

MICROWAVE OBSERVATIONS OF THE CYGNUS X REGION

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ABSTRACT

New observations of the radio region known as Cygnus X have been made at a frequency of 5000 Mc/s with an antenna beam width of $10'.8$. The results are displayed in a radio contour map which shows more than twenty discrete sources superimposed on extended areas of radio emission. Comparison with the observations of Pike and Drake, made at a frequency of 1414 Mc/s with a beam width of $10'.0$, shows every source in the region to have a thermal spectrum, with the exception of the source near the star γ Cygni, which appears to have an intensity spectral index of -0.7 ± 0.3 and thus to be of non-thermal origin. The brightest source in the region is a thermal source of small angular diameter.

I. INTRODUCTION AND OBSERVATIONAL PROCEDURE

The development of low-noise microwave receivers has renewed the interest of radio astronomers in the extended radio region known as Cygnus X. Observations in the microwave range have been made by Davies (1957), Westerhout (1958), Drake (1959), Müller (1959), and by Altenhoff, Mezger, Strassl, Wendker, and Westerhout (1960). More recent studies have been made by Higgs, Broten, Medd, and Raghavarao (1964) and by Pike and Drake (1964). Of these surveys, that made by Pike and Drake had the highest angular resolution, namely, $10'.0$ at a frequency of 1414 Mc/s. These surveys have shown the Cygnus X region to be composed of more than twenty discrete sources. Because of the close spacing of the sources, and because of extended background emission, analysis of the spectra of individual components is rather difficult.

This paper describes new observations of Cygnus X at a frequency of 5000 Mc/s with an 85-foot paraboloid antenna having a circular beam width of $10'.8$ to half-power. This resolution permits direct comparison with the results of Pike and Drake, and allows tentative conclusions to be drawn regarding the spectra of the discrete sources.

The receiver consisted of a parametric preamplifier, operating in the degenerate mode, followed by a zero-intermediate frequency amplifier of band width 100 Mc/s (Hughes, Moley, Parenti, and Whelehan 1965). The receiver was switched between the main receiving horn and a broad-beam comparison horn directed at cold sky 45° away from the Cygnus region. System noise temperature was 270° K. The minimum detectable antenna temperature was 0.09° K for any individual scan, with the output time constant of 4 sec. The radiometer was calibrated hourly with a standard argon noise of the tube, and the over-all system performance was checked daily by observations of the radio source near γ Cygni.

The survey comprised forty-two drift scans spaced approximately 1 beam width apart, taken in an area bounded by right ascension 20^h00^m – 21^h10^m and declination $+37^\circ$ – $+47^\circ$. Most scans were repeated at least once and, over-all, one hundred scans were taken through the region. The level of zero intensity for each scan was assumed to be that recorded at right ascensions 20^h00^m and 21^h10^m . The scans were used to construct a contour map of antenna temperatures. The contours were converted into apparent brightness temperatures by dividing antenna temperatures by the main-beam efficiency, viz., 0.63. This figure was calculated from the antenna-beam pattern and an assumed flux density of $70 \times 10^{-26} \text{ W m}^{-2} (\text{c/s})^{-1}$ for M87 at a frequency of 5000 Mc/s (Conway, Kellermann, and Long 1963). The contours are estimated to be accurate to about 10 per cent. Because the spacing between scans was 1 beam width, the source positions are believed to be accurate to only $\pm 2'$.

II. OBSERVATIONS

Figure 1 shows the contour map plotted from the scans. One contour unit equals 0.15° K antenna temperature, or 0.24° K apparent brightness temperature. The boundaries of some contours are uncertain and are indicated by dashed lines. In particular, the one-unit contour is dashed, because it is only slightly greater than the rms noise fluctuations, and its boundaries may be uncertain by as much as 1° . The map shows the region to be composed of twenty to forty discrete sources as well as very extended and unresolved areas of radio emission.

Several features differ from those on the map made by Pike and Drake at 1414 Mc/s. In the present survey, the highest temperature was recorded at the position of source 21

