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THE EXTENDED RADIO SOURCE IN THE CENTER OF M31

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ABSTRACT

Radio observations of the central 1° × 1° region of the Andromeda Nebula (M31), made with the 1 km configuration of the NRAO VLA, show that at 1465 MHz the central radio source is nearly spherical and 2 kpc (10′) in diameter, with a brightness distribution roughly proportional to $\exp(-R/1.'1)$, where R is the angular distance from the radio maximum located 20″ from the nucleus at a position angle of 70°. The broad structure of this object may be due to a bulge population of many weak supernova remnants or to a cosmic-ray electron-dominated galactic wind.

Subject headings: galaxies: nuclei — interferometry — radio sources: extended

I. INTRODUCTION

The central region of the Andromeda Nebula (M31) has previously been observed, with sufficient resolution and sensitivity to separate a central radio source from the nearby spiral arm emission, by Pooley (1969) with the Cambridge One Mile telescope, by van der Kruit (1972) with the Westerbork array, and by Berkhuijsen and Wielebinski (1974) with the 100 m antenna at Effelsberg. The 408 and 1407 MHz observations of Pooley showed that this central radio source, 5C 3.110, was nonthermal with a 7′ diameter component detected at 408 MHz and a 80″ component detected at both 408 and 1407 MHz. The 1415 MHz observations of van der Kruit showed that the central part of the radio source was resolved into a number of components within 30″ of the nucleus that probably were associated with "an underlying smoother component."

We wish to report observations of the central region of M31 at 1465 and 4885 MHz with the 1 km configuration of the Very Large Array (VLA) telescope. These observations show that the M31 central radio source is a nearly spherical distribution of nonthermal synchrotron emission with a 1465 MHz brightness distribution that falls off exponentially from the center with a scale factor of 1.'1, and which can be traced to distances of 1 kpc (5′) from the nucleus.

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II. OBSERVATIONS

The 1 km array VLA observations of the central region of M31 were made for a 1° × 1° region centered on the nucleus of M31 (Baade and Arp 1964) located at R.A.(1950) = $0^h40^m0^s.2$, decl.(1950) = 40°59′43″. These data were taken 1981 September 17 with 26 antennas operating with a bandwidth of 50 MHz and system temperatures of roughly 45 K at 1465 and 4885 MHz. The instrument and its calibration procedures are described by Thompson *et al.* (1980). We used the point source 2352+495 as a calibrator, assuming flux densities of 2.61 and 1.67 Jy at 1465 and 4885 MHz, respectively. The observations of M31 and the calibrator were alternated at the two frequencies, resulting in 5 hr of tracking and integration time at each frequency. After calibration the M31 data were mapped, cleaned, and self-calibrated (1465 MHz only).

Figure 1 shows a map of a 0.°75 × 0.°75 field at 1465 MHz where the synthesized aperture has been tapered to give a synthesized beam 1′ in diameter. This beam size allows a good compromise between a reasonable signal-to-noise ratio for the partially resolved, nonthermal continuum emission structures corresponding to the N2 and S2 spiral arms and a small enough beam to show the general characteristics of the central, extended radio source. The range of observable surface brightness in Figure 1 is roughly a factor of 10^3, and the even spacings of the logarithmic contour intervals gives the clear indication that the central radio source has an exponential brightness distribution. The peak brightness temperature of the central source at 1465 MHz is 10 K. Most of the other strong compact sources in Figure 1

