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CYGNUS A AT 99 GHz: OBSERVATIONS OF THE THREE PRINCIPAL COMPONENTS AND INTERPRETATION OF THE CENTRAL SOURCE

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ABSTRACT

The three principal emission components of Cygnus A have been observed at 99 GHz, the highest frequency at which radio measurements of this source have been accomplished. The observations show no definite indication of a high-frequency cutoff in the spectrum of the compact central component, which perhaps may be attributed to an optically thin synchrotron source that peaks at a frequency of several hundred GHz.

1. INTRODUCTION

Cygnus A, generally regarded as the prototype of the strong double radio sources, has been the subject of intense study since the late 1940s. The current observational picture of this source (cf. Hargrave and Ryle 1976) incorporates three principal emission regions, the two radio lobes (Jennison and Das Gupta 1953) and the small central component, which coincides with the central region of the associated giant elliptical galaxy. The lobes each consist of an intense "head" (with one or two arc-second size compact components) at the end furthest from the galaxy and a "tail" of weaker radio emission that extends back toward the galaxy (Mitton and Ryle 1969). In the terminology of expanding source models, the head in each lobe has a sharp leading edge and a typical scale size of 3 kpc, assuming a Hubble constant of 50 km s^{-1} Mpc^{-1}. The spectra of the tails are much steeper than those of the heads. Our measurements extend the spectra of the lobes and central component of Cygnus A to 99 GHz.

2. THE CENTRAL COMPONENT

Most radio investigations of Cygnus A have concentrated on the lobes, since the central component is much weaker at the wavelengths of observation and indeed was not even discovered until 1973 (Hargrave and Ryle 1974). Hargrave and Ryle determined that the central source is less than 1 arc second in diameter (i.e., <1.5 kpc at a distance of 323 Mpc, as implied by the redshift $z = 0.0561$) and that it is located between the two apparent optical nuclei of the galaxy, within 1 arc second of the axis that joins the most intense components of the two radio lobes. According to the recent astrometric results of Kronberg, van den Bergh and Button (1977), the central source also is located at the center of symmetry of the optical cD envelope of the associated galaxy. At 7.85 GHz, VLBI measurements can be interpreted in terms of an elliptical gaussian model of the central source that has its major axis aligned with the lobe-lobe axis and with diameters $d = (2 \times 1) \times 10^{-3}$ arc second (Kellermann et al. 1975). (The lobe-lobe axis also is aligned approximately with the galaxy rotation axis as determined from optical emission lines in the nuclear region, according to Simkin 1977.) Interferometric observations at 5 GHz and 15.4 GHz by Hargrave and Ryle (1976) yield $d < 0.3$ arc second and a flat spectrum consistent with the 7.85-GHz measurement of Kellermann et al. The central source also has been observed at 1.666 GHz by Bentley et al. (1975) and at 35 GHz by Hachenberg et al. (1976). The latter paper reports the highest frequency radio detection of the central source in Cygnus A prior to the present study.

Both Hargrave and Ryle (1974) and Hachenberg et al. regard the central component as the source of the energy that powers the radio lobes, presumably by the beaming of relativistic particles or low-frequency waves (Blandford and Rees 1974). It is curious, therefore, that relatively little attention has been paid to it by theorists. The primary observational conclusion of Hachenberg et al. is that the central component's "spectrum is flat or slightly increasing with frequency," in contrast to the well-known spectra of the lobes, which decrease with frequency according to power laws, as discussed later on. Gubbay et al. (1977), in a VLBI experiment, failed to detect the central source at 2.298 GHz. They set an upper limit for any component with d <0.0015 arc second of ~ 0.5 Jy. This is marginally consistent with the source size deduced by Kellermann et al. Alternatively, inspection of the spectrum (Figure 1) shows that this limit is consistent with the possibility that the central source actually consists of two or more subcomponents. Indeed, Kellermann et al. found that a source more complex than the single elliptical gaussian mentioned above would be admitted by their data.

