

The Cygnus X Region XI. Map of Visual Extinction A_V

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Summary. Optical observations of the H α emission and observations of the continuum emission at 2695 MHz have been used to derive the distribution of visual extinction A_V across the Cygnus X complex. Maps of convolved $S_{H\alpha}$, T_b and A_V are presented and discussed.

Key words: Cygnus X — visual extinction A_V

I. Introduction

In an earlier paper of this series (Dickel et al., 1969, Paper V) we presented a catalogue of the optical nebulosities in the Cygnus X complex and estimated the surface brightness of their H α emission from Schmidt plates taken through an H α filter. Radio observations of the complex at 2695 MHz were published in Paper VI (Wendker, 1970) and used with the optical data to derive the approximate visual extinction and distances to the sources. The local spiral structure based on these early results was discussed at IAU Symposium 38 on spiral structure (Dickel et al., 1970). More recently we completed the detailed absolute calibration and analysis of the optical data (Dickel and Wendker, 1977, Paper VIII) which we use in the current investigation to construct a map of the distribution of the visual extinction A_V throughout the complex.

When we began this observational study of the gas and dust in the Cygnus X complex we expected new and more extensive stellar observations to become available so that we could more accurately determine the distances to the H II regions. These data have not become available but in the meantime, the interstellar medium has been found to be extremely complex—formaldehyde was discovered (Snyder et al., 1969) followed by the detection of many other molecules at radio wavelengths. Emission from the dust was also observed at near and far infrared wavelengths. This has opened up investigation of the here-to-fore unexplored realm of star formation and

the evolution of massive molecular clouds. Thus our A_V determination comes at an opportune time for providing a diagnostic probe of the detailed distributions of the dust and its relation to the molecules and gas involved in active star formation. Indeed, several such papers on selected regions within the Cygnus X complex have recently been published and others are in preparation (e.g. Baars and Wendker, 1974; Wendker et al., 1975; Dickel et al., 1977; Baars et al., 1977, Paper X).

II. Derivation of the Visual Extinction A_V

1. Method

The distribution of interstellar extinction in a nebular complex is directly obtainable from a detailed comparison of optical and radio emission from the ionized hydrogen. The observed surface brightness in H α , $S_{H\alpha}$, and the observed radio brightness temperature, T_b , are both related to the emission measure $E (= \int n_i n_e dl)$ by

$$E_{H\alpha} (\text{cm}^{-6} \text{ pc}) = 114.6 S_{H\alpha}$$

$$(\text{in units of } 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sterad}^{-1})$$

and

$$E_{2695 \text{ MHz}} (\text{cm}^{-6} \text{ pc}) = 2450 T_b (\text{K}),$$

where we have adopted an electron temperature T_e of 10^4 K in the relations given by Pengelly (1964) and Oster (1961). In the absence of interstellar extinction, identical emission measures are derived from the observations. In the presence of obscuration, the amount of extinction in the visual, A_V , is obtainable from the ratio of the emission measure found from the radio, $E_{2695 \text{ MHz}}$, to that from the optical, $E_{H\alpha}$. The resulting expression for the visual extinction is

$$\begin{aligned} A_V (\text{mag}) &= 3.2 \log (E_{2695 \text{ MHz}}/E_{H\alpha}) \\ &= 4.25 + 3.2 \log (T_b/S_{H\alpha}). \end{aligned}$$

The numerical constant includes a factor of 1.28 to transform the extinction at H α into A_V . Further details may be found in Paper V (Dickel et al., 1969).

