PART 2

GALACTIC H II REGIONS

"Those southern sources!"
"You'll have to take our word for it that they exist."

B. Zuckerman and B. J. Robinson, in the discussion following the paper by B. J. Robinson

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RECENT RADIO OBSERVATIONS OF GALACTIC H II REGIONS

E. CHURCHWELL

Max-Planck-Institut für Radioastronomie, Bonn, F.R.G.

Abstract. The structure and physics of H II regions are reviewed. The discussion is principally based on the radio mapping of intermediate-size H II regions to measure the energy balance, the mapping of small-scale structure by aperture-synthesis techniques to define the ionization conditions, and determination of helium abundances from radio recombination-line observations of H and He in H II regions.

I. Introduction

An H II region is an almost fully ionized cloud of gas (and dust) which is ionized, in most cases, by the ultraviolet radiation of a hot star(s) embedded in the cloud. H II regions are of astrophysical importance because: they offer a possibility to study the physics of low-density hot plasmas; they imply the radiation properties of O-stars; they provide conditions in the interstellar gas which make the determination of relative abundances possible; they are good tracers of spiral structure in galaxies; they are indicators of recent and in some cases still occurring star formation; and they are an important energy source for the interstellar gas.

Our understanding of the structure and physics of H II regions has improved significantly in the past five years. At radio wavelengths, this is the result of: (1) mapping of intermediate-size H II regions of low surface brightness with beamwidths 2–11′; (2) mapping by the technique of aperture synthesis of small-scale structure which is apparently embedded in an extended, lower-density plasma; and (3) spectroscopic observations of atoms and molecules toward H II regions. This paper briefly reviews the first two areas, as well as radio recombination-line observations of H and He in H II regions.

II. Radio Observations of Optically Visible H II Regions with Intermediate Resolution

Since 1970 several large-scale mapping programs of galactic sources have been published. The most extensive of these are: (1) the Altenhoff *et al.* (1970) survey of the galactic plane in the interval $l = 335°$ to $75°$ and $b = -4°$ to $+4°$ at 1.4, 2.7 and 5.0 GHz, with a resolution of 11 arcmin (356 sources were tabulated); (2) the Goss and Shaver (1970) and Shaver and Goss (1970) 5.0- and 0.4-GHz surveys of 206 southern galactic objects with a resolution of $\sim 4'$; (3) the survey by Wendker (1970) at 2.7 GHz of ~ 90 sources in the Cygnus-X region; the Parkes 2.7-GHz survey of the southern galactic plane in the interval $l = 190°$ through $360°$ to $61°$ and $b = \pm 2°$, which was carried out in part by Beard (1966), Thomas and Day (1969a, b), Day *et al.* (1969), Beard *et al.* (1969), Beard and Kerr (1969), Goss and Day (1970), Day *et al.* (1970), and Day *et al.* (1972); and (5) the survey of 137 optically visible H II regions by

F. J. Kerr and S. C. Simonson, III (eds.), Galactic Radio Astronomy, 195–218.

Felli and Churchwell (1972) at 1.4 GHz with a resolution of 10′. The last survey has shown that most optically visible nebulae have associated radio continuum emission.

In this section I will review some results from radio observations of optically visible H II regions. The following statistics are based on a catalogue of exciting stars and radio data which is presently being prepared by P. Angerhofer, M. Walmsley and myself.

(a) STATISTICAL RESULTS

The nebulae listed by Sharpless (1959) comprise a wide variety of objects, few of which are typical of bright radio H II regions. Many are more extended and have much lower surface brightnesses than bright radio H II regions and therefore may represent a later stage of development. Others in this list may be representative of regions in which star formation is occurring under quite different conditions than that in giant radio H II regions. Hence conclusions based on this sample may not apply to bright radio H II regions.

We eliminate from consideration all nebulae where the identification of the optical with the radio emission is doubtful, and several large optical nebulae which contain numerous physically separate H II regions (e.g., S 108 and S 109 together encompass the whole Cygnus-X radio complex). This leaves a sample of 293 nebulae out of the 313 listed by Sharpless (1959).