3. OBSERVATIONS

The present observations were obtained on 1977 February 10-11 with the 36-ft (11-m) NRAO antenna on Kitt Peak and a cooled mixer radiometer, as part of a program to measure the polarization of discrete radio sources at 99 GHz (Hobbs, Maran and Brown 1977). The system temperature was 330 K, slightly higher than normal because of the polarization system.

The radiometer was mounted at the Cassegrain focus and beam switching was accomplished by means of a nutating subreflector. The beamwidth is 74 arc seconds FWHM and the two beams were separated by 4 arc minutes. The measurements were of the "on-off" type: those of the two principal radio lobes were obtained by the five-point method described by Dent and Hobbs (1973), while the central source was observed by simple on-off measurements. The assumed position of the central source was obtained from Hargrave and Ryle (1976), corrected empirically by offset pointing corrections determined from our measurements of the principal lobes. The observations were obtained with the source alternately in one or the other of the twin beams. A more detailed description of the observing procedures (*i.e.*, antenna control and correction for atmospheric absorption) is given by Hobbs and Dent (1977).

The small diameter galactic source DR21 was used to calibrate the flux density measurements. We assumed that the flux density of this source is 16.9 Jy at 99 GHz (*cf.* Hobbs and Dent 1977). With this calibration, a preliminary reduction of the Cygnus A measurements yielded apparent flux densities as follows:

Np lobe	(5.5 ± 1.6) Jy
Sf lobe	(8.6 ± 2.4) Jy
Central source	(2.0 ± 0.5) Jy.

However, because the beam size is 74 arc seconds and the separation of the central source from each lobe is about 1 arc minute, the measurements of the central source were slightly contaminated by emission from the lobes. From the 35-GHz map of Hachenberg *et al.*, it appears that the lobes are extended, with source sizes (FWHM) of 31 arc seconds (Sf lobe) and 23 arc seconds (Np lobe). Adopting these sizes at 99 GHz, we find that the Sf and Np lobes contributed approximately 0.30 Jy and 0.14 Jy, respectively, to the apparent 99-GHz flux density of the central source. Thus, we find a corrected flux density of (1.6 ± 0.5) Jy for the central source. The flux densities of the two lobes as quoted above are corrected already for the finite lobe diameters that we adopted from the 35-GHz map.

The present results can be compared with those of Fogarty *et al.* (1971), who report a total flux density of (7.2 ± 1.1) Jy for Cygnus A at 90 GHz, based on observations with the Aerospace Corporation 4.6-m antenna with a beam of 3 arc minutes FWHM. Fogarty *et al.* also quote unpublished 86-GHz measurements made by W. J. Wilson in 1970 with the 11-m NRAO antenna, as follows: total flux density of the two lobes = (8.4 ± 2.0) Jy; flux density of the central source < 0.2 Jy. These data are inconsistent with our results on the lobes and are in strong disagreement with our measurement of the central source. However, the following comments should be made: (1) the NRAO system is superior (for this kind of measurement) to that of the Aerospace Corporation; (2) the radiometers available at NRAO have improved substantially since 1970; (3) the procedure by which the Wilson measurements were made has not been published; (4) in the case of the central source where the discrepancy is greatest, a substantial change in the millimetric flux is not unreasonable and indeed such changes have been observed in the nuclei of other radio galaxies.

4. DISCUSSION

The spectra of the principal components of Cygnus A are summarized in Figure 1. The spectra of the two lobes are essentially identical in shape, although the Sf lobe is somewhat stronger, and hence these two spectra have been summed in the Figure. The lobe spectrum shows a low-frequency turnover near 20 MHz, then follows a power law

$$S_\nu \sim \nu^{\alpha}$$

with $\alpha = -0.8$ up to 1 GHz. From ~1 to 100 GHz, $\alpha = -1.2$. The data on the central source are consistent with a rising spectrum ($\alpha \approx 1/3$), although a flat spectrum is not excluded. Extrapolating from the available radio observations, we would expect that with increasing frequency in the millimetric and submillimetric range, the central source will become brighter than the lobes, perhaps near 300 GHz, unless there is a high-frequency turnover. We shall return to this question.

