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Menas Kafatos
Chapman University, kafatos@chapman.edu

R. W. Hobbs
Univ Durham

S. P. Maran
NASA, Goddard Space Flight Center

L. W. Brown
Virginia Commonwealth University

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150 GHz OBSERVATIONS OF THREE RADIO GALAXIES

MINAS KAFATOS[1]
Department of Physics, George Mason University; and
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center

AND

ROBERT W. HOBBS,[1] STEPHEN P. MARAN, AND LARRY W. BROWN
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center
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ABSTRACT

Radio galaxies were observed for the first time at 150 GHz. The central sources in Cyg A and 3C 111 were detected, as were the two radio lobes of Cyg A. No emission was found from the central source in 3C 236. Each of these three central sources has been previously discussed as the site of the energy supply for the associated distant components. The millimeter-wavelength emission from the central sources in Cyg A and 3C 111 is probably due in each case to a compact component that is optically thin to synchrotron radiation above about 35 GHz. These components are similar, although the compact component in 3C 111 is more luminous at both radio and X-ray wavelengths than the one in Cyg A. The 3C 111 central source was much weaker than anticipated on the basis of prior observations at 90 GHz, perhaps due to variability. Even at 150 GHz, there is no evidence of a high-frequency cutoff in the spectrum of the central source in Cyg A, and variability of this source also is expected. The flux densities of the Cyg A lobes are consistent with the power laws derived at lower frequencies, indicating that no steepening occurs in their spectra out to at least 150 GHz. There is no evidence for a compact, optically thick component in 3C 236.

Subject headings: radio sources: spectra — synchrotron radiation

I. INTRODUCTION

High-frequency millimeter-wave observations of radio galaxies yield information on compact radio sources in the galaxy nuclei. The compact sources often are multiple as well as variable. Since the radio spectra of compact components most often are flat, or even rise toward higher frequencies, it is progressively easier to distinguish them from the extended components (lobes) present in double radio sources, even when the radio telescope does not resolve the source. Further, telescope beam size decreases with increasing radio frequency. A typical case is Cyg A, which has been observed over the range 10 MHz to 100 GHz in prior work (Hobbs *et al.* 1978 and references therein). The central component is first distinguished at 1 GHz and its spectrum is flat, or slowly rising, at least up to 100 GHz. On the other hand, the radio lobes, with a spectral index of $\alpha = 1.2$ (where $S_\nu \sim \nu^{-\alpha}$) above 1 GHz, are systematically weaker at higher frequencies. Since it is thought that the lobes in radio galaxies are powered from the nuclei (Wills 1975), it is important to study the nuclear properties at high frequencies. Prior to this work, the highest frequency at which such radio sources had been observed was 99 GHz (Hobbs *et al.* 1978).

[1] Visiting Astronomer at the National Radio Astronomy Observatory, Tucson, Arizona, facility. The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

In this paper, we present the first observations of radio sources at 150 GHz. The central sources in the galaxies Cyg A and 3C 111 were observed, as were the radio lobes of Cyg A. A third galaxy, 3C 236, was searched for emission, with a negative result. It may be of interest that these sources represent three types of galaxies, based on the optical emission line spectra. Cygnus A has a narrow-line spectrum, which resembles the spectrum of the Crab Nebula and the narrow-line component of the Seyfert galaxy NGC 4151 (Osterbrock and Miller 1975). The galaxy 3C 111 has broad lines and appears to be an N-type galaxy with a Type 1 Seyfert galaxy spectrum (Sargent 1977). The galaxy 3C 236 has a weak emission-line spectrum (Sandage 1967; Smith, Spinrad, and Smith 1976).

II. OBSERVATIONS

The present observations were obtained on 1978 December 20–22 with the 36 foot (11 m) NRAO antenna on Kitt Peak and a 150 GHz radiometer. The system temperature was 1100 K.