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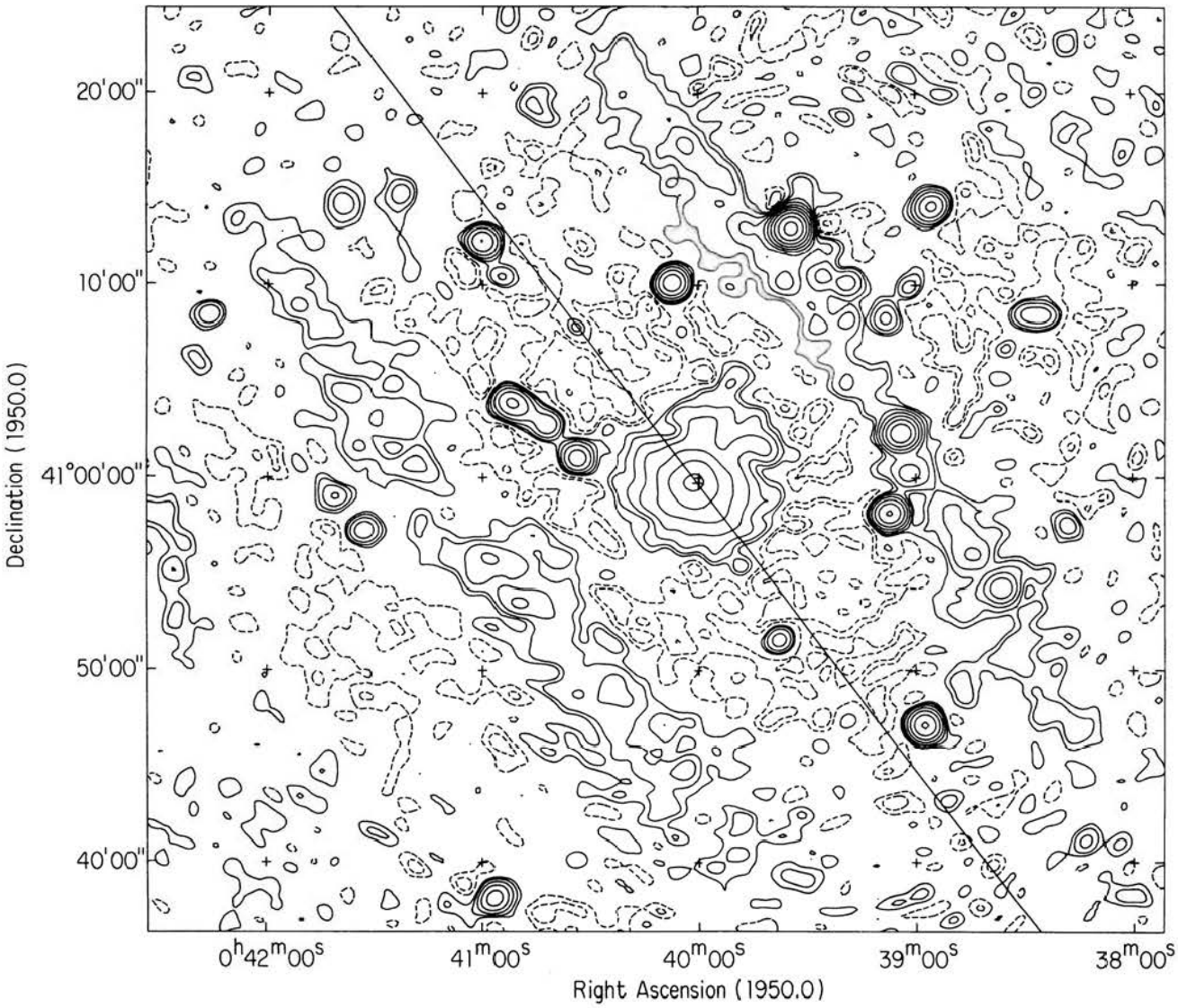


FIG. 1.—A contour display of a 1465 MHz map of the central 0°.75 × 0°.75 region of M31, uncorrected for sensitivity variations of the antenna primary beam. The synthesized beam is 1′ in diameter, and the contours are logarithmic corresponding to the power of two multiples of 0.3 mJy per beam (= 0.15 K brightness temperature), with negative brightnesses indicated by dashed lines. The large plus sign corresponds to the nucleus of M31, the solid line indicates the galactic plane, and the small plus signs in this and subsequent figures are coordinate reference points.

are previously known 5C 3 sources (Pooley 1969); however, the high dynamic range in the map reveals a number of weaker features, particularly the 5′ size scale "triple" radio source located 9′ NE of the nucleus at a position angle of 68°. The NE lobe of this triplet is an extended source with a position corresponding to that of 5C 3.119.