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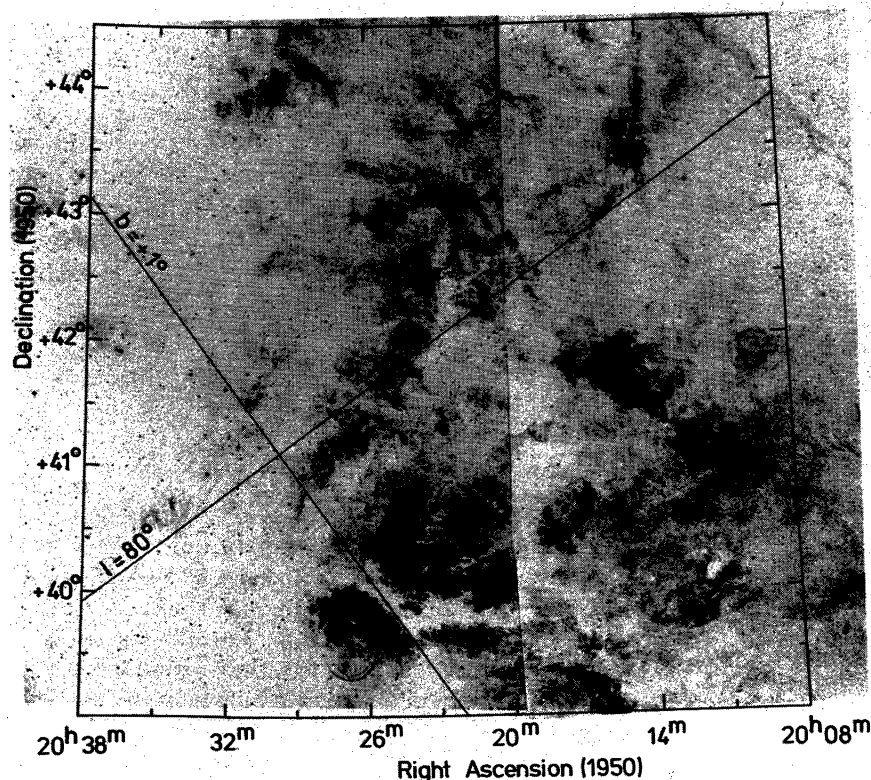


Fig. 1. Red print (courtesy of the Hale Observatories) of the area common to both the optical and radio Surveys of the Cygnus X region (Papers V and VI). Lines of constant galactic longitude and latitude are drawn for $l=80^\circ$ and $b=+1^\circ$

2. Optical Data

Our $H\alpha$ survey (Papers V and VIII) consisted of a network of 24 plates covering the optically-visible western part of the Cygnus X complex. Each plate was taken through an $80 \text{ \AA}$ wide, $H\alpha$ -interference filter on the 48-inch Schmidt telescope of the Hale Observatories. The calibration spots exposed on each plate were used to convert the digital densities into relative intensities. Calibration to obtain the absolute surface brightness, $S_{H\alpha}$, was provided by photoelectric measurements made with a spectral scanner attached to the 24-inch Morgan telescope of the Lowell Observatory. The details of the calibration and star removal, the discussion of errors, the $H\alpha$ photographs, and the $S_{H\alpha}$ contour maps were presented in Paper VIII.

The $H\alpha$ survey includes most of the region covered by the radio survey (described in the next section) and vice versa. The photograph in Figure 1 shows the region common to both for which we were able to calculate A_V . Before deriving A_V , however, we first convolved the optical data so that it had the same (gaussian) resolution ($\sim 11'$) and grid spacing ($\sim 5'$) as the radio data. The resulting map of $S_{H\alpha}$ is given in Figure 2 where one contour unit equals $10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sterad}^{-1}$. At the lowest contour of 0.5 units, the nebular signal is just above the noise. A contour level of 1 on the unconvolved maps is readily visible on the original plates. The mean error in the calibration of the $S_{H\alpha}$ is 16% (see Paper VIII).

3. Radio Data

The radio continuum survey was made with the NRAO 140-ft. telescope which had a resolution of $\sim 11'$ at 2695 MHz. The radio map in Figure 3 is adapted from Figure 1 of Paper VI. The contours are brightness temperatures (in K). Below 0.5 the values become uncertain due to lower signal-to-noise. A mean error of 6% was ascribed to the observed intensity and the mean positional error was estimated as $1'$.