TABLE I

Some statistical results for sources in the Sharpless (1959) catalog

1. Nebulae with one or more proposed exciting stars:	~34%
2. Radio flux density measured at least at one frequency:	~56%
3. Nebulae with determinate radio spectral index:	~32%
Of these,	
(a) thermal spectra:	65±10%
(b) nonthermal:	18± 2%
(c) extragalactic:	1.5± .5%
(d) proposed exciting stars for:	47%
4. Nebulae in the region of sky surveyed by Hoffmann *et al.* (1971) with measured 100μm emission	16± 2%
5. Nebulae observed at two or more frequencies but with uncertain spectral indices:	~11%
6. Nebulae searched for but not detected at radio frequencies:	~19%
Of these,	
a) exciting stars proposed for:	26%
b) optical brightness:	
bright:	10%
intermediate:	37%
faint:	53%
c) Optical size:	
$\theta_s > 30'$	24%
$10' < \theta_s < 30'$	21%
$\theta_s < 10'$	55%
7. Nebulae, with proposed exciting stars, that have been *searched for* and *detected* at radio frequencies:	91%

From Table I several conclusions can be drawn. First there is a striking paucity of both radio and stellar data for these nebulae. Reliable stellar and radio data exists for only ~30% of all optically visible nebulae. Hα or Hβ surface brightnesses are available for even fewer nebulae. A large percentage of these sources have nonthermal

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radio spectra. At least three are apparently extragalactic objects: S 197 (= Maffei II), S 191 (= Maffei I), and S 172. From entry 6 we see that small optically faint H II regions are less likely to be detected at radio frequencies than other types. Finally we note that practically all nebulae with observable exciting stars, which have been searched for at radio frequencies, have been detected.

(b) SELECTED NEBULAE

We have selected from our catalogue all nebulae which satisfy the following criteria:

(i) the optical and radio positions agree to $\lesssim 10\%$ of the optical size or to $\lesssim 2'$ if the optical size is $< 20'$;

(ii) the optical and radio sizes and shapes basically agree.

These two criteria imply that the identification of the optical emission with the radio emission is correct and that the optical extinction is not large. Hence exciting stars in such nebulae should be observable, unless they are 'cocoon' stars.

Sixty-four nebulae, or 22% of our sample, satisfy these criteria. Twenty-six of these have fairly certain exciting star identifications and thermal radio spectra. Thirty-five have no known exciting star but have apparently thermal radio spectra. Three have nonthermal spectra.

An example of the set of nebulae with thermal spectra and an identified exciting star is S 125 (IC 5146). An 11-cm map with a resolution of $\sim 5'$ made with the MPIfR 100-m radio telescope is shown overlayed on the blue print of the Palomar Sky Survey in Figure 1. A BO v star is located at the center of the nebula and the radio and optical emission agree in position and extent.

Assuming the distance derived from the ionizing stars, we have determined the excitation parameter (U_{obs}) from the radio flux densities of these 26 nebulae. The theoretical excitation parameter as a function of spectral type and luminosity class has been derived from stellar atmosphere models of Morton (1969) and Auer and Mihalas (1972) by Churchwell and Walmsley (1973). These are plotted as solid curves in Figure 2 and labeled as ZAMS, V, III and I for the zero-age main sequence, dwarfs, giants and supergiant stars respectively. The derived radio excitation parameter is plotted in Figure 2 with symbols indicating the spectral type and luminosity class of the proposed exciting star.

For this sample of nebulae, Figure 2 suggests that H II regions ionized by O8 or hotter stars are generally density-bounded, whereas those ionized by O9 or cooler stars are generally ionization-bounded. If all H II regions ionized by early O stars are density-bounded, the Lyman continuum (L_c) photon flux which escapes H II regions could make a substantial contribution to the ionization of the interstellar gas. Whether significant L_c-photon fluxes escape depends on what fraction of the stellar L_c-photon flux is absorbed by dust in H II regions. Table II lists three apparently density-bounded H II regions for which the ionizing stars are known and 100-μm and 5-GHz flux densities have been measured. The data in column 3 are from Schraml and Mezger (1969), those in columns 4, 6 and 7 were taken from Churchwell *et al.* (1974). The 100-μm fluxes were taken from Hoffmann *et al.* (1971). For these three

