

STRUCTURE OF A SOLAR ACTIVE REGION FROM RATAN 600 AND VERY LARGE ARRAY¹ OBSERVATIONS

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ABSTRACT

Solar active region AR 3804 was observed on the same days with the RATAN 600 and the VLA in 1982 July. The emission at wavelengths between 2 and 4 cm consisted of narrow ($\phi < 40''$), bright ($T_B \approx 0.2$ to 6×10^6 K) core sources surrounded by a weaker ($T_B \approx 10^4$ – 10^5 K), extended ($\phi \approx 200''$) halo. The brightest core sources are associated with sunspots and are interpreted in terms of the gyroradiation of thermal electrons at the second and third harmonics of the gyrofrequency. Two of the core sources were associated with a filament that lies above the magnetic neutral line in the photosphere. One of these filament-associated sources has a flat spectrum and is attributed to thermal bremsstrahlung. Relatively high magnetic field strengths of $H \approx 536$ G are inferred if the circular polarization of this source is due to propagation of the bremsstrahlung in the presence of a magnetic field, and even higher magnetic field strengths are required if the radiation is thermal gyroemission. Lower magnetic fields can be obtained if the radiation propagates through a region of transverse magnetic fields higher in the corona where polarization inversion occurs. The other filament-associated source had a high brightness temperature and steep radiation spectrum that cannot be attributed to either thermal bremsstrahlung or thermal gyroradiation. The weak magnetic field strengths at photospheric levels require implausibly high electron temperatures if the high brightness temperatures are to be explained. This source might be attributed to currents that enhance coronal magnetic fields. In this event gyroemission might account for the radiation. Alternatively, it may be due to nonthermal radiation such as the gyrosynchrotron radiation of subrelativistic electrons. VLA synthesis maps at 20 cm reveal hot ($T_B \approx 10^6$ K) coronal loops that connect underlying sunspots of opposite magnetic polarity, but RATAN 600 observations reveal the presence of a much more extended source that accounts for the vast majority of the flux detected at this wavelength. This extended source may also be attributed to the gyrosynchrotron radiation of subrelativistic electrons.

Subject headings: radiation mechanisms — Sun: radio radiation — Sun: sunspots

1. INTRODUCTION

Very Large Array (VLA) observations with high angular resolution ($\theta \gtrsim 1''$) at different microwave wavelengths ($\lambda = 2, 6$, and 20 cm) have been used to specify the temperature and magnetic structure at different heights in solar active regions. These multiple-wavelength observations specify the three-dimensional structure of active regions in the transition region and the low solar corona (Lang and Willson 1983, 1984; Lang, Willson, and Gaizauskas 1983; Shevgaonkar and Kundu 1984; Kundu and Lang 1985). However, active regions often have a complex structure with local sources that have different emission mechanisms (Gelfreikh *et al.* 1970; Kundu 1982).

Measurements of the spectrum and polarization of the local sources can help specify their emission mechanisms, while also supplementing the interpretation of the VLA observations. We have therefore begun collaborative observations in which the

same active region is observed by the VLA and the Soviet RATAN 600 (Radio Astronomy Telescope of the Academy of Sciences [Nauk]). The RATAN 600 observations provide high angular resolution in the east-west direction at five wavelengths between 2 and 4 cm, thereby determining the radiation spectra of the local sources. Accurate polarization measurements (to 0.5%) are also made at these wavelengths, while more extended structures are detected at decimetric wavelengths (see Table 1).

The VLA and RATAN 600 observations complement each other. The VLA provides high angular resolution in two dimensions at three wavelengths, but the wavelengths are not close enough to determine the spectra of the local sources, and the polarization accuracy is only $\sim 10\%$. The RATAN 600 provides information on extended sources that are not detected with the VLA because of incomplete UV coverage. On the other hand, confusion arising because of the poor angular resolution (in one dimension) of the RATAN 600 can be overcome by VLA observations.

In this paper we will emphasize the unique capabilities of the

¹ The Very Large Array (VLA) is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1
BEAM WIDTHS^a OF RATAN 600 AT
WAVELENGTHS USED IN SOLAR OBSERVATIONS

WAVELENGTH (cm)	BEAM WIDTH	
	East-West	North-South
2.0	18"	12.5
2.3	21	14.4
2.7	25	16.9
3.2	29	20.0
4.0	36	25.0
13.0	120	81.0
21.0	190	131.0
30.0	270	187.0

^a Full width to half-maximum.