4. A_V Map

The map of visual extinction derived from the above optical and radio data is given in Figure 4. We did not plot A_V for the two regions to the northwest where the signal-to-noise was low (i. e. $T_b \lesssim 0.5 \text{ K}$ and $S_{H\alpha} \lesssim 0.5 \cdot 10^{-5} \text{ c.g.s.}$) since a change of a factor of only 2 in the ratio of T_b to $S_{H\alpha}$ amounts to a difference of 1 mag in the visual extinction A_V . The A_V contours start at 1.0 mag and increase in steps of 0.5 mag with every other contour labelled. The coordinates are for epoch 1950.0. All positions referred to later in the discussion are also for epoch 1950.0.

5. Errors

Errors which affect the map of A_V as a whole are those relating to the calibration of the radio brightness tem-

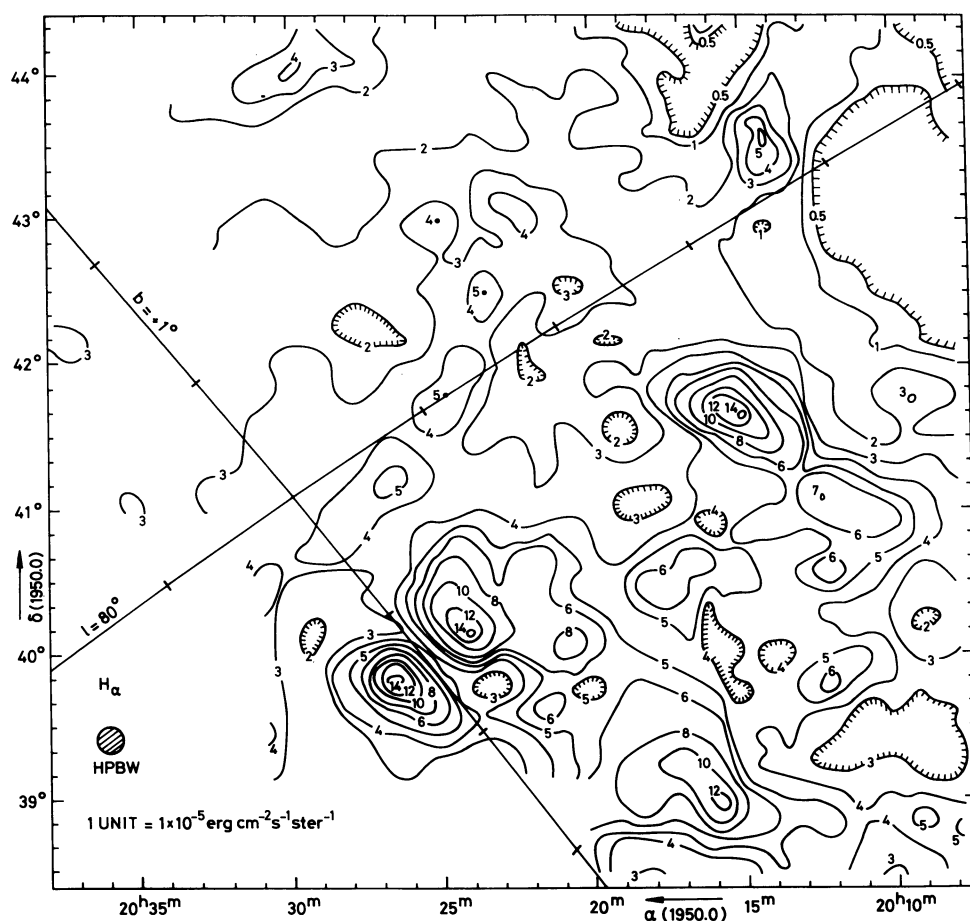


Fig. 2. Contour map of the $H\alpha$ surface brightness $S_{H\alpha}$, with an effective resolution of $11'$. The units are $10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sterad}^{-1}$. The galactic coordinates are as in Figure 1