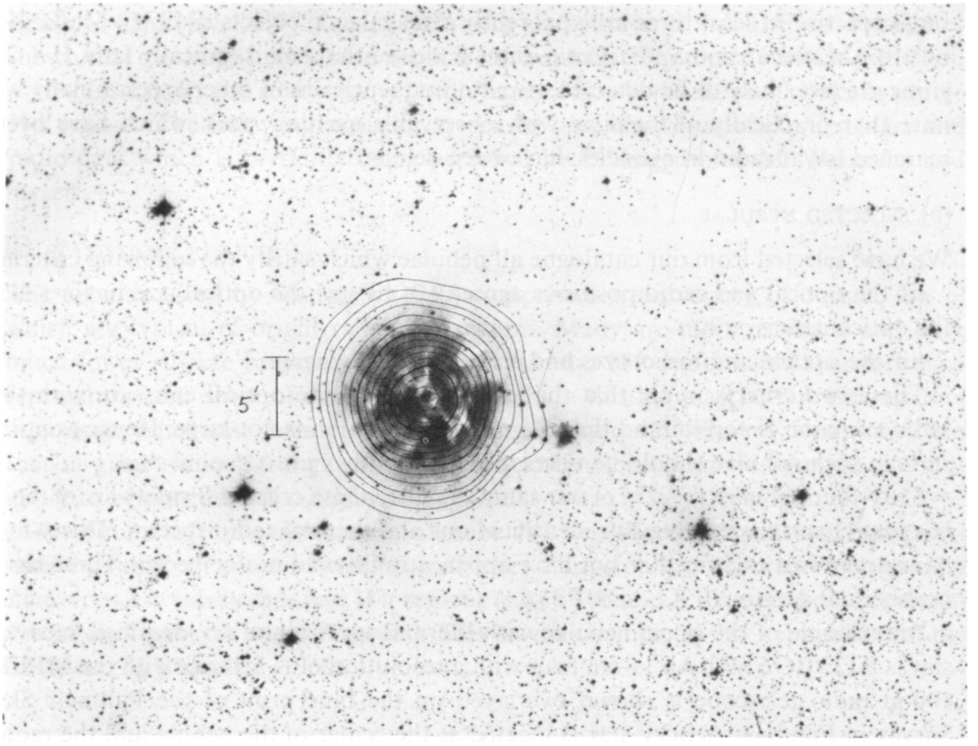

Fig. 1. Overlay on the blue print of the Palomar sky survey of an 11-cm map of S 125 (IC 5146) (resolution ~5′) by Walmsley, Schwartz and Churchwell. (Copyright National Geographic Society – Palomar Observatory Sky Survey. Reproduced by permission from the Hale Observatories.

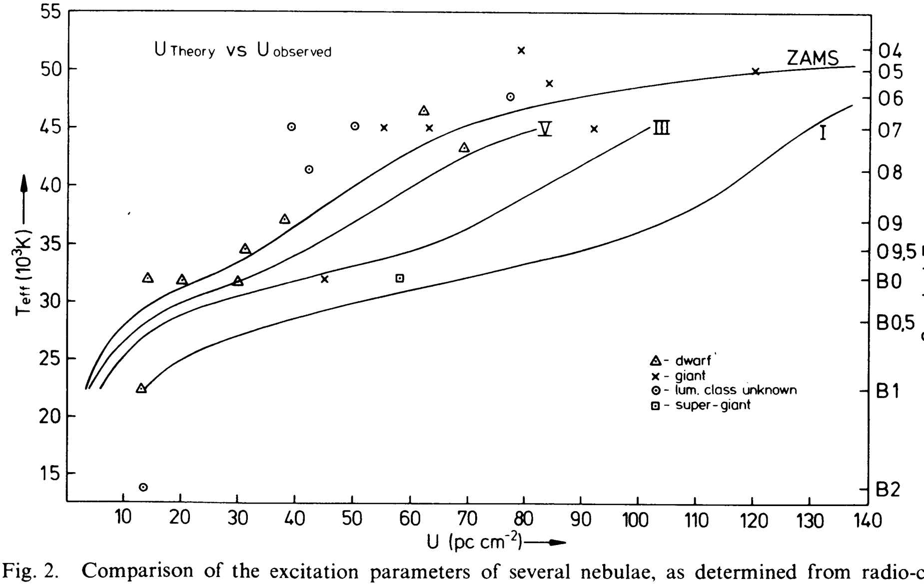

Fig. 2. Comparison of the excitation parameters of several nebulae, as determined from radio-continuum observations, with that of the ionizing star as calculated by Churchwell and Walmsley (1973).

