ON THE NATURE OF THE CYGNUS-X RADIO SOURCE AS DERIVED FROM OBSERVATIONS IN THE CONTINUUM AND AT THE HYDROGEN-LINE FREQUENCY

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Summary

Continuum emission from the Cygnus-X radio source has been studied at seven frequencies in the range 92 Mc/s to 1425 Mc/s. Its spectrum is that expected from an H II region having a peak emission measure of 6,000 and a constant flux density of $47 \times 10^{-8}$ w/m²/c/s. Evidence is presented which indicates that although its structure is irregular it contains no intense regions of small angular diameter.

Measurements taken at the position of Cygnus-X in the 21 cm line of neutral hydrogen show an anomalous "absorption" at the frequency characteristic of the second spiral arm in Cygnus. The results can be explained adequately in terms of the conversion of neutral hydrogen at the position of the source to the ionized state. If Cygnus-X is in the second spiral arm at a distance of perhaps 6 Kpc as the "absorption" effect suggests, its mass is 10⁷ $M_\odot$. There is a concentration of O- and B-stars in the Cygnus-X region, some of which are contained in a cluster at about 2 Kpc. If these stars were within a spiral arm they could produce a large fraction of the ionization required.

Introduction.—All surveys of extra-terrestrial radio emission have indicated an excess of emission near the intense source Cygnus-A (19N4A). Bolton and Westfold (1) showed that it was an extended source centred approximately on Dec. = 40° and R.A. = 20h 30m, and suggested that it might be the excess of galactic background emission associated with the galactic spiral arm extending away from the Sun in this direction. However, Piddington and Minnett (2) who named it Cygnus-X, concluded from observations of its shape and spectrum that it was probably an H II region. Scheuer and Ryle (3) extended this conclusion by suggesting that the Cygnus-X region was the integrated H II emission from a spiral arm. However, Baade and Minkowski (4) were unable to make an optical identification of the source.

Recent observations have been made of the radio and visual emission from the Cygnus region. They include (a) high resolution surveys covering a wide frequency range of the continuum emission from the source; (b) neutral hydrogen absorption measurements which give added information about the source; and (c) recent studies of early-type stars lying in this part of the Galaxy. This paper describes the results of seven high resolution surveys of the continuum emission from Cygnus-X and relates them to 21 cm hydrogen line observations of the region. A more definite statement about the nature of Cygnus-X is now possible.

2. Radio surveys of the Cygnus-X region in continuum emission.—Three high resolution surveys of the Cynus-X region made at Jodrell Bank are described. They were made in the continuum emission of the radio frequency spectrum as distinct from the line emission at 1420 Mc/s.

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(a) 1425 Mc/s.—A total power switched receiver (5) with a bandwidth of 1·1 Mc/s was used in conjunction with a 30 ft paraboloid having half-power beam-widths of 1°·45 and 1°·75 in the H and E planes respectively. A facsimile of a tracing taken at Dec. = 40°·0 using an output time constant of 30 seconds is shown in Fig. 1. The r.m.s. noise ripple on the chart (± 2°K) is greater than

![Facsimile of a total power tracing at Dec. = 40°·0 at 1425 Mc/s.](image)

Fig. 1.—Facsimile of a total power tracing at Dec. = 40°·0 at 1425 Mc/s.

(b) 158 Mc/s (Units of 100°K)

(c) 92 Mc/s (Units of 100°K)

![Contour maps of the Cygnus region at (a) 1425 Mc/s, (b) 158 Mc/s, (c) 92 Mc/s.](image)

Fig. 2.—Contour maps of the Cygnus region at (a) 1425 Mc/s, (b) 158 Mc/s, (c) 92 Mc/s.

expected from mixer noise alone and is attributed to short term instability inherent in the switching process. The brightness temperature calibration was made by the method described in Section 4.
In order to construct a map of this region transits were taken every 0\degree.5 in
decination in the range Dec. = 37\degree and 45\degree. At least two transits were obtained
for each declination setting and the derived mean transits were considered
accurate to \pm 2 \degree/K. The resultant map of the region containing Cygnus-A and
Cygnus-X is shown in Fig. 2(a).

(b) 138 Mc/s.—At this frequency a more detailed examination * was made of
the recordings already taken by Hanbury Brown and Hazard (6) in 1950–51 using the
218 ft transit radio telescope. The aerial beamwidth to half power is 2\degree in
right ascension and 2\degree.2 in declination. The Cygnus region was surveyed from
Dec. = 37\degree to 53\degree. At least two transits were taken at fixed declinations at
intervals of less than 1\degree. The brightness temperatures are those derived in
Section 4. The recordings were corrected for the side lobes of the intense
Cygnus-A source between Dec. = 41\degree and Dec. = 37\degree (the greatest tilt of
the aerial mast at that time). These side lobes of Cygnus-A were symmetrically
placed in right ascension about the main beam and could also be distinguished
since they exhibited ionospheric scintillation along with the main beam. No
attempt was made to derive an absolute zero level for this survey, so the zero was
taken as the minimum level observed within 50\degree of the galactic plane. The
contours of the region are plotted in Fig. 2(b).