perature at 2695 MHz ($\sim 6\%$) and of the optical surface brightness ($\sim 16\%$). These combine to give an overall uncertainty of about 0.25 mag on the map of visual extinction in Figure 4. Other errors may have been introduced by our assumption of a constant value of 0.5 for $S_{\text{NII}}/S_{H\alpha}$ and a constant value of 10000 K for T_e . A 20% increase in $S_{\text{NII}}/S_{H\alpha}$ increases A_V by only 0.1 magnitude. If a value of 7500 K rather than 10000 K is used for T_e [as was the case in our preliminary version of the A_V map for the IC 1318 b-c area by Dickel et al. (1977)], then the values of A_V are increased by 0.25 mag.

III. Discussion

1. A Remark about the Resolution

At first glance it may seem outdated to use the rather low resolution of around $11'$ when there are higher resolution radio data available (e.g. Baars and Wendker, 1974; Wendker, 1977). The purpose of this paper, however, is to point out the overall structure of the interstellar extinction in the Cygnus X area and to locate those regions which are promising candidates for future detailed observations of molecular and of infrared emis-

sion. Preliminary analysis of a 4.8 GHz survey (Wendker 1977) of this area with the Effelsberg 100 m-antenna shows that with an increase of resolution from $11'$ to $2.6'$ a critical scale length is reached where source structure suddenly appears. As a matter of fact, all sources except DR 21 show components at 4.8 GHz. The general features of the extinction would be lost in the details of the individual sources. Although this process will smooth sharp peaks considerably, we conclude that for our purpose the optimal resolution is between $10'$ and $15'$.

2. Inclusion of the Background

The unresolved background of the radio map of the Cygnus X region is entirely of thermal nature. We attribute this background to two large H II complexes: i.e. some of the Lyman continuum quanta are escaping from the IC 1318 b and c area (Baars and Wendker, 1974) and some from the Cyg OB 2 association (Huchtmeier and Wendker, 1977, Paper IX). Therefore the background intensity must be included in the calculation of A_V , rather than subtracted beforehand. In Figure 4 it can be seen that the average A_V for this background lies near 3^m .