TABLE II

Energy balance in several H II regions

Source	Proposed ionizing star	n_e (cm^{-3})	N_c (star) $\times 10^{48}$ (s^{-1})	100 μm flux $\times 10^4$ (Jy)	$S_{5\,GHz}$ (Jy)	N_c (gas) $\times 10^{48}$ (s^{-1})	N_c (dust) $\times 10^{48}$ (s^{-1})	% L_c-photons escaping
Orion A	06	2237	24	35	382	9.0	7.0	~33
M8	07	391	9.7	3.4–3.7	85–192[a]	7.0	0.8	~20
NGC 6357 (353.2+0.9)	07	774	9.7	5.4	87	7.8	1.9	~ 0

[a] Lower $S_{5\,GHz}$ value for M8 is the value taken from Reifenstein *et al.* (1970), and $S_{5\,GHz} = 192$ is from Goss and Shaver (1970).

nebulae it is possible to determine (with some reasonable assumptions) what fraction of the L_c-photon flux is absorbed by gas and dust, and what fraction escapes. N_c (dust) was calculated using the stellar properties given by Mezger *et al.* (1974) and the data in column 5.

In order to have N_c (star) $= N_c$ (gas) $+ N_c$ (dust) in Orion A one would have to double $S_{5\,GHz}$ or triple the 100-μm flux. This is far outside the uncertainties of both the radio and IR data. It has been implicitely assumed that the 100-μm flux originates from heated dust that is well mixed with the ionized gas which gives rise to the radio source and that the 100-μm flux represents ~25% of the total IR flux, which would be the case if the dust grains have a temperature 80–100 K and radiate like black-bodies. Thus relatively large uncertainties enter the calculation of N_c (dust). Also N_c (star) values are probably not accurate to better than a factor of two; therefore an inequality in the above relation of ~30% is not meaningful. On the other hand the sense of the inequality in Table II (i.e., density-boundedness) appears to be supported by other evidence. The interstellar radio recombination lines observed by Gordon and Cato (1972) seem to be confined to regions in the Galaxy where OB stars are concentrated; particularly, in tangential directions to known spiral arms. Observations of Hα and Hβ emission by Carranza *et al.* (1968), Monnet (1971), and Benvenuto *et al.* (1973) have shown that much of the gas outside well defined discrete H II regions in the spiral arms of M33 is ionized. Courtès (1960) and Cruvellier (1967) have observed the same phenomenon in our own Galaxy. Finally, the Hα and/or Hβ observations of Dachler *et al.* (1968), Reay and Ring (1969), Johnson (1971), and Reynolds *et al.* (1973) have shown that in the solar neighborhood ionized gas not associated with known H II regions and with a low emission measure is seen over large solid angles.

To get a rough estimate of the effect on the interstellar radiation field by density-bounded H II regions let us suppose that 30% of the L_c-photon flux from all O6 stars escapes into the surrounding interstellar gas. The space density of O6 stars in the solar neighborhood is $\sim 5 \times 10^{-8}$ O6 stars pc^{-3} (Allen, 1963), which gives a mean distance between O6 stars of ~340 pc. The excitation parameter of O6 stars is ~90 pc cm^{-2} (Churchwell and Walsmley, 1973); therefore the effective excitation parameter for the interstellar gas is $(0.3)^{0.33} \times 90 = 60$ pc cm^{-2}. Hence the interstellar medium would be fully ionized for an electron density of $n_e = [60 \text{ pc cm}^{-2}/170 \text{ pc}]^{3/2} \simeq$ $\simeq 0.2$ cm^{-3} (neglecting absorption by dust). The mean photon density in the galactic plane from O6 stars alone would be $\sim 2 \times 10^{-4}$ cm^{-3}. The mean energy per L_c-photon from O6 stars is ~ 24 eV (Mezger *et al.*, 1974 thus the average kinetic energy transmitted to the interstellar gas per ionization would be ~ 10 eV.

A further point related to this consideration is the question of the relative and cumulative contribution by each spectral type to the total L_c-photon flux of a statistically typical O-star cluster. This has been computed by Mezger *et al.* (1974) and is shown in Figure 3. The non-LTE atmosphere models of Auer and Mihalas (1972) and Salpeter's (1955) 'original' luminosity function were used for this calculation.

O6 stars apparently make the major contribution to the L_c-flux of an O-star cluster and early O stars dominate the integrated cluster luminosity.

A consequence of these considerations is that, if H II regions ionized by O6 stars or earlier are density-bounded, even by a small amount, they will make a major contribution to the interstellar radiation field and should be surrounded by a very extended, low density ionized region.