In Figure 2 we show both 1465 and 4885 MHz maps of the 20′.3 × 13′.3 regions which contain 5C 3.110 and the nearby triple radio source. In Figure 2*a* the emission regions in the lower left and upper right corners are due to predominantly nonthermal emission from the spiral arms S2 and N2, respectively; all maps have the nucleus marked with a large plus sign, the galactic plane marked with a solid line, and an × marking the maximum in the 1465 MHz radio emission. Figure 2*a* is a display of an untapered 1465 MHz map with a 35″ synthesized beam using contour levels that step in factors of $2^{1/2}$ from the lowest level of 0.2 mJy beam^{-1} (= 0.1 K brightness temperature). Figure 2*b* is a 4885 MHz map of the same

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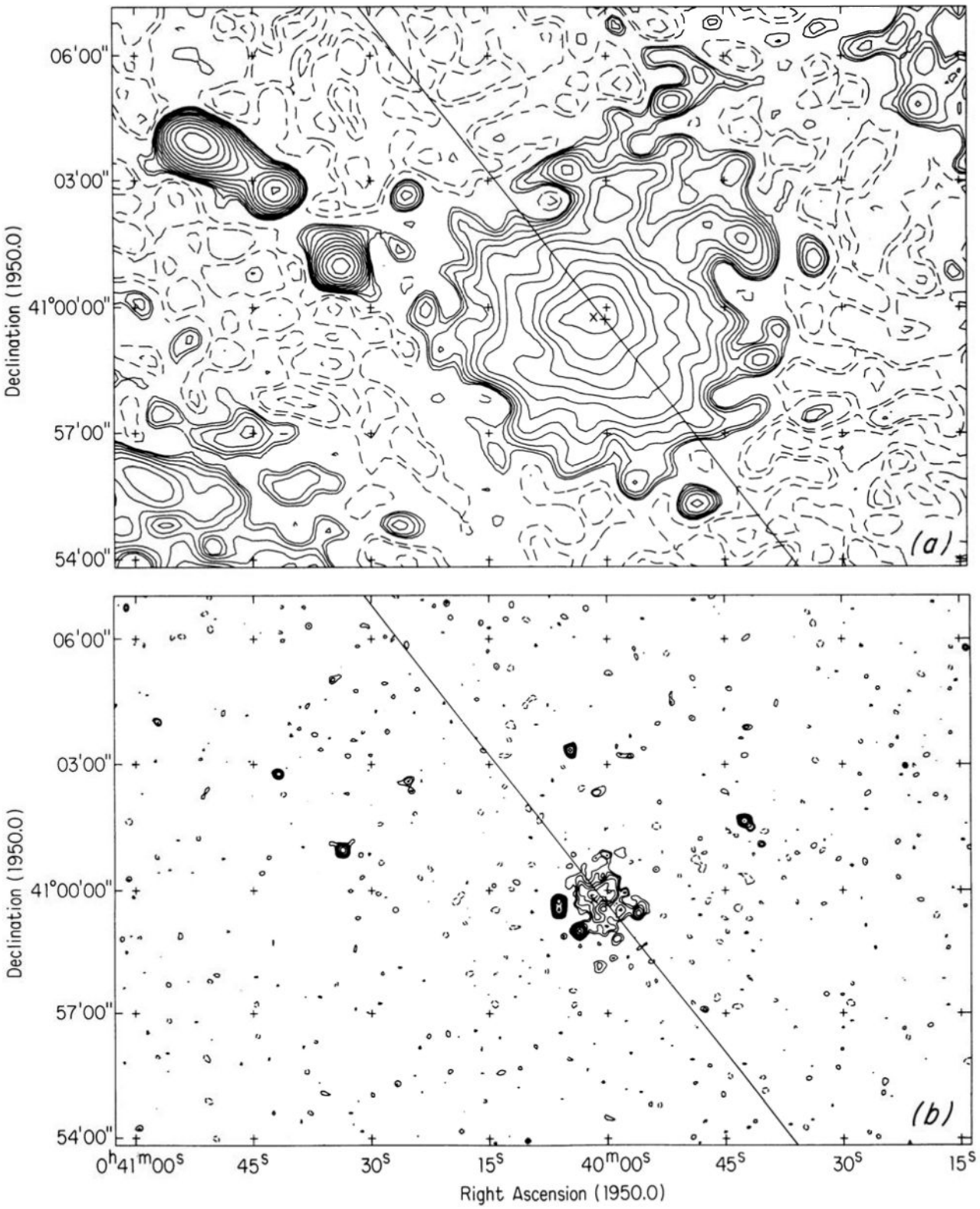