TABLE 1
POSITIONS AND INTENSITIES OF CYGNUS X SOURCES AT 5000 MC/S

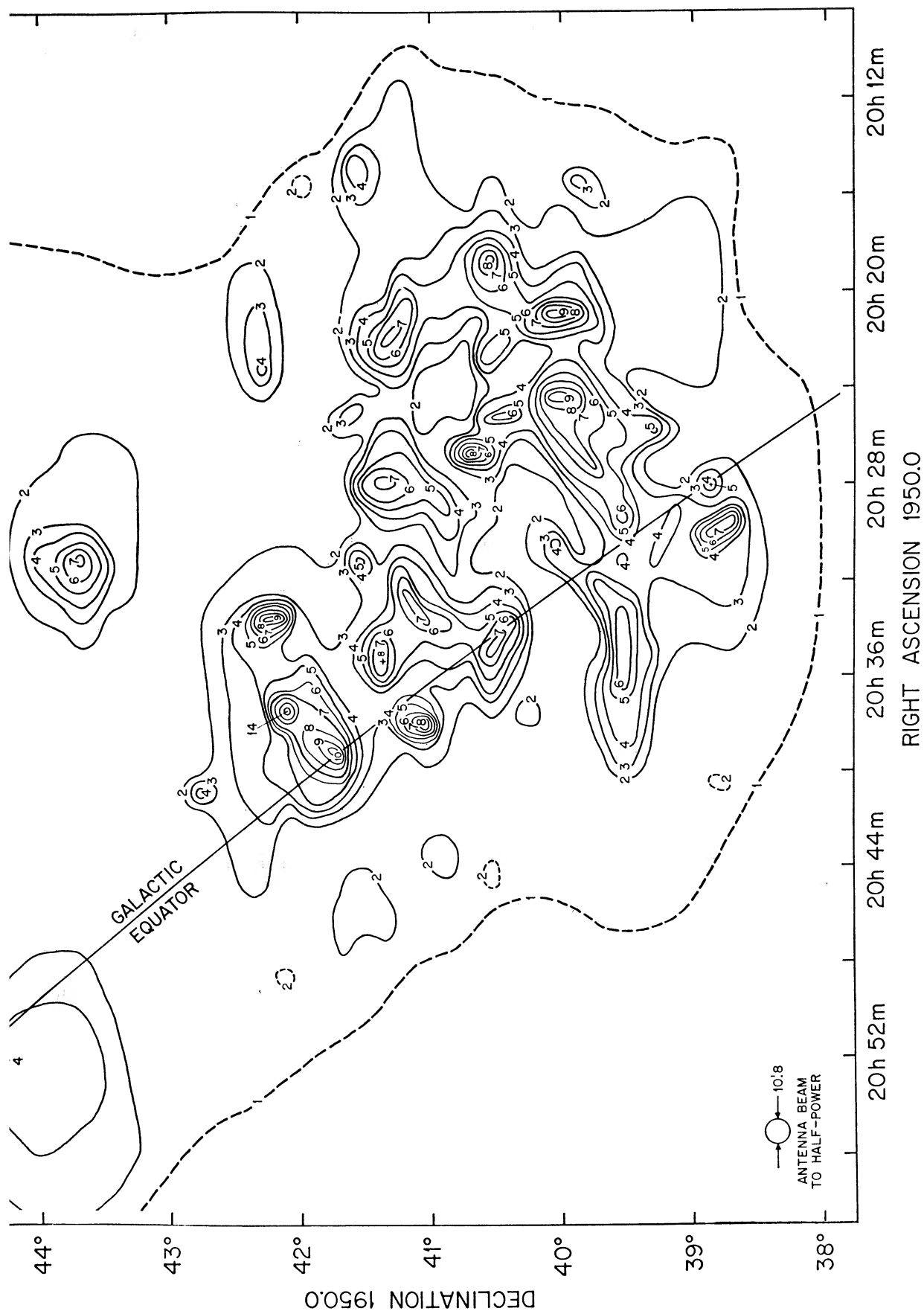
Source	Right Ascension (1950 0)	Declination (1950 0)	T_b ($^\circ$ K)	Apparent Source Diameter	Flux Density ($\times 10^{-26}$ MKS Units)
1	20 ^h 14 ^m 53 ^s	41 $^\circ$ 33'	0 72	0 $^\circ$ 43 $\times$ 0 $^\circ$ 66	54
3 ..	20 18 34	40 33	1.44	0 34 $\times$ 0 51	66
4 ..	20 20 46	40 04	1.68	0 33 $\times$ 0 51	75
5. .	20 24 11	40 01	1 68	0 46 $\times$ 0 87	178
6*	20 25 38	39 18	0 96	0 18 $\times$ 0 18	8
7*	20 26 31	40 43	1 44	0 18 $\times$ 0 29	20
9*	20 27 50	38 53	0 96	0 18 $\times$ 0 18	8
10	20 27 43	41 22	1 20	0 50 $\times$ 0 50	80
11 ..	20 28 28	40 58	0 72	0 34 $\times$ 0 51	33
12 ..	20 30 00	39 13	0 48	0 29 $\times$ 0 63	23
13 ..	20 29 39	38 47	1 44	0 27 $\times$ 0 46	47
15 .	20 30 22	40 03	0 72	0 23 $\times$ 0 34	15
16	20 30 53	43 43	1 20	0 44 $\times$ 0 50	70
17 .	20 33 34	42 15	1 68	0 23 $\times$ 0 34	35
18 .	20 33 15	41 05	0 96	0 20 $\times$ 0 57	29
19	20 34 27	40 31	1 20	0 29 $\times$ 0 57	53
20. .	20 35 13	41 22	1.20	0 23 $\times$ 0 34	25
21*	20 37 17	42 08	2 40	0 18 $\times$ 0 18	21
22	20 37 51	41 04	1 44	0 24 $\times$ 0 33	30
23	20 39 05	41 46	1 92	0 45 $\times$ 0 50	114
27	20 52 00	44 00	0 72	1 10 $\times$ 1 60	340