(c) 92 Mc/s.—The Cygnus region was surveyed at 92 Mc/s in collaboration
with Mr D. Walsh using the 218 ft transit radio telescope. The aerial beam-
width to half power was 3\degree.2 in declination and 3\degree.0 in right ascension. Two
transits of the region were taken at fixed declinations at intervals of 2\degree.5 in the
range Dec. = 32\degree to 48\degree. The brightness temperature scale is that derived in
Section 4. Again, the zero level is the lowest observed within 50\degree of the galactic
plane. The final map is shown in Fig. 2(c) and indicates that there are no side-
lobes of Cygnus-A greater than 2 per cent.

3. Observations of the Cygnus region at the hydrogen-line frequency. (a) Equipment.—The double comparison spectrometer previously described (5) was
used in conjunction with a 30 ft paraboloid. The spectrometer bandwidth was
reduced to 18 Kc/s. A time constant of 20 seconds was used when taking spectra
and this was increased to 1.5 minutes when taking drift curves through the region
at a particular frequency. The brightness temperature scale was standardized
against the peak temperature at \ell = 50\degree and \b = 0\degree, taken as 100 \degree/K.

(b) Spectra.—It is necessary to obtain the absorption spectrum of the Cygnus-X
radio source in order to determine its distance. This involves deriving two spectra
characteristic of Cygnus-X; the first is the spectrum actually observed in the
direction of the source, \Tb (\nu), and the second is the spectrum of the background
neutral hydrogen emission, \Th (\nu), expected if the source were not present.
The difference between \Th (\nu) and \Tb (\nu) is the difference or absorption spectrum \TD (\nu).
The determination of \TD (\nu) involves an extrapolation of the spectra taken in the
vicinity of Cygnus-X.

Since the source is elongated across the galactic plane, sets of spectra were
taken along a line parallel to the galactic plane, i.e. across the source. This
procedure has the added advantage that the hydrogen-line spectra change less
sharply with change in distance along such a line and interpolation across the
source is more trustworthy. An attempt was made to obtain \TD (\nu) at Dec. = 40\degree.5
and R.A. = 20\degree.28\degree, near the centre of Cygnus-X. Spectra were accordingly

* Dr Hazard kindly assisted with the interpretation of these results.
taken at the following points along a line: Dec. = 36°, R.A. = 20\textdegree\ 19\textprime; Dec. = 38°5, R.A. = 20\textdegree\ 24\textprime; Dec. = 40°5, R.A. = 20\textdegree\ 28\textprime; Dec. = 42°5, R.A. = 20\textdegree\ 32\textprime; and Dec. = 45°, R.A. = 20\textdegree\ 38\textprime.; Smoothed curves through one such set of spectra are shown in Fig. 3. The spectra show the existence of 3 spiral arms in the direction of Cygnus-X. In addition there is a frequency drift with declination which is different for each spiral arm. It can be seen that the spectrum at the position of the source, $T_B(\nu)$, is clearly reduced at the frequency of the first and second spiral arms. The spectrum $T_B(\nu)$ was derived by interpolating, both with respect to position and frequency, between spectra on opposite sides of the source. $T_D(\nu)$ is then obtained by subtraction of $T_B(\nu)$ from $T_B(\nu)$.

Four sets of spectra were obtained at these coordinates with the spectrometer and then averaged to give the full line curves of $T_B(\nu)$ and $T_D(\nu)$ shown in Fig. 4. The standard deviation of any point on these curves for $T_B(\nu)$ and $T_D(\nu)$ is $\pm 3$ K.
The difference spectrum $T_D(v)$ shows (a) clear absorption in the nearby spiral arm, (b) a fall in temperature in the second spiral arm greater than the observed brightness temperature of Cygnus-X, and (c) no absorption greater than the limits of error in the outer arm. The Cygnus-X source must accordingly lie nearer to the Sun than the outer arm and it exhibits a value of $T_D(v)$ for the second spiral arm which is anomalous (see Section 5).

(c) Drift curves.—In order to investigate the difference spectrum of Cygnus-X more fully, and in particular to confirm the anomalous value of $T_D(v)$ in the second spiral arm, this spectrum was derived from a different set of observations. Accordingly, drift curves were taken at the declination of Cygnus-X and at adjacent declinations with the spectrometer set at given frequencies. These curves were normally taken at Dec. = $36^\circ$, $38^\circ\cdot5$, $40^\circ\cdot5$, $42^\circ\cdot5$, $45^\circ$ and $47^\circ$. Since the frequency of a given spectral component changes with declination the frequency setting at each declination was always chosen to be similarly placed relative to the spiral arm under investigation, e.g., in order to obtain $T_D(v)$ for Cygnus-X at the mid-frequency of the second spiral arm, the drift curves were taken at the mid-frequency of the second spiral arm at each declination. One such set of drift curves has been smoothed and is shown in Fig. 5(a). The contours of $T_D(v)$ over the Cygnus-X

Fig. 5 (a).—A set of drift curves taken at the centre frequency of the second spiral arm in Cygnus.