FIG. 2.—Contour maps of a 20'.3 × 13'.3 region of the center of M31 for (*a*) 1465 MHz with a 35″ synthesized beam and primary beam correction applied; and (*b*) 4885 MHz with a 35″ synthesized beam and no primary beam correction. The contour intervals are logarithmic corresponding to factors of $2^{1/2}$ multiples of 0.2 and 0.1 mJy per beam for 1465 and 4885 MHz maps, respectively. The structure in the upper right and lower left corners of (*a*) corresponds to emission from the spiral arms N2 and S2, respectively. The solid line indicates the galactic plane, the large plus sign indicates the nucleus, and the × indicates the centroid and maximum of 1465 MHz radio emission.

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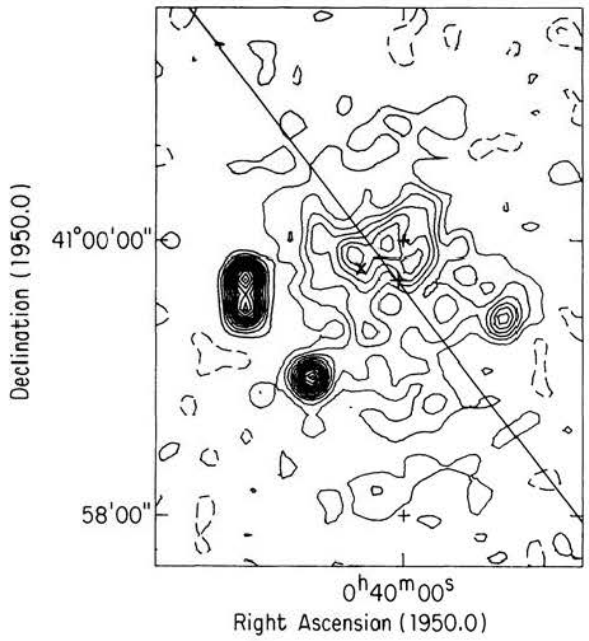


FIG. 3.—Contour map of the inner 4′ of the 4885 MHz map of M31 using linear contour intervals ranging in steps of 0.075 mJy beam^{-1} from 0.075 mJy beam^{-1} up to 12.75 mJy beam^{-1}. The large plus sign indicates the nucleus, the solid line the galactic plane, and the × marks the centroid of the 1465 MHz brightness distribution.

region with a 12″ synthesized beam. The peak intensity of the central radio source is located at R.A.(1950) = $0^h40^m1^s.5$, decl.(1950) = 40°59′49″, 20″ from the nucleus at a position angle of about 70°. Figure 3 shows a larger scale display of the central 4885 MHz radio source using linear contour intervals.

In Figure 4 we plot the 1465 MHz surface brightness from Figure 1 as a function of angular displacement (R) from the center of the radio source for radial cuts to the east (open circles), west (triangles), north (filled circles), and south (×); we also plot a straight line corresponding to a radial decay proportional to $\exp(-R/1.1)$ which fits all four radial cuts. We see from Figure 2 that there are local structural features that appear mainly at the lower brightness levels, many of which correspond to sources in the 4885 MHz map that are outside a 30″ radius, particularly in the NW quadrant. Removal of components corresponding to these sources would result in a distinctly smoother, spherical distribution of surface brightness.

The maps shown in Figure 2 show a "triple" radio source which is 9′ NE of the nucleus of M31 with a position angle of about 70°. The NE lobe of this triple, seen only in the 1465 MHz maps in Figures 1 and 2*a* because of the reduced (2%) antenna sensitivity 11′ from the center of 4885 MHz maps, is coincident with the position of 5C 3.119 and is an extended object with an extension pointing toward the central source in the triplet. The central source of the triplet appears as a point source while the SW lobe is an extended source at both frequencies, with structures roughly aligned with an axis through the central source of the triplet. Table 1 lists the total fluxes, peak brightness temperatures, and spectral indices for each component. As is normal with "Cygnus A–like" radio sources, the central component has a flat spectrum while the NE and SW lobes have spectral indices of 0.7 and 0.4, respectively.