The radiometer was mounted at the Cassegrain focus, and beam switching was accomplished by means of a nutating subreflector. The two beams were separated by 2′40″. The measurements were of the ON-OFF type and were obtained with the source alternately in one or the other of the beams. Pointing corrections were derived from Jupiter and DR 21 by the five-point method of Dent and Hobbs (1973). A more detailed description of observing procedures (i.e., antenna control and correction for atmospheric absorption) is given by Hobbs and Dent (1977). Scans and pointing-mode observations of Jupiter were used to determine the beam diameter, namely 63″ FWHM. No significant sidelobes or other unusual beam properties have been found. Extensive tests at wavelength 2 mm indicate that the beam is widened by spherical aberration and that there is no significant coma (Ulich 1979).

The small-diameter galactic sources DR 21 and NGC 7027 were used as calibrators; 150 GHz flux densities of 18.0 Jy and 4.8 Jy, respectively, were assumed. With this calibration, the Cyg A measurements yielded apparent flux densities as follows: Np lobe, (2.4 ± 0.7) Jy; Sf lobe, (4.6 ± 0.8) Jy; central source, (1.5 ± 0.4) Jy. However, because the beamwidth is 63″ and the separation of each lobe from the nucleus is about 1′, the measurements of the central source were slightly contaminated by the lobes. The 35 GHz map of Hachenberg *et al.* (1976) shows that the lobes are extended with FWHM of 31″ (Sf) and 23″ (Np). Adopting these sizes and the measured 150 GHz beamwidth, we find that the Sf and Np lobes contributed about 0.13 Jy and 0.06 Jy, respectively, to the apparent flux density of the central source. Thus, we find a corrected 150 GHz flux density of (1.3 ± 0.4) Jy for the central source. This is not significantly lower than the 99 GHz result, $S_\nu = (1.6 \pm 0.5)$ Jy, of Hobbs *et al.* (1978). Thus, even at 150 GHz, there is still no evidence of a high-frequency cutoff in the spectrum of the central source. The apparent flux densities for the lobes, listed above, are already corrected for the stated values of the lobe diameters.

The nucleus of 3C 111 was observed with similar procedures. The apparent flux density at 150 GHz is (1.76 ± 0.71) Jy. The Nf, extended component was observed at 90 GHz by Wills (1975), who reports a flux density of (0.69 ± 0.11) Jy. Extrapolating this value to 150 GHz by taking $\alpha = 0.55$ (Wills 1975, Fig. 1), and allowing for a contribution from the Sf lobe that is 80% of the extrapolated value, we estimated that the total flux density of the radio lobes at 150 GHz is 0.94 Jy. The lobe size at 1.4 GHz was estimated as $\sim 16'' \times 8''$ by Mitton (1970), and the separation of the lobes is 3′. Thus, the contamination of central source emission by the lobes in our observations is less than 0.01 Jy and can therefore be neglected.

Finally, observations of the central source in the giant radio galaxy 3C 236 were negative. The measurements yield a formal flux density of (-0.23 ± 0.07) Jy. This is consistent with observations of the source at lower frequencies, as discussed in the next section.

III. DISCUSSION

The compact central component in 3C 236 has been observed by Fomalont and Miley (1975) at 0.4, 1.4, 2.7, and 8.1 GHz and by Willis, Strom, and Wilson (1974) at 0.6 GHz. Fomalont and Miley distinguished two main subcomponents, of which one is itself resolved into at least two parts. The spectra of all of these components are similar, with $\alpha \approx 0.6$. Extrapolating these spectra to 150 GHz, we would expect a flux density of 0.2 Jy from the central source; this value is consistent with our negative result. In any case, it appears that there is no evidence for a compact, optically thick component at the center of 3C 236. There is then no reason to anticipate appreciable variability at radio frequencies.

Wills (1975) interpreted the radio emission of the central source in 3C 111 in terms of two components. One is optically thin at frequencies above 100 MHz, with $\alpha \sim 0.57$. The other is optically thick below ~ 30 GHz, and has a flux density of 10 Jy at 90 GHz. The angular size, θ, of the optically thin component is probably $0.2'' \lesssim \theta \lesssim 3''$ (Mitton 1970; Readhead and Hewish 1974). Wills estimated $\theta = 5 \times 10^{-4}{''}$ for the optically thick component, with a magnetic field $H \approx 4$ gauss. VLBI observations (Pauliny-Toth *et al.* 1976; Preuss *et al.* 1977) show that this component is in fact resolved into two subcomponents, with appropriately reduced angular sizes and inferred magnetic fields. From the millimeter-wave data, we would anticipate that a diameter $\theta = 2.6 \times 10^{-4}{''}$ would be appropriate for the high-frequency emitting subcomponent, in order that the synchrotron losses are not too severe. This is consistent with the diameters measured by VLBI (Pauliny-Toth *et al.* 1976).