* Unresolved with the present antenna beam width.

(see Table 1), whereas at 1414 Mc/s, the highest temperature was observed at the position of source 4, the radio source near the star γ Cygni. The relative brightness temperatures on the two maps also vary at other places: e.g., at 5000 Mc/s, sources 4 and 5 have temperatures in the ratio 1:1 whereas at 1414 Mc/s the ratio is 3:2. Furthermore, at 5000 Mc/s there is an extended source, No. 27, centered on 20^h52^m, +44 $^\circ$ 00', which was excluded from the 1414-Mc/s map because of difficulties in choosing the zero level (Pike and Drake 1964). This source has been identified by Westerhout (1958) with the North American and Pelican Nebulae.

Table 1 summarizes position and intensity data for twenty-one conspicuous sources on the 5000-Mc/s map. To avoid unnecessary confusion, we have followed the numbering scheme used by Pike and Drake. These identifying numbers are given in the first column of Table 1. The fourth column gives the peak brightness temperature at 5000 Mc/s after the background temperature in the vicinity of the source has been sub-

FIG. 1.—Cygnus X region at 5000 Mc/s. One contour unit equals 0.15° K antenna temperature, or 0.24° K apparent brightness temperature



tracted; the fifth column lists the apparent source diameter, that is, the half-power widths of the beam as broadened by the source; the sixth column gives the source flux density, S , from the formula

$$S = 2kf^2 c^{-2} (3.45 \times 10^{-4} T_b R_1 R_2),$$

which is valid for Gaussian sources. T_b is the brightness temperature given in the fourth column; R_1 and R_2 are the apparent diameters given in the fifth column; k is the Boltzmann constant; c is the velocity of light; and f is the observing frequency. Errors in subtracting background temperatures and in measuring apparent diameters of the sources contribute an estimated uncertainty of 30–40 per cent to these values of flux density. Flux densities of sources that could be separated clearly from adjacent sources were checked by contour planimetry.

Spectral indices for the sources were determined by direct comparison of brightness temperatures at 5000 and 1414 Mc/s from the relation

$$S_1/S_2 = f_1^2 \int T_{b_1} d\Omega / f_2^2 \int T_{b_2} d\Omega = (f_1/f_2)^\alpha,$$

where f_1 and f_2 are any two observing frequencies, α is the intensity spectral index, and the integrals are taken over the solid angle subtended by the source. Since the surveys at 5000 and 1414 Mc/s use the same antenna beam width, this relation simplifies to

$$T_{b_1}/T_{b_2} = (f_1/f_2)^{\alpha-2}.$$

Where possible, the spectral index α was also checked by direct comparison of the flux densities determined at 5000 Mc/s with those reported by Pike and Drake (1964) at 1414 Mc/s and by Yang and West (1964) at 610.5 Mc/s. Spectral indices computed by both methods were in agreement.

The spectral indices of the sources are given in the second column of Table 2. Nearly all of the indices have the value -0.1 ± 0.2 . Such spectra are interpreted to mean that the sources radiate by thermal processes in optically thin H II regions. This interpretation is also supported by the flat spectrum of the total flux density from the Cygnus X area. Planimetry of the contours in Figure 1 gives the total flux density from the region inclosed by the dashed one-unit contour as $6000 \times 10^{-26} \text{ W m}^{-2} (\text{c/s})^{-1}$. Mathewson, Large, and Haslam (1960) measured the total flux density within the same region from three other maps: their own at 408 Mc/s gave 8600 MKS units, Westerhout's (1958) at 1390 Mc/s gave 7400 MKS units, and Drake's (1959) at 1396 Mc/s gave 6200 MKS units. These figures are in good agreement with the total flux density at 5000 Mc/s.