The least likely but most interesting possibility is that the "triplet" is an extension of radio emission from the nucleus, i.e., a "jet" analogous to the jets in M87 and many radio galaxies. Such a jet in association with a spiral galaxy has not been seen before, so this interpretation is presently unlikely. Next is the possibility that the triplet is associated with a compact object in M31, analogous to the extended structures associated with the X-ray stars Sco X − 1 (Hjellming and Wade 1982; Geldzahler *et al.* 1981) and SS 433 (Hjellming and Johnston 1981, 1982). If the triplet is in M31, it is about

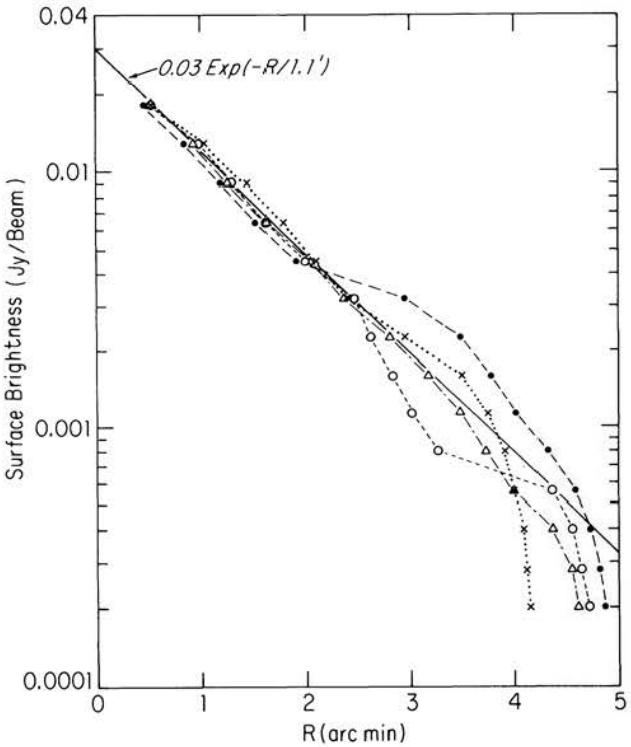


FIG. 4.—The surface brightness of the 1465 MHz map with a 1′ beam plotted for radial cuts to the east (*open circles*), west (*triangles*), north (*filled circles*), and south (×) as a function of angular displacement (R) from the center of the source, together with a line indicating the single exponential distribution which fits all four radial cuts.

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TABLE 1

PROPERTIES OF THE TRIPLE RADIO SOURCE

COMPONENT	S(408 MHz)[a] (mJy)	S(1465 MHz) (mJy)	S(4885 MHz) (mJy)	SPECTRAL INDEX 408–1465 MHz	SPECTRAL INDEX 1465–4885 MHz
NE = 5C 3.119 ...	57 ± 5	22 ± 2	< 10	0.75 ± 0.1	> 0.7
Center	< 12	6 ± 1	10 ± 3	< 0.6	-0.4 ± 0.3
SW	< 12	9 ± 1	5 ± 0.4	< 0.3	0.5 ± 0.15

[a]Pooley 1979.

1 kpc in size. However, the most likely possibility is that the radio triplet is associated with a background elliptical galaxy coincident in position with the central source in the triplet. In this case, the size scale of the triplet is probably of the order of 100 kpc or more; this is a normal size scale for extragalactic triple radio sources.