Our observations of the radio lobes of Cyg A fit the power law with $\alpha = 1.2$, consistent with the previous measurements at frequencies above 1 GHz (Hobbs *et al.* 1978). Thus, even at 150 GHz, there is no evidence for a steepening of the spectrum of either lobe.

The central component of Cyg A was investigated by Kafatos (1978). He finds that the radio data can be fitted with two subcomponents: an "extended" ($\theta \approx 7.6 \times 10^{-4}{''}$) source that is optically thick below ~ 3 GHz, and a compact ($\theta \approx 7.6 \times 10^{-5}{''}$) source that is optically thick below ~ 35 GHz. The observations of the nucleus of Cyg A along with model spectra for these two subcomponents are shown in Figure 1. Each is assumed to have an electron energy spectrum exponent, γ, of 2, which corresponds to $\alpha = 0.5$. Various parameters for these models were calculated by Kafatos (1978) using the Jones, O'Dell, and Stein (1974) methodology for synchrotron self-Compton models.

For comparison with the Cyg A models, we computed the corresponding parameters for the compact, optically thick source in 3C 111. We assume $\alpha = 0.5$ for this source, corresponding to the power-law exponent of the extended component. The frequency at which the spectrum steepens to $S_\nu \sim \nu^{+2.5}$, due to synchrotron self-absorption, is $\nu_a \approx 35$ GHz, in accord with the model of Pauliny-Toth *et al.* (1976). The radio luminosity is 3.5×10^{44} ergs s^{-1}, if the upper break frequency due to radiation losses is $\nu_b \approx 300$ GHz. To apply the synchrotron self-Compton formulae, one needs to know the (self-Compton) X-ray luminosity. This was taken from Culhane (1978) as 9×10^{44} ergs s^{-1}.

In Table 1, the most compact millimeter-wave components in the nuclear sources of Cyg A and 3C 111

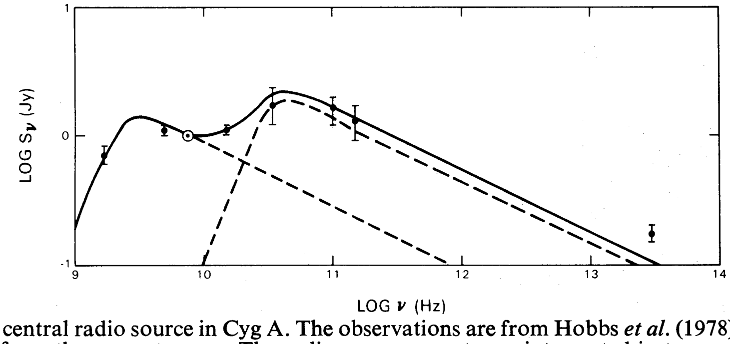

FIG. 1.—Spectrum of the central radio source in Cyg A. The observations are from Hobbs *et al.* (1978) and references therein, plus the 150 GHz measurement from the present paper. The radio measurements are interpreted in terms of two subcomponents, after Kafatos (1978), as shown by the dashed lines. At higher frequencies, the stronger subcomponent is the one that becomes optically thick to synchrotron self-absorption below about 35 GHz; if its spectrum continues without a break to the infrared region, then *in situ* production of the radiating electrons is required. Alternatively (and perhaps more likely), the synchrotron spectrum bends down at submillimeter frequencies and the infrared flux (Rieke and Low 1972) is thermal in origin.