RATAN 600. It consists of a ring-shaped primary reflector that is 576 m in diameter and provides a total collecting area of 13,000 m². The radiation reflected off a sector of this ring is collected by a secondary reflector that transforms the cylindrical waves from the primary ring sector into spherical waves that are detected by a set of radiometers operating at different wavelengths (see Table 1 and Parijskij *et al.* 1976). At each wavelength the total intensity I and circular polarization V are measured.

In the work reported here, a flat, tiltable reflector was used to direct solar radiation toward the southern sector of the primary ring. This periscope reflector is ~ 8 m high and 400 m long in the east-west direction. It permitted observations at five different azimuths (19°, 11°, 0°, 348°, and 340°), two on each side of meridian (Shivris 1980). Although the RATAN 600 provides fan beam scans with high angular resolution in only one direction (close to east-west), the observations at different azimuths provide fan beam scans in slightly different directions. They can be combined to specify the positions of the local sources.

The VLA is a system of 27 antennae with individual diameters of 25 m (or 30' beam width at 20 cm) spread out in a Y-configuration with separations as large as 34 km. The antennae are interconnected electronically to provide a total of 351 interferometer pairs and a combined angular resolution of a few seconds of arc. Synthesis maps of total intensity I and circular polarization V are made for time intervals as short as 10 s for solar bursts and over longer time intervals of several hours for quiescent microwave emission when complete UV coverage is desired.

II. OBSERVATIONS OF SOLAR ACTIVE REGION AR 3084

Solar active region AR 3084 was observed with the RATAN 600 at daily intervals between 1982 July 7 and August 2. As illustrated in Figure 1, the local radio sources could be most easily identified with their optical counterparts on July 15 when the active region was in the center of the disk and was very extended.

Several narrow (angular size $\phi \leq 40''$), bright (brightness temperature $T_B \approx 0.2\text{--}6 \times 10^6$ K) core sources were superposed upon a weaker ($T_B \approx 10^4\text{--}10^5$ K), extended ($\phi \approx 200''$) halo. The halo is the residual radiation left over when Gaussian-shaped core sources are subtracted from the one-dimensional fan beam scans. Here we will concentrate on the core sources designated by the letters "A," "B," and "C," and "D" in Figure 1. The location of these sources was accurately

specified by combining one-dimensional fan beam scans taken in different directions. The core sources A and C are associated with sunspots whose longitudinal magnetic field strengths (at the photosphere) are between 2100 and 2500 gauss. In contrast, core sources B and D are associated with the filament designated by the solid line in the sunspot picture. This filament lies above the magnetic neutral line in the photosphere.

The observed one-dimensional intensities I , the angular sizes, ϕ , in the east-west direction, the degree of circular polarization, ρ_c , and the estimated brightness temperatures, T_B , of the four core sources are given in Table 2 at various wavelengths. Here the data have been corrected for the convolution effects of the antenna beam, and the brightness temperature has been inferred under the assumption of circular symmetry. The two filament-associated sources have angular sizes, ϕ , that do not change with wavelength, but the sunspot-associated sources have angular sizes that increase with wavelength.

The flux density $S = I \times \phi$ has been plotted as a function of wavelength in Figure 2. Three of the core sources have a flux density that increases with wavelength between 2.0 and 4.0 cm. The filament-associated source B has the flat spectrum that is associated with optically thin thermal bremsstrahlung.

A 20 cm VLA synthesis map of AR 3084 on July 12 is superposed on the relevant sunspot picture in Figure 3. The 20