III. THE NATURE OF THE CENTRAL RADIO SOURCE IN M31

The broad central radio source seen in Figures 1 and 2 is a remarkable structure of a type not clearly seen before either in our Galaxy or any other galaxy. Its principal features are: (1) a near spherical symmetry, and (2) a surface brightness decreasing exponentially with radius that can be traced out to 1 kpc from the center. Since this radio source is due to synchrotron radiating electrons, for reasons that we will review in a moment, it represents either a distribution of hundreds of very weak sources or a distribution of cosmic-ray electrons. The spherical distribution indicates either a spherical bulge population of sources or a spherical potential for a galactic wind. If a source like this were present at the center of our Galaxy, its angular size would be 12°, with a surface brightness roughly 20% of what is observed at 20 cm (Westerhout 1957); hence, it would be difficult to distinguish from the total galactic radio emission.

Van der Kruit (1972) and others have discussed the "point" sources in the central part of 5C 3.110. However, Crane, Brown, and van der Hulst (1981) have reported high-resolution VLA observations indicating that all of these sources have size scales greater than an arcsecond, and there is nothing in the center of M31 corresponding to Sgr A. Thus the sources within 30″ of the nucleus in Figure 3 are either extended objects in the central region or structural features in the overall exponential brightness distribution.

There are two principal indications that 5C 3.110 is predominantly a synchrotron radiation source, although one cannot exclude the possibility that some of the features seen in both 1465 and 4885 MHz maps are H II regions. The first is the nonthermal spectral index. Pooley (1969) found 5C 3.110 to have a total flux density of 240 ± 50 mJy at 408 MHz and 100 ± 20 mJy at 1407 MHz. We obtain a total flux density of 160 ± 20 mJy for this source at 1465 MHz, significantly larger than the result of Pooley and also larger than the 130 mJy obtained at 1415 MHz by van der Kruit (1972), probably because we were able to detect broader structures in the source. The only other published measurements that should have included all of the source is the 86 mJy complex of sources at 2695 MHz discussed by Berkhuijsen (1977). These measurements indicate an average spectral index of 0.32 between 408 and 1465 MHz and 1.1 between 1465 and 2695 MHz. Despite the uncertainties in the various measurements, the bulk of the broad radio source is certainly nonthermal. The second source of evidence for the synchrotron nature of most of 5C 3.110 is our detection of extended, linearly polarized emission in the extended radio source. Several millijanskys of polarized flux are found in the extended radio source, largely on the SE side of the galactic plane, exactly as would be expected if there were extra Faraday depolarization due to an excess of thermal gas along the line of sight on the NW side, which is the near side of M31. Due to lack of space we will defer discussion of the polarization structure for a later paper.

Using a distance of 690 kpc and the assumption of equipartition of energy, the roughly 20 mJy per beam seen in the 1465 MHz maps of the inner 30″ region of the source gives a magnetic field of a few microgausses, an average relativistic electron energy density of about 0.5 eV cm^{-3}, and a total energy in a 30″ size volume of 2×10^{50} ergs. The relativistic electrons in the central part of the source will therefore have synchrotron loss lifetimes greater than 10^8 yr.

Although it is clear that most of the broad central radio source is due to synchrotron emission from relativistic electrons interacting with magnetic fields, this object could be either due to hundreds of small sources too weak to detect individually with the high-resolution VLA (Crane, Brown, and van der Hulst 1981) or due to a distribution of cosmic-ray electrons. In the former case, one woud need hundreds of weak sources which could be supernova remnants, radio stars, or whatever; supernova remnants are perhaps most likely because these numbers are consistent with a supernova rate of $1/36$ yr^{-1} (Tammann 1978) and a supernova remnant lifetime of 4×10^5 yr. A cosmic-ray distribution would be a galactic wind or breeze, in which cosmic-ray pressure dominates, possibly of the type discussed by Ipavich

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(1975) and extensively reviewed by Cesarsky (1980); the structural details in the outer parts of the central source in Figures 1 and 2*a* are then due to either differences in the way the galactic wind expands into the surrounding medium or instabilities in the radial flow. The relativistic particles may be produced mainly in the central 200 pc of M31 by supernova remnants, Fermi acceleration processes, or particle accelerating shocks; the structural features observed in this region are then due to some combination of fossil remnants of supernovae, cloud distributions participating in Fermi acceleration processes, or particle accelerating shocks. It is beyond the scope of this *Letter* to evaluate the relative merits of these possibilities.

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