If the central source does in fact become the dominant component of Cygnus A at frequencies above 300 GHz, it will clearly be of great interest to measure this source in the infrared. Unfortunately, only one infrared observation of Cygnus A has been reported (Rieke and Low 1972). This measurement at wavelength 10 μm with a 6 arc second diameter beam revealed that the 7.9 - 13.3 μm luminosity in the central core of the galaxy is $\approx 3 \times 10^{44}$ erg/s, leading Rieke and Low to characterize Cygnus A as one of four "ultrahigh-luminosity" galaxies among the 57 extragalactic sources that they observed. Rieke (1977) has recently repeated this measurement and has obtained the same result at high statistical confidence.

The optical fluxes of Cygnus A, as plotted in Figure 1, are derived as follows: B and V are from Sandage (1972) and U is from van den Bergh (1976). These data refer to the central 10-kpc diameter area surrounding the nuclear region and have been corrected for interstellar absorption, as determined by van den Bergh. The error bars indicate an uncertainty of 0.3 magnitude, corresponding to an apparent systematic difference between the Cygnus A photometry of these two authors. The optical flux measurement labeled "L" refers to a weak extended object that Kronberg, can den Bergh and Button (1977) have reported to exist within the Np lobe. As such, it is indicative of the order of magnitude of the optical emission from the extended components, or at least represents an upper limit to such emission. The dominant contributor to the optical flux from the nuclear region of Cygnus A may well be the nebular emission lines (Mitton and Mitton 1972) and starlight as well as other thermal continua may also be significant. However, even so the optical fluxes constitute a useful constraint on synchrotron models for the central source. In any case, the optical emission is of particular interest because it is largely generated within a few arc seconds of the galactic nucleus and (as shown by the presence of forbidden Fe X emission) includes a hot phase ($T \approx 2 \times 10^6$ K) which has a cooling time of a few times 10^4 yr at most. Mitton and Mitton therefore conclude that the hot gas in the nuclear region requires a continuing source of energy.

If the central source is a single cloud of radiating plasma, then the most reasonable explanation for the gentle slope of the radio spectrum, as shown in Figure 1, is one that invokes an optically-thin synchrotron model but assumes that all of the radio observations made to date are at frequencies below the peak frequency of the lowest energy radiating electrons (Kafatos 1977). Kafatos has examined a variety of such models, based on such standard assumptions as equipartition ofmagnetic and particle energies, as further described in his paper. He finds that if the electrons are injected at the center and the source is stationary (i.e., not expanding relativistically), then such a model cannot satisfy both the small diameter found in the 7.85-GHz VLBI observations and the observed strength of the 10-μm emission. This may indicate that the infrared radiation arises by an independent process. Alternatively, the electrons may be injected in situ or the source may be nonstationary. In either such case, all of the radio and infrared observations can be satisfied by a single synchrotron model, but one might expect flux variations on time scales of a few months.

The calculated synchrotron luminosities for the central source are $\gtrsim 10^{44} - 10^{45}$ erg/s, depending on the details of the model. Clearly, further observations in both the infrared and high-frequency radio regions are urgently needed.