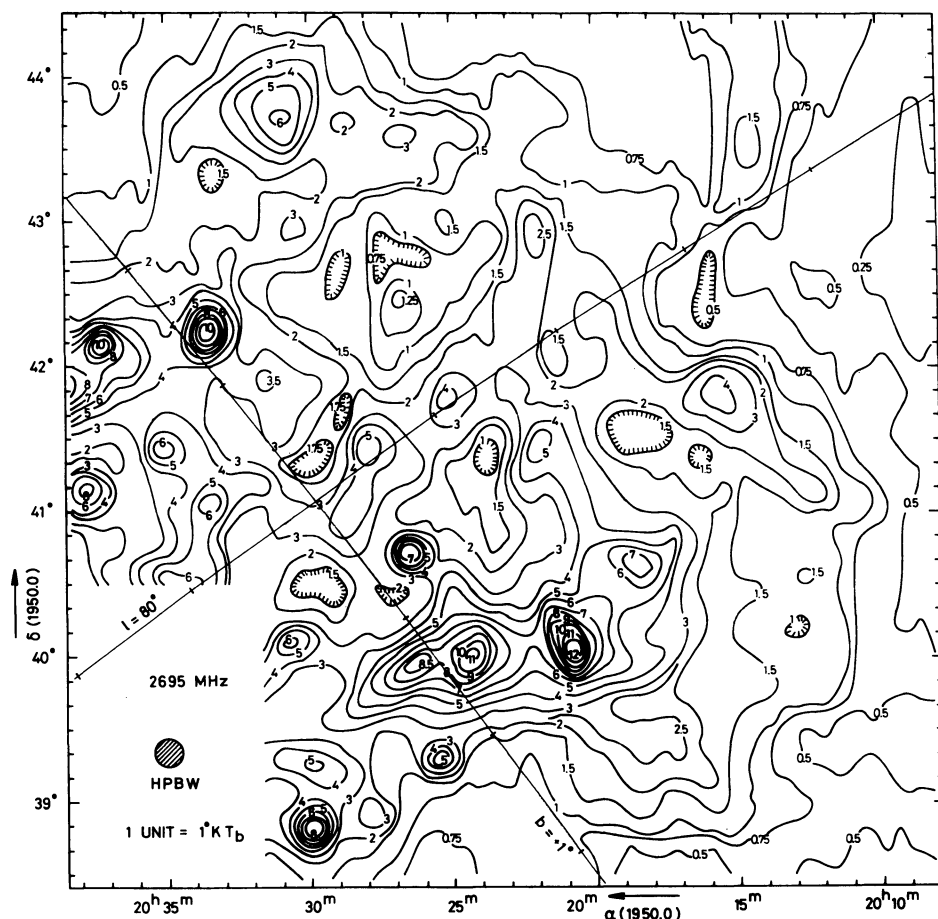


Fig. 3. Contour map of the radio brightness temperature, T_b , at 2695 MHz with the resolution of 11' (adapted from Fig. 1 of Paper VI). The units are Kelvin. The galactic coordinates are as in Figure 1

3. Overall Extinction

The extinction varies from about 1 mag in the southwest corner of the map in Figure 4 to 6.4 mag at the compact source DR 17. Near the center of the map, the general absorption appears to range between 2 and 4 mag. In the southwest at galactic longitude $l \approx 77^\circ$, A_V falls below 2 mag. Perhaps the obscuring material is less dense in this area and/or the nebulae are closer, which is consistent with the line of sight passing near the edge of the local spiral arm or spur. In the northwest above galactic latitude $b \approx 4^\circ$ where the long optical streamers are seen, both the optical and radio brightness are low so that A_V is ill-determined.

4. Distances

The procedure for determining distances was discussed in detail in Paper V. Basically our derivation of A_V assumes that both the $H\alpha$ and radio radiation are generated in the same volume of space so that the extinction is all from foreground material in front of the source. Ikhsanov (1959) derived curves of the mean extinction as a function of distance from stellar data in eight extended re-

gions covering most of the Cygnus X complex. Thus for every given H II region, for which we have determined A_V , we can find the corresponding distance d . The main difference between the current distance determination and the earlier one is that we now have improved values of A_V everywhere in the form of a calibrated map.

Another, basically interpretative, difference which does not change the distance derived earlier, will now be discussed. As mentioned in the introduction and amplified in the following sections, there is mounting evidence that much of the extinction shown in Figure 4 is due to dust within molecular clouds associated with the H II regions themselves and, especially where the H II regions are visible optically, much of the dust and the associated molecules are located just behind or to one side to the H II regions. Thus, the appropriate A_V 's to use in conjunction with Ikhsanov's curves to derive the distance to the H II regions are the lower values found toward the optical nebulosities and not, for example, the highest A_V found in a dust lane such as between IC 1318 b and c. The distance to the H II region is effectively the minimum distance to the associated molecular-dust cloud.