III. Small-Scale Structure in H II Regions

(a) OVERVIEW

More than 30 galactic H II regions have now been synthesized at Cal. Tech., Cambridge, NRAO and Westerbork with effective resolutions ranging from $\sim 90''$ (at 0.4 GHz) to $\sim 2''$ (at 5 GHz). Almost every H II region so far synthesized has small, dense components (exceptions are IC 1318b and c, G78.1+0.6 and G79.3+1.3 [Baars and Wendker, 1974]), which generally represent only a small fraction of the total radio emission from the H II region. The component sizes so far observed range from that of the whole Orion nebula ($\lesssim 0.5$ pc) in Sgr B2 (Martin and Downes, 1972) to that expected for single protostar clouds ($\lesssim 0.1$ pc) in Orion A itself. Similarly, the electron densities and emission measures range respectively from 10^3–10^5 cm^{-3} and 10^6–10^8 pc cm^{-6}.

Harper and Low (1971) have shown that H II regions emit strongly at IR wavelengths. It is generally believed that this is due to radiation by heated dust grains which are well mixed with the ionized gas. Maps of IR emission from several H II regions (e.g., W3 in the interval 1.65–20 μm by Wynn-Williams *et al.*, 1972; M17 at 21 μm by Lemke and Low, 1972; and Orion A at 21 μm by Lemke, private communication) show close agreement with comparable resolution radio maps. Sources of OH and H_2O emission lie close to compact H II regions (Raimond and Eliasson, 1969; Robinson *et al.*, 1970; Hardebeck, 1971; Hills *et al.*, 1972).

It is not possible to discuss the peculiarities of each synthesized H II region in this paper. Instead, I have chosen to consider in some detail the W3 main source complex and to use it as an illustrative example of several points which may pertain to small-