Fig. 5 (b).—Interpolation of $T_D(v)$ (broken line) across the Cygnus-X region at this frequency. $T_D(v)$ is shown full-line.
region for a given frequency are derived by interpolation across the region along lines of galactic longitude. Fig. 5(b) illustrates the interpolation procedure applied to the drift curves of Fig. 5(a) at four different galactic latitudes which pass through Dec. = 40°·5 at the right ascensions given; the interpolated brightness temperature, $T_B(\nu)$, is plotted as a broken line and the observed value of $T_B(\nu)$ is plotted full-line. The derived contour map of $T_D(\nu)$ at the mid-frequency of the second spiral arm is plotted in Fig. 5(c). It can be seen that the contours of $T_D(\nu)$ are similar in shape* to those of the continuum emission from Cygnus-X plotted in Fig. 2(a) taken with the same aerial at a nearby frequency in the continuum.

This procedure was repeated at 20 frequencies in the neutral hydrogen spectrum of the Cygnus-X region. The map of $T_D(\nu)$ for each frequency was similar in shape to that in Fig. 5(c). The values of $T_D(\nu)$ and $T_B(\nu)$ at Dec. = 40°·5, R.A. = 20h 28m for each map are plotted as crosses on Fig. 4 in order to give a comparison with the results of the previous method. The scatter in the crosses gives a measure of the errors involved in interpolation; the difference between the results of the two methods lies within the errors of each. Moreover, the large value of $T_B(\nu)$ at the frequency of the second spiral arm is confirmed and its value at the centre frequency appears to be 34° ± 2°K. The corresponding value of $T_B(\nu)$ is 64°K.

(d) The distribution of neutral hydrogen in the spiral arms in Cygnus.—The distribution in right ascension of the brightness temperature of neutral hydrogen in Cygnus is given by the interpolated plots of $T_B(\nu)$ already derived for Dec. = 40°·5. The optical depth, $\tau(\nu)$, of the neutral hydrogen at each point in the distribution may be obtained from the value of $T_B(\nu)$ at that point using

$$T_B(\nu) = T_K(1 - e^{-\tau(\nu)})$$

(1)

where $T_K$ is the kinetic temperature and is assumed† to be 125°K. The distribution of neutral hydrogen in each spiral arm may be expressed in terms of the

* The relatively smaller values of $T_D(\nu)$ at the position of Cygnus-A are expected (see Section 5) since Cygnus-A is 5° from the "radio" galactic plane where the optical thickness of the neutral hydrogen is about half that at the position of Cygnus-X.

† This assumption may not be justified for the outer spiral arms (see Section 5).
number of neutral hydrogen atoms per cm$^2$ in the line of sight ($= \int N_H \cdot dl$) at each point on the distribution. It can be shown (7) that

$$\int N_H \cdot dl = 4.62 \times 10^{13} \tau_0 \eta T_K$$

(2)

where $\tau_0$ is the optical depth at the centre frequency of an arm and $\eta$ is the half width of the $\tau$ spectrum of the spiral arm.

The distribution of $\int N_H \cdot dl$ across each of the three spiral arms is given in Fig. 6 along with the brightness temperature distribution across Cygnus-X at 1425 Mc/s. It can be seen that the neutral hydrogen is more broadly distributed in right ascension than is the emission from Cygnus-X. In addition, all four distributions show the same sharp rise and slow fall with increasing right ascension. The shape and position of each distribution is summarized in Table I.

![Diagram showing the distribution of $\int N_H \cdot dl$ across the three spiral arms in Cygnus. The brightness distribution across Cygnus-X at 1425 Mc/s is also shown.]

**Table I**

<table>
<thead>
<tr>
<th>Arm</th>
<th>Distance (kpc)</th>
<th>Position of peak intensity (R.A.)</th>
<th>$\int N_H \cdot dl$ at peak (cm$^{-2}$)</th>
<th>Width between half values</th>
</tr>
</thead>
<tbody>
<tr>
<td>First spiral arm</td>
<td>0.4</td>
<td>20h 20m 5</td>
<td>17 x 10$^{21}$</td>
<td>11°5</td>
</tr>
<tr>
<td>Second</td>
<td>5.8</td>
<td>20h 20m</td>
<td>4.5 x 10$^{21}$</td>
<td>9°5</td>
</tr>
<tr>
<td>Third</td>
<td>10.0</td>
<td>20h 20m</td>
<td>4.3 x 10$^{21}$</td>
<td>9°5</td>
</tr>
<tr>
<td>Cygnus-X</td>
<td>10.0</td>
<td>20h 20m</td>
<td>4.3 x 10$^{21}$</td>
<td>5°5</td>
</tr>
</tbody>
</table>