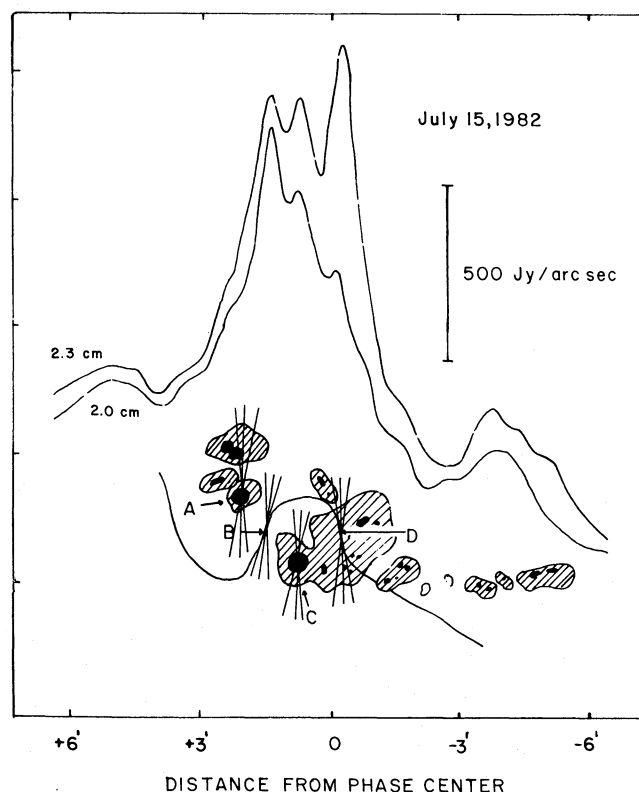


FIG. 1.—One-dimensional fan beam scans of AR 3084 taken at wavelengths of 2.0 and 2.3 cm with the RATAN 600 on 1982 July 15. They are compared with a sunspot picture (umbrae black and penumbrae crosshatched) provided by M. N. Gnevyshev using the photoheliogram at the Kislovodsk station of the Pulkovo Observatory. RATAN 600 scans in slightly different directions, or azimuths, have been combined to determine the positions of the four core radio sources designated by "A," "B," "C," and "D." Their positions are inferred from the four sets of three intersecting lines, each set corresponding to three different azimuths.

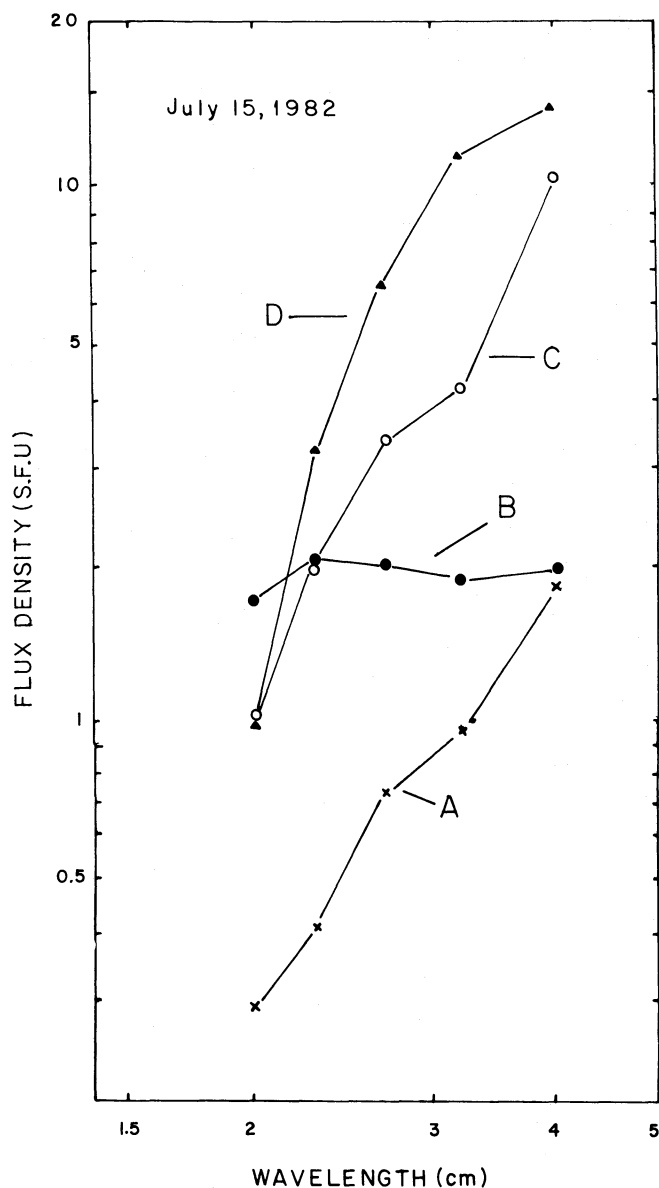


FIG. 2.—Radiation spectrum of four core sources. Here the flux density in solar flux units (sfu) has been plotted as a function of wavelength. For comparison purposes, $1 \text{ sfu} = 10^4 \text{ fu} = 10^{-19} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$.