For the thermal sources, maximum values of emission measure and electron density, together with minimum mass estimates, are listed in the last three columns of Table 2. These values have been calculated from the formulae of Westerhout (1958), which are derived on the assumption that the sources are composed mainly of ionized hydrogen, that their electron temperature is 10000° K , and that their shapes are cylindrical. The minimum distance to the sources is assumed to be 1500 pc. This figure is based on optical estimates of the distances to dark nebulae in the Cygnus Rift (Miller 1937). This value also agrees with distances to the Cygnus X sources derived by Ikhsanov (1960) and Moriyama (1961) from optical absorption arguments. Véron (1965) believes that the Cygnus X radio sources, presumably H II regions, are ionized by the association of O and B stars known as VI Cygni. The distance to the VI Cygni association is also 1500 pc (Johnson and Morgan 1954).

III. DISCUSSION

Analysis of the radio data on source 4, the source near the star γ Cygni, reveals an intensity spectral index of -0.7 ± 0.3 . This value provides firmer evidence that the

source is of non-thermal origin, a conclusion that had been tentatively reached by Mathewson *et al.* (1960), by Haslam, Davies, and Large (1962), and by Higgs *et al.* (1964). By contrast, Pike and Drake (1964) concluded that the source was probably thermal. The measured positions (1950.0) of source 4 and the star γ Cygni are as follows:

	Right Ascension	Declination
Radio source 4	$20^{\text{h}}20^{\text{m}}46^{\text{s}} \pm 2^{\text{s}}$	$+40^{\circ}03'7 \pm 1'$
Star γ Cygni	20 20 26	40 05 7

The radio position was measured relative to that of Cygnus A. It agrees with the position measured by Pike and Drake, within estimated errors of 1'. The optical position for γ Cygni was taken from Becvar (1959). The measurements show that the radio source is displaced from the star γ Cygni by 4' in right ascension, which suggests that the radio object may have no connection with the star, although such an association has been implied in previous literature by naming it the " γ Cygni source." Drake (1959) has pointed

TABLE 2
SPECTRAL INDICES AND EMISSION PARAMETERS
FOR CYGNUS X SOURCES

Source	Intensity Spectral Index (a)	Emission Measure (cm ⁻⁶ pc)	Electron Density (cm ⁻³)	M/M $\odot$
1	-0 2	8200	26	1100
3.	- 2	18000	42	810
4*	- 7		.	
5.	- 3	19000	36	2600
6†	- 1	.	.	.
7†	- 2	.	.	.
9†	+ 1		.	
10	0	14000	34	1200
11	- 2	8900	30	570
12	- 2	6200	25	480
13	- 3	21000	54	460
15	- 2	13000	49	160
16	0	14000	36	1000
17	- 3	30000	74	240
18	+ 2	22000	67	230
19	- 1	17000	43	640
20.	+ 1	22000	63	200
21†	+ 3		.	
22	- 3	25000	69	230
23	- 2	23000	46	1300
27	-0 1	7500	15	11500

* Non-thermal. † Unresolved

out the existence of a bright nebula, seen in red light, near the position of source 4 and has suggested that the nebula is excited by the star γ Cygni. Pike and Drake agree with Ikhsanov, however, that the ultraviolet radiation of the star, of spectral type F8 Ib, would not suffice to generate the observed radio flux. The non-thermal nature of the radio emission may be a further indication that the star γ Cygni is not associated with the radio source.

As shown in Figure 1, source 21 has the highest temperature at 5000 Mc/s in the Cygnus X region. Additional observations, made by the authors at 8250 and 15500 Mc/s with a paraboloid antenna having angular resolutions of $4'2$ and $2'2$, show that the spectrum of the source is flat in the range 5000–15500 Mc/s, and further show that its angular diameter is less than $1'$. If the spectrum is interpreted in terms of a thermal emission mechanism, then the angular diameter is remarkably small when compared with existing measurements of the radio diameters of thermal objects in the galactic plane.

The OH radio lines have been seen in absorption against the Westerhout source W75 in the Cygnus X region (Gundermann 1965). A line at 1665 Mc/s has also been observed in emission at the position of W75 (Weaver, Williams, Dieter, and Lum 1965). Because the beam widths used in these observations were relatively large, $52'$ and $30'$, respectively, it is difficult to compare the positions of the spectral-line sources with those tabulated in the present paper. Source W75 may correspond either to the extended source 23, or to the nearby point source 21.

Véron (1965) has suggested that the Cygnus X region is a large Strömgren sphere of angular diameter 6° . At a distance of 1500 pc, this corresponds to linear dimensions of 160 pc. The sphere is centered on the association of O and B stars, VI Cygni, which is presumably responsible for the excitation. From hydrogen-line observations of Cygnus X, Kaftan-Kassim (1961) has concluded that there may also be an expanding H I region around the association VI Cygni. The diameter of this expanding region is believed to be about 150 pc.

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