4. *An analysis of the radio continuum measurements in Cygnus.* (a) *A determination of the galactic background spectrum and distribution.*—Before an estimate can be made of the radio emission from Cygnus-X it is necessary to determine the contribution due to the galactic background. Seven surveys of the Cygnus region have been made with beamwidths of 3° or less; 92, 158 and 1425 Mc/s (Jodrell Bank), 242 Mc/s (8), 400 Mc/s (9), 600 Mc/s (10) and 900 Mc/s (11).
These were used to determine the distribution of background emission at Dec. = $40^\circ\cdot5$, the declination of Cygnus-X. An examination of the seven radio maps showed that the background distribution changed only slowly with galactic longitude through the position of Cygnus-X and was nearly the same on either side of it. The distribution at Dec. = $40^\circ\cdot5$ was accordingly derived by smooth interpolation from either side of the source. The observed radio galactic plane (defined as the line of peak intensity) in this region is at $+0^\circ\cdot5$ galactic latitude (defined by the Lund pole). The brightness temperature, $T_B'$, at each frequency is obtained by a comparison with the intensity of the Cygnus-A source and is given by the equation

$$T_B' = \frac{\mu a_0 S}{2k} \cdot \frac{P(b-g)}{P(Cyg-A)}$$

where $\mu$ represents the fraction of the energy falling into the main lobe compared with that falling into the area containing the major side lobes ($\pm 4$ beam widths from the main lobe), $a_0$ is the physical area of the aerial, $S$ is the flux density of Cygnus-A derived from a recent study by Adgie and Whitfield, kindly supplied in advance of publication, $k$ is Boltzmann's constant, and $P(b-g)$ and $P(Cyg-A)$ are the chart deflections of the background and Cygnus-A respectively. $\mu$ and $a_0$ are given in Table II.

<table>
<thead>
<tr>
<th>Frequency (Mc/s)</th>
<th>$a_0$ (m$^2$)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>3485</td>
<td>1.0</td>
</tr>
<tr>
<td>158</td>
<td>3485</td>
<td>0.85</td>
</tr>
<tr>
<td>242</td>
<td>327</td>
<td>1.0</td>
</tr>
<tr>
<td>400</td>
<td>490</td>
<td>1.0</td>
</tr>
<tr>
<td>600</td>
<td>94.3</td>
<td>1.0</td>
</tr>
<tr>
<td>900</td>
<td>44.4</td>
<td>1.0</td>
</tr>
<tr>
<td>1425</td>
<td>65.9</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The resultant brightness temperature distribution is plotted for each frequency in Fig. 7. Furthermore, the peak brightness temperature of each distribution is plotted against frequency on a log–log scale in Fig. 8; the best-fitting spectral law is $T_B' \propto \nu^{-2.24 \pm 0.16}$.

(b) The brightness temperature distribution across Cygnus-X.—The background component of galactic radiation derived above can now be removed from the observed intensity contours in the region of Cygnus-X. Then, after the removal of the effect of Cygnus-A, the emission from Cygnus-X itself remains. However, there is some uncertainty in plotting the faint preceding edge of Cygnus-X owing to the proximity of the intense Cygnus-A source. Maps of Cygnus-X at the seven frequencies are plotted in Fig. 9 along with the aerial polar diagram used at each frequency. The shape of Cygnus-X is seen to be similar at all frequencies, apart from the effect of aerial smoothing. A comparison of detailed structure not readily seen in the maps is provided in Fig. 10, which plots the brightness temperature distribution across the source in right ascension at Dec. = $40^\circ\cdot5$.

The source covers $12^\circ$ in right ascension, with a width of $5^\circ\cdot5$ between half intensity points. It shows broad maxima at R.A. = $20^h\ 24^m$, $20^h\ 36^m$ and $20^h\ 48^m$ on the highest resolution surveys. The extension of the source in declination is
Fig. 7.—The brightness temperature distribution of the galactic background emission at Dec. = 46°.5 at 7 different frequencies.

Fig. 8.—The spectrum of the peak of the galactic background radiation in Cygnus.
Fig. 9.—Brightness temperature maps of Cygnus-X at 7 frequencies. The aerial polar diagrams used at each frequency are also shown.
less than in right ascension and may be obtained, after correction for aerial
smoothing from the relation *

$$A^2 = O^2 - B^2$$

(4)

where $A$, $O$ and $B$ are the half power widths of the actual and observed dis-
butions across the source and the aerial beam respectively. The half power
width of the resultant declination distribution averages $2^\circ\cdot5$ over the frequency
range; there is some indication that the source width may vary from $3^\circ$ at the low
frequencies to $2^\circ$ at the high frequencies, although such an effect is close to the
limits of error.