cm emission consists of two components: one elongated component that connects underlying sunspots of opposite magnetic polarity, and a more compact source that also lies between oppositely polarized sunspots. The radiation at 20 cm wavelength is therefore attributed to the hot ($T_B \approx 10^6 \text{ K}$), dense plasma that is trapped within magnetic loops that connect underlying sunspots of opposite magnetic polarity. The linear extent of the 20 cm coronal loops is 10^9 – 10^{10} cm . These results confirm previous work indicating that 20 cm VLA observations delineate the structure of the ubiquitous coronal loops that had previously only been detected at X-ray wavelengths (Lang, Willson, and Rayrole 1982; Dulk and Gary 1983; McConnell and Kundu 1983).

The RATAN 600 observations at 13 and 21 cm indicate an extended source whose angular size $\phi \approx 4'$ is comparable to that of the entire active region. Such extended sources are often

TABLE 2
PARAMETERS FOR FOUR CORE RADIO SOURCES

Core	Wavelength (cm)	I (Jy per arcsec)	ϕ	ρ_c (%)	T_B (10^6 K)
A	2.0	≥ 315	$\leq 8''$	...	≥ 0.23
	2.3	360	10	53	0.28
	2.7	535	13	100	0.43
	3.2	560	17	100	0.49
	4.0	765	23	...	0.77
B	2.0	941	17	...	0.32
	2.3	1374	14	8	0.75
	2.7	1162	16	30	0.77
	3.2	972	18	40	0.80
	4.0	1024	18	...	1.32
C	2.0	807	12	...	0.39
	2.3	1356	14	7	0.74
	2.7	2080	15	19	1.46
	3.2	1944	20	11	1.44
	4.0	4012	24	...	3.88
D	2.0	315	30	...	0.06
	2.3	1308	23	28	0.44
	2.7	2648	23	45	1.22
	3.2	4212	25	33	2.50
	4.0	6675	24	...	6.45

undetectable on VLA synthesis maps. The total flux density of the 21 cm extended source detected with the RATAN 600 is $1.5 \times 10^5 \text{ Jy}$, whereas the total flux density of the 20 cm loops detected with the VLA is $3.0 \times 10^3 \text{ Jy}$. This indicates that the flux of the 20 cm coronal loops detected with the VLA is only $\sim 2\%$ of the total flux of the entire active region at 21 cm. Thus, the coronal loops may be superposed upon much more extended sources that account for most of the active region flux at these wavelengths.

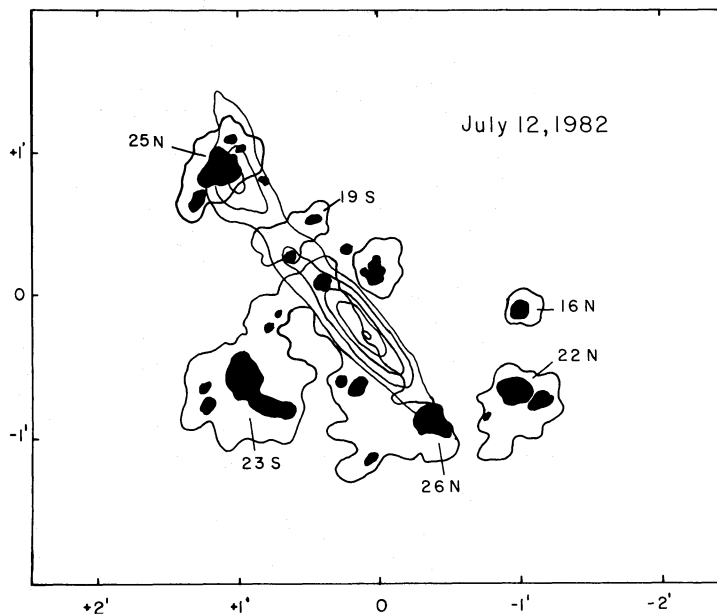


FIG. 3.—VLA synthesis map of the 20 cm emission from AR 3084 on 1982 July 12 is superposed upon the sunspot picture provided by M. N. Gnevyshev. The sunspots (black) have numbers corresponding to the longitudinal magnetic field strength in hundreds of gauss and letters denoting the magnetic polarity ("N" or "S"). The 20 cm contours are of equal brightness temperature corresponding to 0.2, 0.4, 0.6, 0.8, and 1.0 times the peak brightness temperature of $1.8 \times 10^6 \text{ K}$.