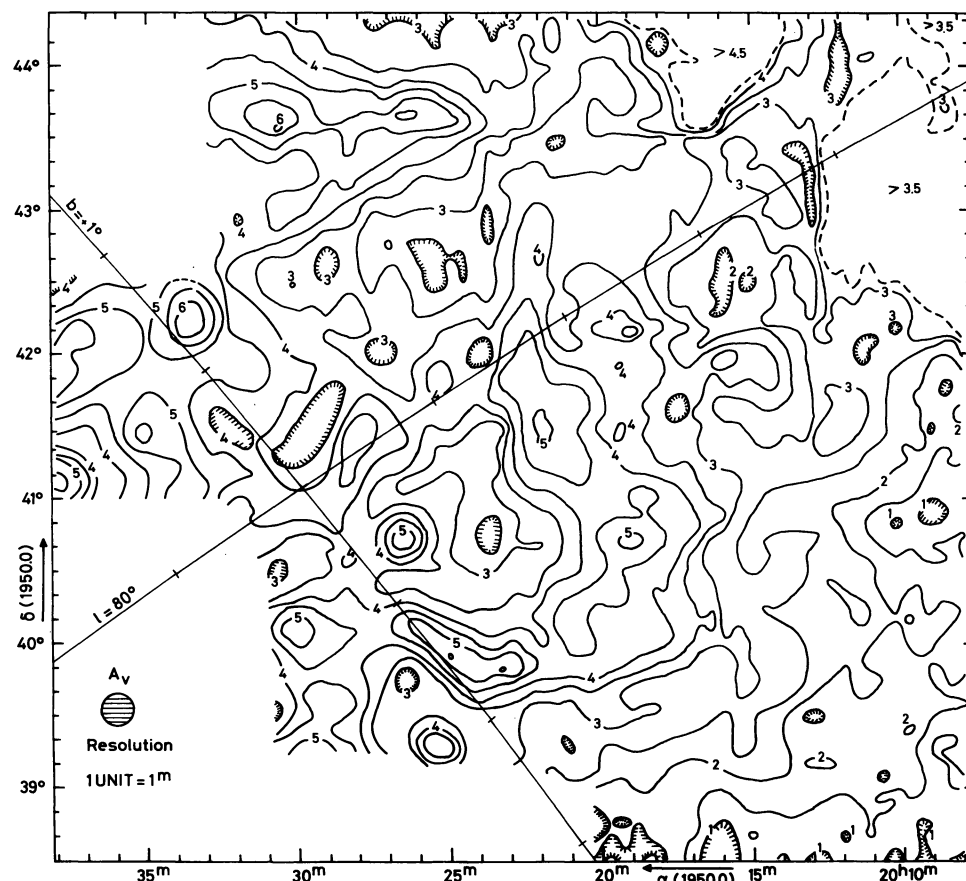


Fig. 4. Contour map of visual extinction, A_V , in the Cygnus X region. The effective resolution is $11''$. The contours start at 1.0 mag and increase in steps of 0.5 mag. Every other contour is labeled. Dashed contours in the northwest part indicate that A_V is ill defined there. The galactic coordinates are as in Figure 1

There is another reason for not choosing the highest A_V to derive the distance. As each of Ikhsanov's curves cover a large area and they extend only to twelfth apparent magnitude, it is likely that they cannot include many stars located behind small dense clouds. This is again certainly true for the IC 1318 b-c region where stars in the dust lane which are included in Ikhsanov's curve No. 4 are all foreground stars with $d < 1.2$ kpc. Thus Ikhsanov's curve for that large region of the Cygnus X complex represents the average distribution in distance for the overall dust which is unassociated with the dense molecular clouds. By using these curves with the lower value of A_V (i.e. where the optical emission is the brightest) found for an H II-molecular cloud complex, we thus derive the most likely distance. Except where the new results differ from before or a different method was used, we simply quote the "best" distance d or its lower limit.

5. Optically Bright Nebulae

It was pointed out in Paper VI that where both optical and radio features are clearly delineated, the positions of their maximum emission often differ by as much as