(c) The spectrum of Cygnus-X.—The flux density of the total Cygnus-X
complex can be compared directly with the flux density of the Cygnus-A source

<table>
<thead>
<tr>
<th>Frequency (Mc/s)</th>
<th>Flux of Cygnus-X</th>
<th>Flux of Cygnus-A</th>
<th>Standard flux density of Cygnus-A ($\times 10^{24}$ W/m$^2$/c/s)</th>
<th>Estimated flux density of Cygnus-X ($\times 10^{24}$ W/m$^2$/c/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>0.42</td>
<td></td>
<td>118</td>
<td>49</td>
</tr>
<tr>
<td>158</td>
<td>0.67</td>
<td></td>
<td>87</td>
<td>58</td>
</tr>
<tr>
<td>242</td>
<td>0.97</td>
<td></td>
<td>62</td>
<td>60</td>
</tr>
<tr>
<td>400</td>
<td>1.2</td>
<td></td>
<td>43</td>
<td>52</td>
</tr>
<tr>
<td>600</td>
<td>1.6</td>
<td></td>
<td>29</td>
<td>47</td>
</tr>
<tr>
<td>900</td>
<td>1.4</td>
<td></td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>1425</td>
<td>2.6</td>
<td></td>
<td>13</td>
<td>37</td>
</tr>
</tbody>
</table>

* This relation is correct for Gaussian distributions.
by integration of the intensity contours of the two sources. The relative flux densities are given in Table III for the seven frequencies. The best estimate of the flux density of Cygnus-X is then obtained, applying the standardized flux density spectrum for Cygnus-A used above.

Table III suggests that the flux density of Cygnus-X is some 20 per cent greater at low than at high frequencies; however, this difference is scarcely significant since uncertainties in specifying the background distribution at the lower frequencies could lead to such errors. The mean flux density of the Cygnus-X complex is \(47 \times 10^{-24}\) W/m\(^2\)/c/s.

A second and independent method of specifying the spectrum of Cygnus-X is to measure the brightness temperature of a given region of the source at different frequencies. The brightness temperature of the most intense part of the source (Dec. = 40°, R.A. = 20\(^{\circ}\)25\(^{m}\)) at each frequency is given in the second column of Table IV.

### Table IV

<table>
<thead>
<tr>
<th>Frequency (Mc/s)</th>
<th>Observed temperature (°K)</th>
<th>Aerial dilution factor</th>
<th>Derived temperature (°K)</th>
<th>(T) (1000 Mc/s) (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>2200</td>
<td>1.3</td>
<td>2900</td>
<td>34</td>
</tr>
<tr>
<td>158</td>
<td>1400</td>
<td>1.2</td>
<td>1700</td>
<td>42</td>
</tr>
<tr>
<td>242</td>
<td>140</td>
<td>3.0</td>
<td>420</td>
<td>25</td>
</tr>
<tr>
<td>400</td>
<td>210</td>
<td>1.2</td>
<td>250</td>
<td>39</td>
</tr>
<tr>
<td>600</td>
<td>53</td>
<td>1.5</td>
<td>81</td>
<td>29</td>
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<tr>
<td>900</td>
<td>23</td>
<td>1.8</td>
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<td>35</td>
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<tr>
<td>1425</td>
<td>16</td>
<td>1.2</td>
<td>19</td>
<td>38</td>
</tr>
<tr>
<td>3200</td>
<td>4</td>
<td>1.0</td>
<td>4</td>
<td>40</td>
</tr>
</tbody>
</table>

Included in the table is a value of 4° at 3,200 Mc/s; the value given by Haddock, Mayer, and Sloanaker (12) was converted to a brightness temperature and then reduced by 1 °K to allow for the background contribution at this frequency (see Fig. 8). In order to derive the actual brightness temperature of the source at each frequency, the reduction in temperature by the aerial beamwidths is first calculated. Column 3 of Table IV gives for each frequency this dilution factor which was obtained by a method of graphical integration; Column 4 gives the derived brightness temperature; each value is reduced to that expected at 1000 Mc/s assuming a \(T_B' \propto \nu^{-2}\) spectrum * and is given as \(T(1000 \text{ Mc/s})\) in the table. \(T(1000 \text{ Mc/s})\) has a mean value of 35 °K and shows no significant variation with frequency.

\(d)\) The fine-structure of Cygnus-X.—Information relating to the fine structure within the Cygnus-X complex was derived from interferometer observations taken at Jodrell Bank. A swept-lobe interferometer operating at 158 Mc/s with a spacing of 56 \(\lambda\) showed no feature less than 1° diameter with an intensity greater than 15 per cent of the peak value of Cygnus-X †.

These results were confirmed by a search for scintillations on the 92 and 158 Mc/s records. At the time of large fluctuations on Cygnus-A no fluctuations

* If this spectrum arises from free-free emission from ionized hydrogen at \(10^4\) °K, the finite optical depth at the lowest frequency would cause an apparent reduction in the value of \(T(1000 \text{ Mc/s})\) by approximately 15 per cent.