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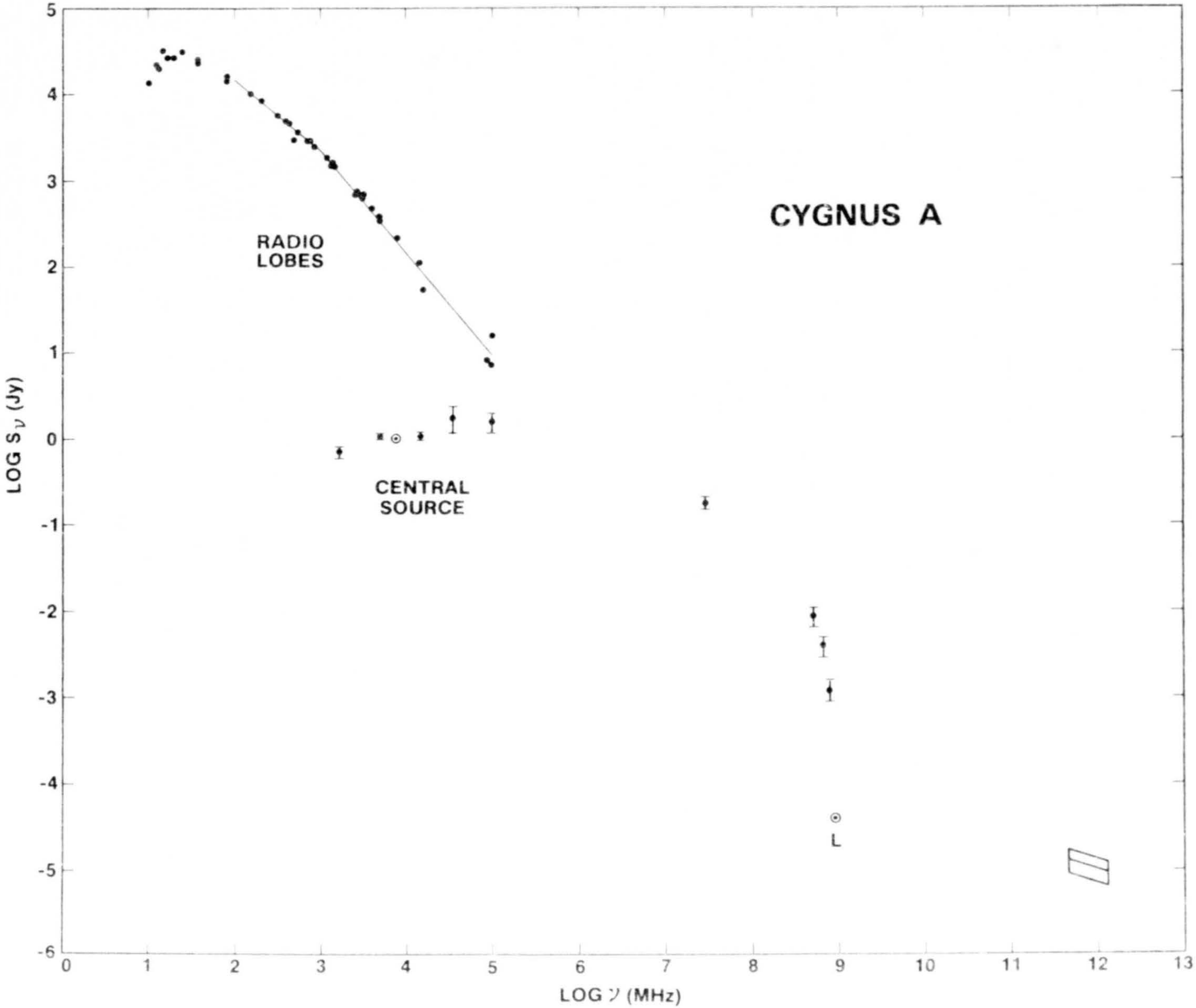
FIGURE 1. Electromagnetic spectrum of Cygnus A. Data for the radio lobes are from Parker (1968), Braude _et al._ (1969), Mitton and Ryle (1969), Hargrave and Ryle (1974, 1976), Fogarty _et al._ (1971) and this paper. Data for the central source are from Hargrave and Ryle (1974, 1976), Bentley _et al._ (1975), Kellermann _et al._ (1975), Hachenberg _et al._, 1976, and this paper. The infrared measurement is by Rieke and Low (1972). Optical fluxes are from Sandage (1972) and van den Bergh (1976) for the central region; the point L represents the extended object within the Np lobe observed by Kronberg, van den Bergh and Button (1977). The x-ray data are from Longair and Willmore (1974); however, the x-rays may originate in the associated cluster of galaxies rather than in Cygnus A itself.


CYGNUS A
RADIO LOBES
CENTRAL SOURCE
L
LOG S$_\nu$ (Jy)
LOG ν (MHz)
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
0
1
2
3
4
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