$10'$, e.g. IC 1318a at $\alpha \approx 20^h 16^m$, $\delta \approx 41^\circ 45'$, $d \approx 1.7$ kpc (Paper VI); IC 1318b at $\alpha \approx 20^h 24^m$, $\delta \approx 40^\circ 05'$, $d \approx 1.5$ kpc (Paper V); and near $\alpha \approx 20^h 28^m$ and $\delta \approx 41^\circ 25'$, $d > 2.1$ kpc (see Section 6). It was suggested that the extinction by interstellar dust was probably responsible for this positional discrepancy. From a comparison of the maps in Figures 2–4 we see that this is indeed the case. The extinction of the optical nebulae increases toward the positions of the radio peaks. However, the position of the maximum A_V does not necessarily coincide with the radio peak; often it is even further displaced from the brightest optical spot. This is probably an important feature of the present work. It indicates that the excess absorption of the bright nebulae over the usual background is generated in the immediate neighbourhood of the H II region. Thus the dust clouds and the H II regions are required to be bordering each other. Different projections of the two give rise to different apparent separations.

6. Cygnus OB 2 Association

The Cygnus OB 2 association is located near the bottom of a depression in both the radio and A_V contours at a

position $\alpha \approx 20^{\text{h}}30^{\text{m}}9$ and $\delta \approx 41^{\circ}13'$. It is at a distance of 2.1 kpc (Reddish et al., 1967 and the present analysis). In Paper IX negative results of a search for compact H II regions inside the association were presented. They concluded that the sink for the large amount of available Lyman continuum photons must be the surrounding 4° region of diffuse gas which is seen as a background component in the radio map of Paper VI. We conclude here that this association must be closer than the majority of other sources within this 4° field. Reddish et al. (1967) and Voelker and Elsässer (1973) find an average visual extinction of 3.5 mag for the stars whereas the radio sources have extinctions of 5–6 mag. This seems to us sufficient proof that the “background” extinction between the sources is actually a foreground extinction due to the large thin H II region surrounding Cyg OB 2. Therefore most of the sources will be further away than 2 kpc.

7. Compact H II Regions

In the vicinity of compact H II regions, such as DR 21 at $20^{\text{h}}37^{\text{m}}13^{\text{s}}$ and $42^{\circ}09'$ and $d \gtrsim 2$ kpc (see last sentence above). A_V is greater than 4 mag and the optical nebulosities are faint and uniform. Here the pattern of calculated extinctions is governed by the variation in T_b so that the A_V contours peak at T_b maxima with values of 5–6 mag. This means on the one hand that the compact H II regions are so small in angular size that the effective instrumental pattern governs their appearance. On the other hand the true interstellar extinction will be even several magnitudes greater on a smaller scale. Although some of this increased extinction is due to the sources being further away than the dust which gives rise to the “foreground” extinction as mentioned earlier, most of it is probably due to the compact H II regions still being embedded in the clouds of dust and molecules out of which they formed. Indeed from a few interferometer maps it is seen that many of them split into several components (e.g. Baars and Wendker, 1974; Harten, 1977) which suffer substantially higher extinction than is indicated by the average extinction within an $11'$ beam. Besides DR 21 the following sources in Figure 4 show this effect:

G 78.1 + 0.6 at $20^{\text{h}}25^{\text{m}}30^{\text{s}}$, $39^{\circ}20'$, $d \approx 1.5$ kpc

G 79.3 + 1.3 at $20^{\text{h}}26^{\text{m}}27^{\text{s}}$, $40^{\circ}44'$, $d \approx 1.5$ kpc

G 81.4 + 1.2 at $20^{\text{h}}33^{\text{m}}30^{\text{s}}$, $42^{\circ}16'$, $d > 3$ kpc

G 80.9 – 0.2 at $20^{\text{h}}37^{\text{m}}48^{\text{s}}$, $41^{\circ}08'$, $d > 3$ kpc.

The first two sources along with IC 1318 b and c belong to one giant H II complex and thus must be at the distance of IC 1318 b and c, see Section 10 (Baars and Wendker, 1974). Our previous estimate in Paper VI placed them at $d > 2$ kpc.

Also, the formaldehyde line observed in the 4.8 GHz survey by Wendker (1977) is very pronounced for the

objects mentioned (this has been known for DR 21 for a long time, of course). These sources may be very productive for future molecular line studies.