† Data kindly supplied by Dr H. P. Palmer.
greater than 15 per cent of Cygnus-X could be detected. Fluctuations would occur for a source having angular dimensions much less than the angular extent of the small dimension of an ionospheric irregularity; this is taken as $0'.4$.

5. Interpretation of results.

(i) The radio results.—Measurements at the hydrogen-line frequency show a fall in the observed brightness temperature at the peak of Cygnus-X of $16^\circ, 34^\circ$ and $0'.4$ in the first, second and third spiral arms respectively. These results may be compared with the fall in temperature, $\Delta T(v)$, expected when the continuous radiation of a source of brightness temperature $T_S'$ passes through a spiral arm of optical depth $\tau(v)$ at a frequency $v$

$$\Delta T(v) = T_S'(1 - e^{-\tau(v)}) = \frac{T_S' \cdot T_B(v)}{T_K}$$

The maximum value of $\Delta T(v)$ is $T_S'$ (which is $16^\circ K$) and occurs when the spiral arm is optically thick. Accordingly, for the first spiral arm where $T_B(v)$ is $117^\circ$ at the peak frequency and assuming $T_K$ to be $125^\circ K$, $\Delta T(v)$ is expected to be $15^\circ K$ at this frequency, if Cygnus-X lies behind this arm. The observed value is consistent with this picture, and moreover the distribution of $\Delta T(v)$ and $T_B(v)$ with frequency are similar, as expected.

On the other hand, the observed value of $\Delta T(v)$ in the second spiral arm is twice the value expected on the above picture. This result cannot then be interpreted in terms of an absorption effect alone. However, all the available data may be explained satisfactorily by supposing that hydrogen in the neutral state has been removed from the position of Cygnus-X. Arguments will now be presented which suggest strongly that a large fraction of the neutral hydrogen in the second spiral arm has been ionized to produce the Cygnus-X complex of H II regions.

(a) The contours of the deficiency of neutral hydrogen emission, $T_B(v)$, and consequently of neutral hydrogen itself (if $\Delta \tau(v) < 1$), are similar to the emission contours of the Cygnus-X complex. Hence the two phenomena are related. Such an effect is expected if the original neutral hydrogen atoms have been ionized and are now radiating by the process of free–free emission. Since the neutral hydrogen emission from unit cross-sectional area is proportional to $\int N_H \cdot dl$ and the free–free emission is proportional to $\int N_e^2 \cdot dl$ there may be differences in the two contours if $N_H$ and consequently $N_e$ are not constant over the whole extent of the Cygnus-X source. $N_H$ will begin to fall near the outer edges of a spiral arm, which, in the case of the second spiral arm in Cygnus, is beyond the R.A. limits of the Cygnus-X source. Consequently the contours of $T_B(v)$ (or more accurately $\Delta \tau(v)$) are likely to be similar to the contours of the brightness temperature (or more accurately the optical depth) of the free–free emission from the associated source.

(b) The spectrum of the Cygnus-X complex is that of an H II region since its flux density is constant within the limits of error, having the value $4.7 \times 10^{-23} \text{W/m}^2/\text{c/s}$. Moreover, for an H II region the optical depth, $\tau'(v)$, is proportional to $v^{-2}$ so the brightness temperature of the source is given by

$$T_S'(v) = T_e(1 - e^{-\tau'(v)})$$

$$= T_e \cdot \tau'(v) \text{ for } \tau'(v) \leq 0'.4 \text{ say.}$$

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For the frequency range used in this investigation \( \tau'(\nu) < 0.4 \) if we assume the electron temperature, \( T_e \), is \( 10^4 \,^\circ\text{K} \), and consequently

\[
T_s'(\nu) \cdot \nu^2 = \text{constant}.
\]  

(7)

As is seen from the last column of Table IV this quantity has the average value \( 3.5 \times 10^{19} \,^\circ\text{K} \,\text{sec}^{-2} \) for the peak of the Cygnus-X complex. Its constant value over the frequency range confirms the \( \text{HII} \) region nature of the source.

(c) The density and depth of the assumed \( \text{HII} \) region and of the neutral hydrogen deficiency are compatible and lead to acceptable values of these quantities. This can be shown as follows with the simplifying assumptions that the hydrogen density is the same throughout the volume of Cygnus-X.

The optical depth of an \( \text{HII} \) region with electron density \( N_e \) and depth \( l \) is given by (13)

\[
\tau'(\nu) = 0.53 \, T_e^{-3/2} \nu^{-2} N_e^2 l \times 10^6
\]  

(8)

where \( l \) is measured in parsecs.

Whence the emission measure

\[
\text{E.M.} = N_e^2 l = 1.89 \times 10^{-6} \cdot T_e^{12} (T_s'(\nu) \nu^2)
\]  

(9)

The emission measure for the peak of the Cygnus-X source has the value 6,600 for \( T_e = 10^4 \,^\circ\text{K} \); it will not vary markedly with \( T_e \). This relation between \( N_e \) and \( l \) will be compared with a similar relation for the neutral hydrogen.