III. DISCUSSION

The sunspot-associated core sources A and C may be attributed to gyroradiation of thermal electrons at the second and third harmonic of the gyrofrequency. Strong evidence for gyroresonance absorption at coronal levels in solar active regions was provided by Kundu, Schmahl, and Gerassimenko (1980) through a comparison of microwave, EUV, and X-ray observations. The near equality of the microwave brightness and electron temperatures indicated that the microwave emission was thermal. The measured electron densities and temperatures indicated that free-free absorption is inadequate and that gyroresonance absorption at the second or third harmonic of the gyrofrequency provides sufficient optical depth at microwave wavelengths. Thermal gyroradiation at coronal levels above sunspots was additionally confirmed by the detection of circularly polarized ring-shaped or horseshoe structures (Alissandrakis and Kundu 1982; Lang and Willson 1982) that were predicted using the theory of gyroresonant emission from individual sunspots (Gelfreikh and Lubyshev 1979). It is also consistent with the 100% circular polarization observed for the core source A.

The magnetic field intensity, H_c , at the bottom of the corona may be inferred from the short wavelength limit, λ_c , of the polarized gyroresonant emission through the relation (Akhmedov *et al.* 1982)

$$H_c = \frac{3570}{\lambda_c} \text{ gauss}, \quad (1)$$

for the third harmonic. For core source A, a value of $H_c = 1690$ gauss is obtained. This may be compared with the magnetic field strength $H = 2100\text{--}2600$ gauss for the sunspots in the underlying photosphere.

The filament-associated core source B has the flat spectrum of optically thin thermal bremsstrahlung. A lower estimate to the emission measure, $\int N_e^2 dl$, can be obtained by assuming that the electron temperature, T_e , is equal to the brightness temperature, T_b , at longer wavelength $\lambda = 4.0$ cm. The relevant formulae (Lang 1974) then give $\int N_e^2 dl = 5.6 \times 10^{29} \text{ cm}^{-5}$ and an electron density $N_e \approx 2.1 \times 10^{10} \text{ cm}^{-3}$ for core source B.

The observed circular polarization of the filament-associated source B might be explained in terms of a propagation effect in which the optical depths of the ordinary and extraordinary waves differ. In the quasi-longitudinal (Q-L) approximation for wave propagation in the direction of an external magnetic field, the degree of circular polarization $\rho_c \approx 2\nu_H \cos \theta / \nu$, where the gyrofrequency $\nu_H = 2.8 \times 10^6 H$ Hz in a longitudinal magnetic field strength of H , the angle between the line of sight and the direction of the magnetic field is θ , and ν is the frequency of the radiation. At our observing wavelength of $\lambda \approx 3$ cm where the circular polarization $\rho_c \approx 30\%$ we obtain $H = 536$ gauss for Q-L propagation. Although this longitudinal magnetic field strength may be large for a filament associated source, it cannot be avoided by an appeal to the alternative gyroresonant emission process.

The optical thickness due to gyroresonant absorption increases with increasing angle, θ , between the line of sight and the direction of the magnetic field, and we might expect a large θ near the magnetic neutral line. However, even with $\theta = 85^\circ$, plausible values for the electron temperature, $T_e \approx 2 \times 10^6$ K, electron density $N_e \approx 10^{10} \text{ cm}^{-3}$, and extent $L \approx 10^9$ cm indicate that the highest harmonic, s , of the gyrofrequency that is consistent with the observed brightness temperature of $T_b =$

1.0×10^6 K is $s = 5$ (see McConnell and Kundu 1983, for the relevant formulae). This harmonic corresponds to a longitudinal magnetic field strength of $H \approx 714$ gauss if the gyrofrequency is at $\lambda = 3$ cm. Higher harmonics that correspond to weaker magnetic fields require implausibly high electron temperatures to produce the observed brightness temperature.

One method of accounting for circular polarization with lower magnetic field strengths involves a polarization inversion in a region of quasi-transverse (Q-T) magnetic field (Cohen 1960). The coupling of the ordinary and extraordinary modes as the radiation passes through the Q-T region will cause an inversion in the sense of circular polarization if the frequency ν is less than the critical frequency, ν_T , given by $\nu_T^2 = 10^{17} N_e L_H H^3$. Assuming $N_e = 10^{10} \text{ cm}^{-3}$, a magnetic scale length of $L_H = 10^9$ cm and $\nu_T \geq 10^{10}$ Hz, we find $H \geq 46$ gauss. This inversion occurs high in the corona above the region where the radiation is formed. However, because source B is located above a magnetic neutral line, we have no evidence for whether or not a polarization inversion has taken place.