8. Supernova Remnant

As well as the thermal emission any non-thermal emission if it exists is included in our calculations of A_V so that in the direction of a non-thermal source the calculated values of extinction will be fictitiously high. The only definite supernova remnant in the area covers about 1° between $20^{\text{h}}22^{\text{m}}$ and $20^{\text{h}}27^{\text{m}}$ and $39^{\circ}50' - 40^{\circ}50'$ (see Paper X and Higgs et al., 1977). Outside this region A_V is less than 4 mag but running diagonally through the middle is a ridge of higher apparent extinction. With A_V between 3 and 4 mag, d is between 1.5 and 3 kpc (see also Paper X). By different arguments Higgs et al. (1977) find a likely distance of 1.8 kpc. The excess is attributed to the nonthermal radiation. Thus, in reality, the average extinction by dust between us and this SNR is $\lesssim 4$ mag.

9. NGC 6888 Area

In an earlier paper (Wendker et al., 1975) the filamentary ring nebula NGC 6888 ($\alpha \approx 20^{\text{h}}10^{\text{m}}$, $\delta \approx 38^{\circ}15'$), which is just off the maps toward the southwest in Figures 1–4, was investigated. The adopted $d = 1.45$ kpc is that determined for the central star HD 192163. In that paper excellent detailed agreement was found between the distributions of radio and optical emission which indicated a low and rather uniform extinction across the nebula. Our map of A_V in Figure 4 shows that the extinction is low and still decreasing towards the region of NGC 6888, thus strengthening the assumption that uniform extinction covers a larger area and is due only to foreground dust.

10. IC 1318 b and c

Values of extinction as high as 5 or 6 mag generally occur only where there is a compact H II region but the extinction is equally high in the prominent dust lane which separates the optical nebulosities IC 1318 b and c which are at a distance of 1.5 kpc as given in Paper V (see Figures 1 and 4 at $\alpha \approx 20^{\text{h}}25^{\text{m}}$ and $\delta \approx 39^{\circ}45'$). In view of this Dickel et al. (1977) searched for and mapped the absorption by H_2CO at 6 cm in the dust lane. They also detected emission from H_2CO at 2 mm where A_V is highest in the dust lane which indicates the presence of higher molecular densities. This region was mapped with the Westerbork survey (Baars and Wendker, 1974) and observations of continuum emission, recombination lines and formaldehyde absorption line are included in the 4.8 GHz survey of Wendker (1977). These new high resolution and sensitivity data reveal local concentrations of material within the dust lane which is also an excellent candidate for studies of other molecules.

11. Two Extended Regions of Obscuration

There are two more regions of extended (around 1°) and rather high extinction with values well over 5^m . The first is roughly centered at the H II region No. 87 in the catalogue of Paper V or the source G 79.4+2.4 of Paper VI at 20^h22^m , 41.4° and $d \approx 2.6$ kpc (from present mean A_V and Ikhsanov's curves). Weak H_2CO absorption has been detected in the area by Seacord and Gottesman (1977) and Wendker (1977). The other region coincides with the source G 82.3+2.4 of Paper VI or H II region No. 155 of Paper V at 20^h31^m , 43.9° with $d > 1.6$ kpc from present mean A_V . Relatively strong H_2CO absorption is seen in the survey by Wendker (1977).

In neither case do the extinction features seem to follow the optical or radio surface brightness. Detailed mapping of molecular and recombination lines is being done to determine whether there are molecular clouds associated with the H II regions or whether the high A_V represents only density fluctuations of the foreground dust of the Cygnus Rift system.

IV. Conclusion

We have presented a map of interstellar extinction covering most of the Cygnus X region. We were able to point out areas which might be fruitful for future studies of many molecules. It further strengthens the hypothesis put forth by Dickel et al. (1970) that the objects in Cygnus X are distributed along the line of sight instead of being clumped at one distance.

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