The line integral of the neutral hydrogen removed from the second spiral arm at the peak of Cygnus-X can be estimated from the expected brightness temperature, \( T_B(\nu) \), of 64 \,^\circ\text{K} \) and the observed brightness temperature, \( T_s(\nu) \), of 30 \,^\circ\text{K} \). Now,

\[
T_B(\nu) = T_K (1 - e^{-\tau'})
\]  

(10)

where \( T_K \) is the kinetic temperature of the neutral hydrogen. Then, if \( T_B(\nu) \) is reduced to \( T_s(\nu) \) by the removal of neutral hydrogen of optical depth \( \Delta \tau(\nu) \), it can be shown that

\[
\Delta \tau(\nu) = \ln \frac{T_K - T_s(\nu)}{T_K - T_B(\nu)}
\]  

(11)

Furthermore the line integral of the neutral hydrogen which has been removed will be given by (see equation (2)),

\[
N_H \cdot l = \Delta \tau(\nu) \cdot T_K \eta \times 1.54 \times 10^{-5}
\]  

(12)

where \( l \) is measured in parsecs; \( \eta \) is 10 km/sec for \( T_B(\nu) \) in the second spiral arm.

Accordingly the estimate of \( N_H \cdot l \) is dependent upon the kinetic temperature of neutral hydrogen in the Cygnus-X region. The value of \( T_K \) found for the inner parts of the Galaxy is 125 \,^\circ\text{K} \) (14) but there is some evidence of strong local variations (15). In the case of the two outer spiral arms in Cygnus the brightness temperature nowhere reaches 80 \,^\circ\text{K} \); this represents a possible lower limit of \( T_K \).

Table V illustrates the variation of \( N_H \cdot l \) with \( T_K \) in the range 80° to 125° K.

<table>
<thead>
<tr>
<th>( T_K ) (°K)</th>
<th>( \Delta \tau(\nu) )</th>
<th>( N_H \cdot l ) (cm(^{-2}) parsecs)</th>
<th>( N_e = N_H ) (cm(^{-3}))</th>
<th>( l ) (parsecs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>1.14</td>
<td>1410</td>
<td>6.6</td>
<td>310</td>
</tr>
<tr>
<td>100</td>
<td>0.66</td>
<td>1020</td>
<td>6.5</td>
<td>160</td>
</tr>
<tr>
<td>125</td>
<td>0.44</td>
<td>850</td>
<td>7.8</td>
<td>110</td>
</tr>
</tbody>
</table>

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Now if the ionized hydrogen is derived from the neutral hydrogen removed from the second spiral then $N_e$ and $N_H$ may be equated and equations (9) and (12) will yield the estimates of $N_e$, $N_H$ and $l$ given in Table V for different values of $T_K$. Thus the suggestion that the HII region can be identified with the neutral hydrogen deficiency leads to no contradictions, and it will be shown that it results in quite acceptable values of $N_e$, $N_H$ and $l$.

The depth of the region $l$ can be compared with the transverse dimensions of the Cygnus-X complex at the distance of the second spiral arm (6 kpc); the half-intensity dimensions are 270 parsecs by 600 parsecs. The neutral hydrogen density is perhaps a factor of two greater than is normally found in the centre of spiral arms (14), but it is not excessive. Moreover the number of neutral hydrogen atoms per cm$^2$ in a line through Cygnus-X is about $3 \times 10^{21}$ compared with $2 \times 10^{22}$ for the Cygnus region and $1 - 2 \times 10^{22}$ elsewhere in the galactic plane (14). The mass of the Cygnus-X complex ranges from $8 - 11 \times 10^6$ solar masses for the range of $T_K$ in Table V. It would correspond to $1 - 9 - 2 - 7 \times 10^6$ solar masses if at a reduced distance of 3 kpc and may be compared with the galactic mass of $1 - 6 \times 10^{11}$ solar masses (16).

(d) The brightness distribution across the Cygnus-X complex is that expected from an HII region rather than an aggregate of "point" sources. The results of Section 4(d) showed that only a small amount of the radiation of the Cygnus-X complex could arise from intense regions of the order of 10' - 20' of arc in diameter. The source would appear to be irregular in shape and to show only smooth variations in intensity across its area.

(e) Further evidence for the HII nature of Cygnus-X comes from the 22 Mc/s survey by Burke (17) which shows that "this area of the sky is less bright than a suitable average over the remaining sky". Such an effect is expected if the kinetic temperature of the HII region is less than the brightness temperature of the emission from behind the source. An extrapolation of the spectrum in Fig. 8 indicates that the brightness temperature of the total background component at 22 Mc/s will be of the order of 25 000 °K compared with a likely kinetic temperature of the Cygnus-X HII region of 10 000 °K. Thus the Cygnus-X region would absorb the high temperature background radiation and appear cooler than its surroundings at 22 Mc/s.