are compared. We adopted $\alpha = 0.5$, $\nu_a = 35$ GHz, and $\nu_b = 300$ GHz for each source. The synchrotron, t_s, and inverse-Compton, t_c, lifetimes are given for the electrons that radiate at 100 GHz (isotropy of pitch angles is assumed). The short Compton lifetimes for 3C 111 explain the strong variability for the millimeter-wave component reported by Wills (1975) at 90 GHz. Our observations at 150 GHz are consistent with strong variability, since the measured flux density is about 6 times lower than the value extrapolated from the Wills 90 GHz measurement, made 4 years earlier. (A drop of a factor of 6 between 90 GHz and 150 GHz is too steep to be attributed to a nonthermal constant spectrum.) Note, however, that our measurement is a 2.5 σ result. Dent and Hobbs (1979) have detected variability in 3C 111 at lower frequencies with a time scale of $\sim$3 months, in accord with our theoretical calculation. The time scale t_d, tabulated in Table 1, is the minimum diffusion time for electrons streaming out from the center at the speed of light.

As already noted, the compact sources summarized in Table 1 have similar spectra, notably similar ν_a. The Cyg A source is 3 times smaller and emits 8 times less energy in the radio range and 6 times less energy in X-rays than the 3C 111 source. On the basis of the apparent variability of the 3C 111 source and the comparable time scales and smaller size of the Cyg A source, we expect that the central compact source in Cyg A is variable at high radio frequencies. Cygnus A has not yet been reported as a variable source, probably because most measurements have been made at lower frequencies, where the emission of the lobes dominates. Additional measurements are needed at high frequencies.

The spectrum of the compact source in Cyg A is shown in Figure 1, along with the infrared measurement at wavelength 10 μm by Rieke and Low (1972), which has been confirmed by Rieke (1977). If the spectrum actually extends without a break to the infrared range, *in situ* production of relativistic electrons is required. Otherwise, we would expect the spectrum to steepen near 300 GHz, as assumed above. Thus the radiation observed by Rieke and Low is most likely of thermal origin. It would be very desirable to check this by observing Cyg A at other infrared wavelengths. (For example, if the flux near 3 μm is a few times less than that measured at 10 μm, a thermal origin in a medium at temperature $\sim$500 K would be likely.) In that case, the infrared flux density, unlike that at millimeter wavelengths, would not necessarily be variable.

In conclusion, the high-frequency millimeter-wave measurements that have recently become practicable enable us to distinguish compact and probably variable components in the nuclear regions of radio galaxies. Of three sources observed, Cyg A and 3C 111 have

TABLE 1

COMPACT COMPONENTS IN CYGNUS A AND 3C 111

Parameter	Cygnus A	3C 111
Angular diameter, θ (arcsec)	7.6×10^{-5}	2.6×10^{-4}
Magnetic field, H (gauss)	0.25	0.1
Synchrotron (radio) luminosity, L_s (ergs s^{-1})	4.5×10^{43}	3.5×10^{44}
Inverse-Compton (X-ray) luminosity, L_x (ergs s^{-1})	1.4×10^{44}	9×10^{44}
Synchrotron lifetime,[a] t_s (yr)	1.2	4.6
Inverse-Compton lifetime,[a] t_c (yr)	0.34	0.27
Diffusion time, t_d (yr)[b]	0.19	0.60

[a] For electrons that radiate at 100 GHz.

[b] For electrons with velocity $v = c$.

compact millimeter-wave components and 3C 236 does not. Various authors have suggested that in each of these three radio galaxies the central source is associated with the energy supply for the outer lobes (cf. Pauliny-Toth *et al.* 1976; Hobbs *et al.* 1978). The present results suggest that there is a significant difference between the central components of Cyg A and 3C 111, on the one hand, and that of 3C 236 on the other.

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LARRY W. BROWN and ROBERT W. HOBBS: Laboratory for Astronomy and Solar Physics, Code 685, NASA Goddard Space Flight Center, Greenbelt, MD 20771

MINAS KAFATOS: Department of Physics, George Mason University, 4400 University Drive, Fairfax, VA 22030

STEPHEN P. MARAN: Laboratory for Astronomy and Solar Physics, Code 680, NASA Goddard Space Flight Center, Greenbelt, MD 20771