Kundu *et al.* (1977) and Kundu and Alissandrakis (1984) have provided evidence for polarization inversion in the regions of bright 6 cm sources ($T_b \approx 2 \times 10^6$ K) associated with magnetic neutral lines. Their observations led to an estimate of $H \sim 20$ gauss for the Q-T region. Similar values of magnetic field strength in the Q-T region have been inferred from centimeter-wavelength polarization inversions by Peterova and Akhmedov (1973).

Of special interest is the filament-associated core source D. This source has a large brightness temperature of $T_b \approx 7 \times 10^6$ K at $\lambda = 4$ cm and an exceptionally rapid increase of flux density with wavelength. Because the optical depth must be less than unity in order to account for the observed circular polarization, the electron temperature must be greater than 7×10^6 K. This unusually high electron temperature argues against thermal emission processes. Moreover, the steep radiation spectrum rules out thermal bremsstrahlung.

Although one can obtain a steep spectrum from thermal gyroemission as the result of an exponential term in the optical depth (see McConnell and Kundu 1983), the region must have an implausibly high magnetic field strength. If the radiation were due to gyroemission at the second harmonic of the gyrofrequency, then a magnetic field strength of $H = 1800$ gauss is implied. This is inconsistent with the fact that the source lies above a magnetic neutral line in the solar photosphere where much weaker magnetic fields prevail. When more plausible magnetic field strengths of $H \sim 140$ gauss are assumed for the regions where $T_e \approx 10^6$ K, then the observed radiation must occur at high harmonics of the gyrofrequency ($s = 26$ for $\lambda = 3$ cm). The optical depth due to gyroresonance absorption is then negligibly small, and implausibly high electron temperatures of $T_e \gg 10^7$ K are inferred. However, there is the possibility that strong currents produce higher magnetic fields in the low corona than those expected from current-free extrapolations from photospheric values. In this event thermal gyroemission might account for the radiation.

An alternative explanation for the radiation from the core source D may be some sort of nonthermal emission mechanism (Gelfreikh *et al.* 1970). Such a mechanism was suggested by observations of 6 cm sources of high brightness temperature in regions where the magnetic fields are weak (Webb *et al.* 1983). These sources have been attributed to the nonthermal synchrotron emission of mildly relativistic electrons (Chiuderi Drago and Melozzi 1984).

One possibility is that source D is the gyrosynchrotron radiation of subrelativistic electrons. The theoretical formulae describing gyrosynchrotron radiation have been given (Ramaty 1969; Takakura and Scalise 1970; Ramaty and Petrosian 1972; Petrosian 1981). Theoretical results of the gyrosynchrotron radiation from mildly relativistic electrons have been summarized by Dulk and Marsh (1982), who provide simplified expressions for nonthermal (power-law) and thermal (Maxwellian) distributions. Using their formulae, we find that a nonthermal electron energy distribution with a power-law index $\delta = -4.0$ and a magnetic field strength of $H = 40$ gauss describes the flux density spectrum of source D between 2.0 and 4.0 cm. The observed flux density can be accounted for with a magnetic field of strength $H = 40$ gauss and an electron density $N = 2 \times 10^9 \text{ cm}^{-3}$ for electrons with energies $E > 10$ keV. These values of H and N may plausibly account for the observed emission from source D.

The extended component of decimetric emission at 13 and 21 cm wavelength may be similarly accounted for by gyrosynchrotron radiation. Plausible magnetic field strengths of $H \approx 80$ gauss can be inferred from the observed circular polarization (15%–50%) and Takakura and Scalise's (1970) formulae for the volume emissivity of the ordinary and extra-

ordinary waves. Because of the much larger volume of the extended emission, the required electron density $N_e \approx 10^2 \text{ cm}^{-3}$ may be relatively low.

One possible difficulty with this explanation is that some as yet unspecified mechanism must be continually accelerating the electrons. For example, the energy loss by synchrotron radiation (Lang 1974) with a power-law electron energy distribution has a half-time for the total emitted radiation (Chiuderi and Chiuderi-Drago 1967) of several hours for a magnetic field strength of $H = 40$ gauss.

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