(ii) Optical studies of the Cygnus-X region.—This region of Cygnus is rich with HII regions interspersed with dust clouds. However a direct identification between HII regions and parts of the Cygnus-X complex will be difficult because of the heavy obscuration amounting in places to 7 magnitudes (18). Nevertheless recent studies (19, 20) of early type stars in Cygnus reveal a likely origin of the intense ionization required. A catalogue of the types of O-star given by Hiltner and Johnson (20) within the boundary of Cygnus-X is given in Table VI. These stars lie beyond the Cygnus Rift at 700 parsecs (21). The value of the quantity

<table>
<thead>
<tr>
<th>Star type</th>
<th>Number of stars within Cygnus-X complex</th>
<th>$\int N_e^2 \cdot dV$ for one star</th>
<th>$\int N_e^2 \cdot dV$ for all stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>05</td>
<td>5</td>
<td>$3'4 \times 10^{62}$</td>
<td>$17'0 \times 10^{62}$</td>
</tr>
<tr>
<td>06</td>
<td>6</td>
<td>$1'6 \times 10^{62}$</td>
<td>$9'6 \times 10^{62}$</td>
</tr>
<tr>
<td>07</td>
<td>8</td>
<td>$0'81 \times 10^{62}$</td>
<td>$6'5 \times 10^{62}$</td>
</tr>
<tr>
<td>08</td>
<td>8</td>
<td>$0'35 \times 10^{62}$</td>
<td>$2'8 \times 10^{62}$</td>
</tr>
<tr>
<td>09</td>
<td>13</td>
<td>$0'12 \times 10^{62}$</td>
<td>$1'6 \times 10^{62}$</td>
</tr>
</tbody>
</table>
$\int N_e^2 \, dV$ integrated over the volume $V$ ionized by each star type was estimated from the data of Strömgren (21) and is given in the third column.

The total value of $\int N_e^2 \, dV$ for all these stars is $3.7 \times 10^{63}$ cm$^{-3}$. An estimate of this quantity can be derived from the flux density measurements of Cygnus-X in the continuum. It can be shown that for free–free emission from an H II region

$$\int N_e^2 \, dV = \frac{c^2 T_e^{1/2}}{\sigma_{354} k} D^2 \cdot S$$

(13)

where $c$ = velocity of light
$T_e$ = electron temperature, taken as $10^4 \, ^\circ \text{K}$
$k$ = Boltzmann’s Constant
$D$ = distance of the source
$S$ = flux density of the source in c.g.s. units.

For the source at 3 kpc and 6 kpc the values of $\int N_e^2 \, dV$ are $7.1 \times 10^{68}$ and $2.8 \times 10^{64}$ cm$^{-3}$ respectively. Hence the stars already classified can produce a substantial fraction of the ionization required. Most of these stars are found within the preceding half of Cygnus-X; the following half is much more heavily obscured.

An early-type star cluster, 1/2° in diameter and called VI Cygni, has been discovered within the boundary of Cygnus-X at Dec. = 41° and R.A. = 20h 29m (18, 23, 24.) This cluster, provisionally placed at 2 kpc, shows absorption up to 7 magnitudes and colour excesses up to 3 on the $B–V$ index (25). 20 members have been classified as O-type and another 65 fainter members are shown, in low dispersion spectral surveys (26), to have similar spectra. The 14 stars classified would give an emission measure (27) of 2800* if $N_e$ were taken as 4 (see Table V). The radio surveys indeed show a peak in this position and the emission measure appears to be 4000. This difference in emission could readily be accounted for by the unclassified stars of the cluster.

6. Conclusion.—The above analysis shows that Cygnus-X is not the integrated effect of radio sources following the Cygnus spiral arms as defined by the neutral hydrogen measurements. The shape, extent and spectrum are inconsistent with such an hypothesis. The continuum measurements indicate that the source is an H II complex; this suggestion is confirmed by a marked absence of neutral hydrogen within the contours of the source. This neutral hydrogen effect occurs in the second spiral arm at an apparent distance of 6 kpc. Optical observations show a concentration of O stars in the section of the Galaxy between $l = 40^\circ$ and $48^\circ$ and the stars already catalogued could provide a large amount of the observed H II emission if they were within the hydrogen of a spiral arm. The VI Cygni O-star cluster, 1/2° in diameter, is most likely responsible for the observed emission maximum at Dec. = 41° and R.A. = 20h 29m. However, the measured distances of the radio and optical phenomena do not agree closely; this does not invalidate the above results since neither measurement is capable of great accuracy in this region. It is concluded that the Cygnus-X source can probably be identified with the H II regions likely to be produced by the observed concentration of O-type stars.

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* By virtue of the heavy absorption this would be reduced in the optical range to about 30 which is on the limits of detection, even in a clear part of the sky (28).
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Jodrell Bank Experimental Station:
1957 June 20.

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