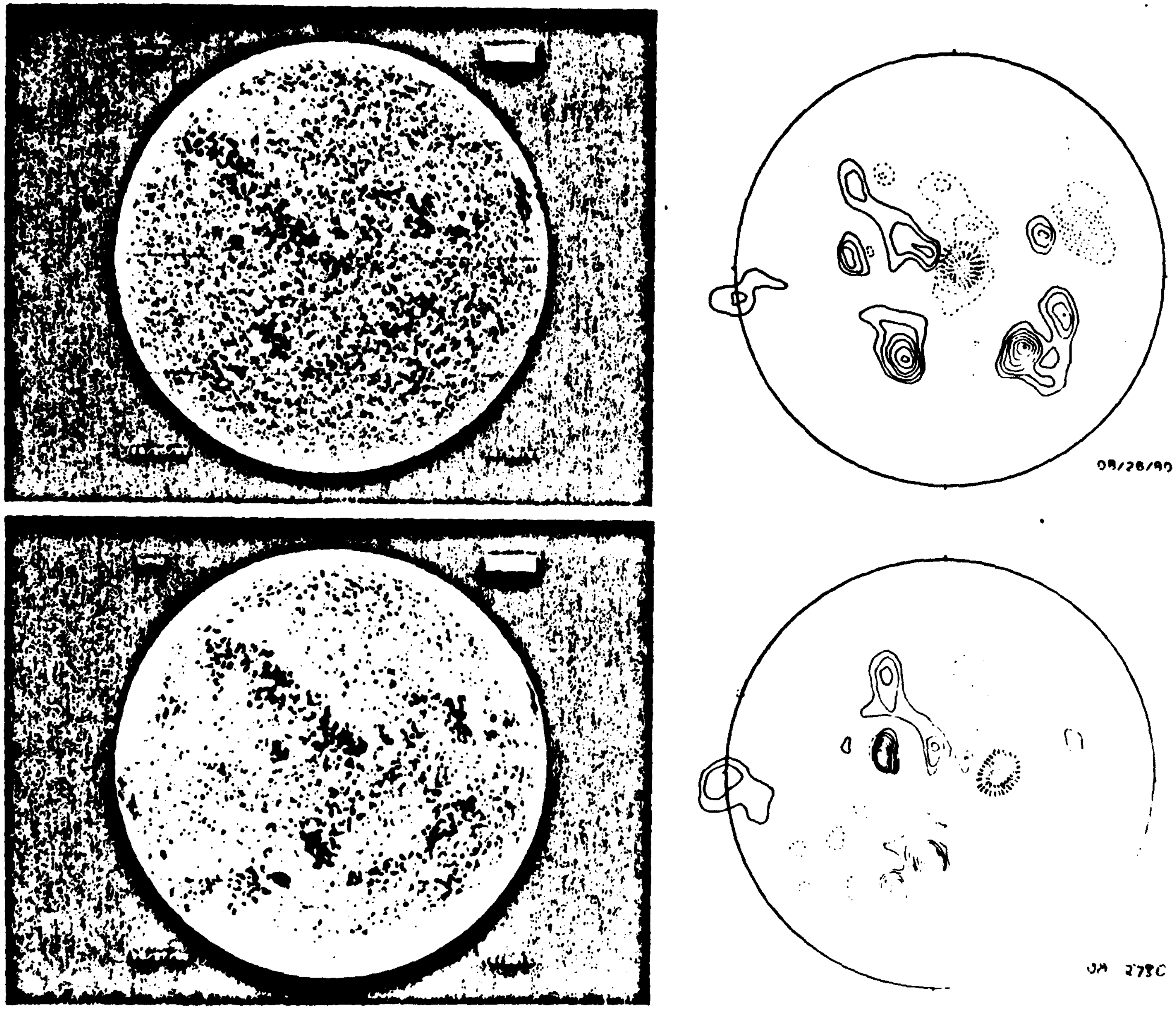
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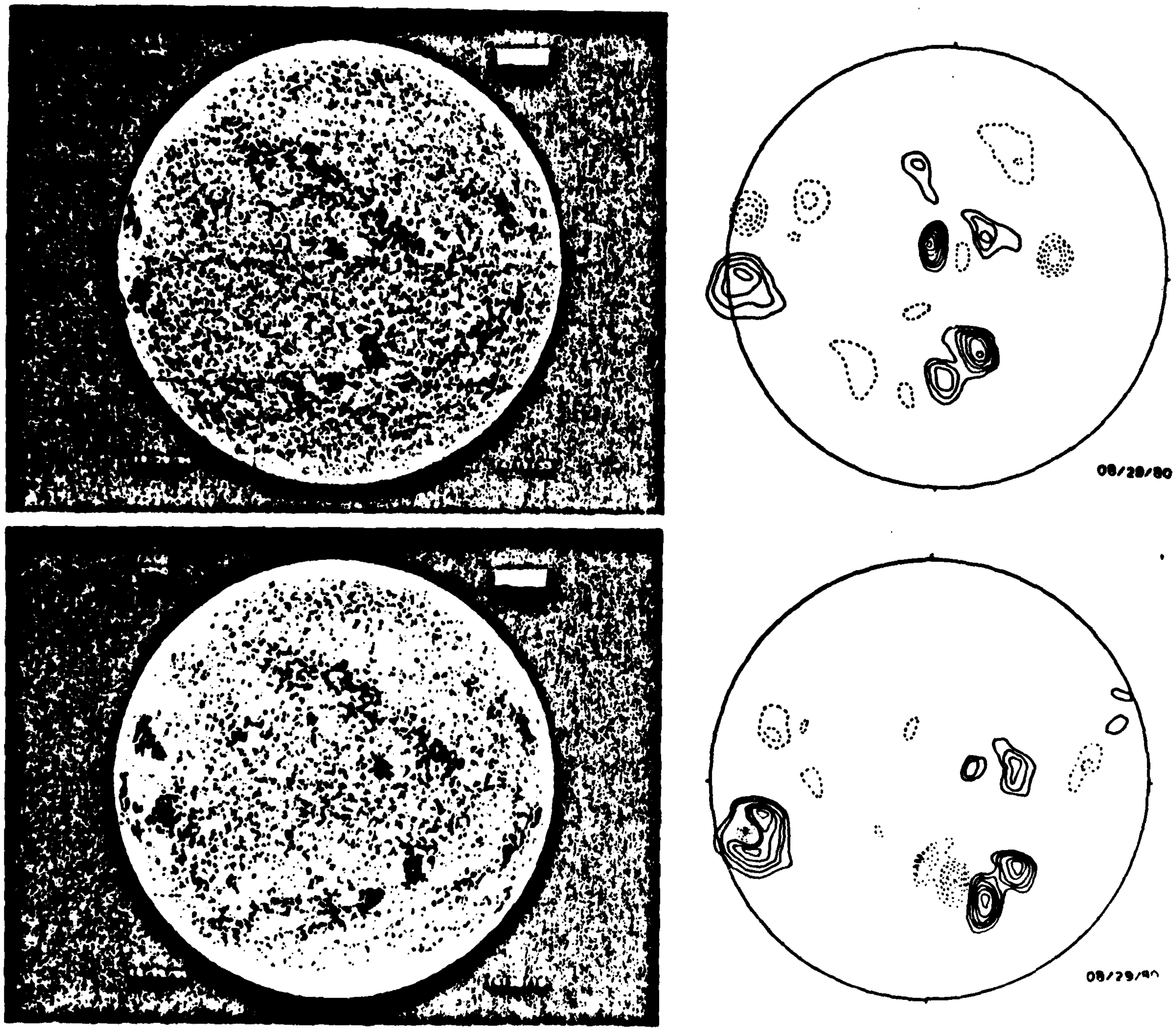
08/28/80
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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR- 83-0848
2. GOVT ACCESSION NO.: AD-A133 668
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): THE CIRCULARLY POLARIZED SUN AT 12.6 cm WAVELENGTH
5. TYPE OF REPORT & PERIOD COVERED: Interim
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): Kenneth R. Lang and Robert F. Willson
8. CONTRACT OR GRANT NUMBER(s): AFOSR-83-0019
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Tufts University, Department of Physics, Medford, MA 02155
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F, [redacted] 2311/A1
11. CONTROLLING OFFICE NAME AND ADDRESS: AFOSR/NP, Bolling AFB, Bldg. #410, Washington, DC 20332
12. REPORT DATE: June 1983
13. NUMBER OF PAGES: 12
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES: To appear in Astronomy and Astrophysics
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
Sun: radio radiation - Sun: magnetic fields
Sun: active regions

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Unclassified

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