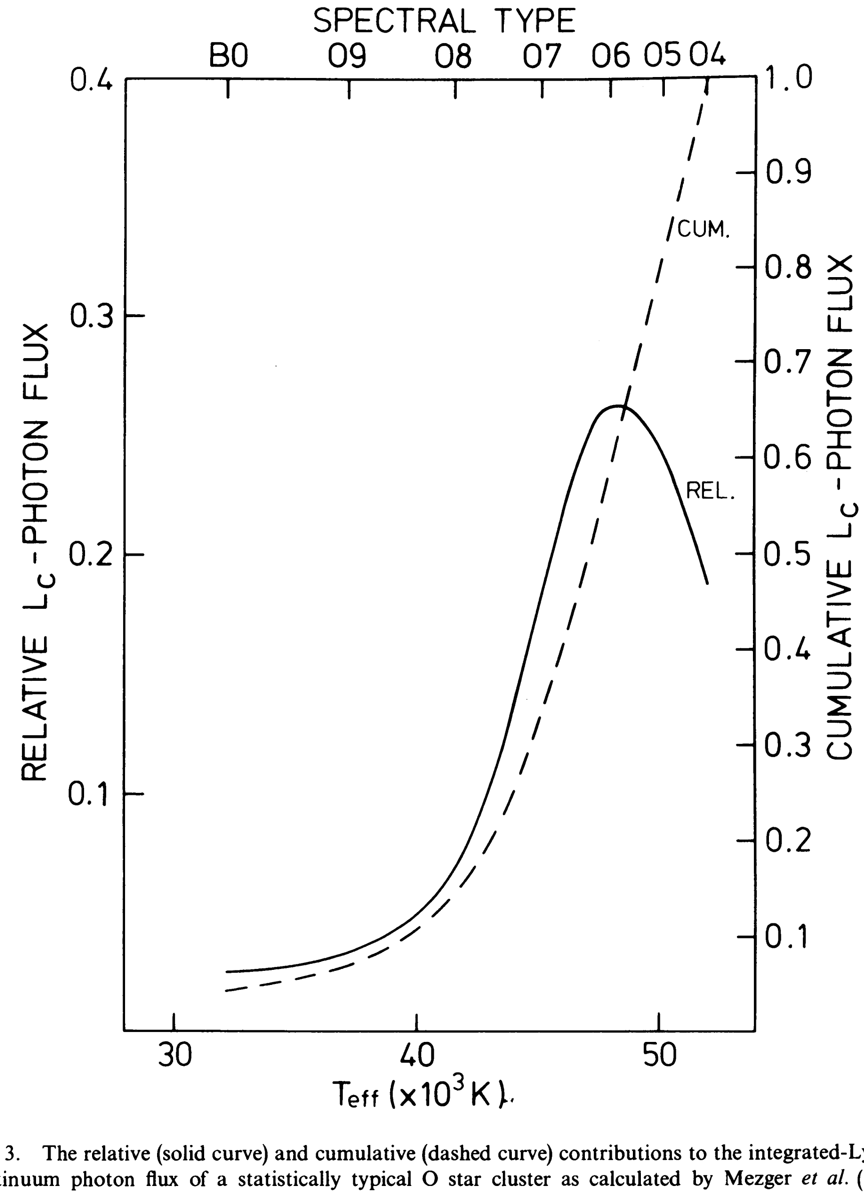

Fig. 3. The relative (solid curve) and cumulative (dashed curve) contributions to the integrated-Lyman-continuum photon flux of a statistically typical O star cluster as calculated by Mezger *et al.* (1974).

scale structure in H II regions in general. W3 is a good source for this purpose for several reasons: (1) its distance is ~3 kpc so that at the best resolution so far attained (~2″) components of ~0.03 pc can be resolved; (2) its high declination permits uncomplicated synthesized beam shapes; (3) it has been observed in the IR, in radio recombination and molecular lines, and it has been synthesized at at least five frequencies; and (4) it has several kinds of compact components.

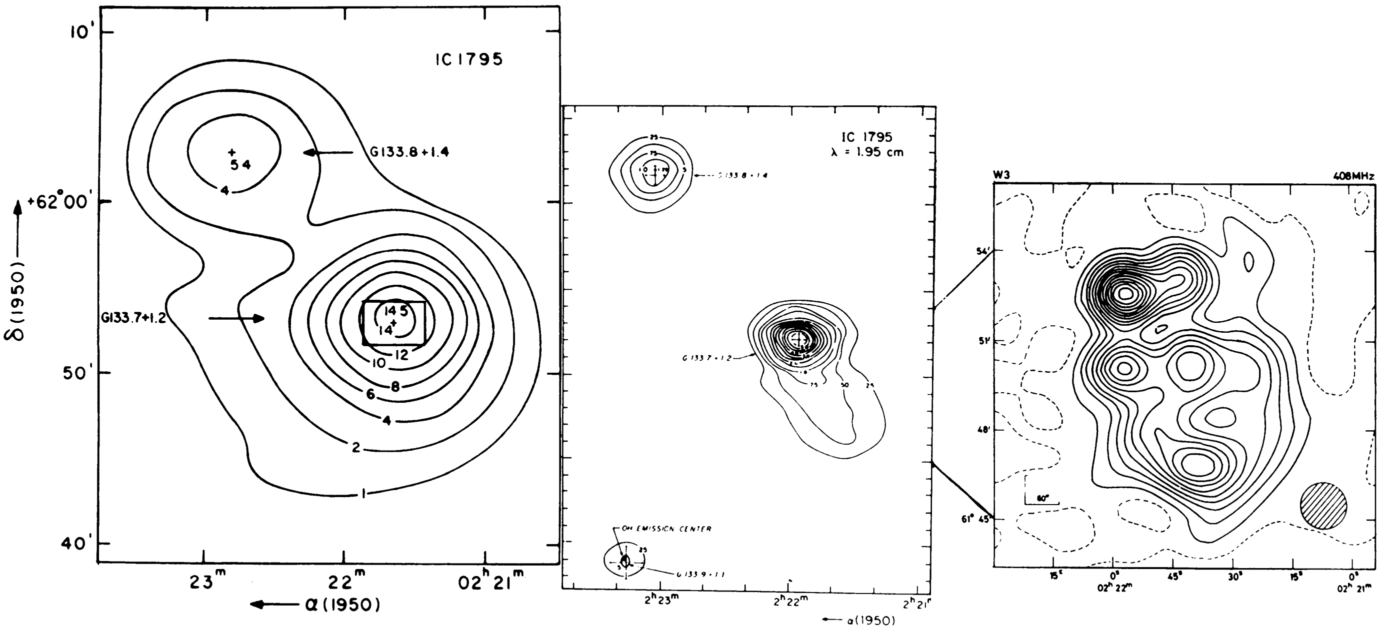

Fig. 4. *Left* – The 5.0-GHz (6-cm) map of W3 by Mezger and Henderson (1967) with a HPBW ~ 6′. The rectangle on G133.7 + 1.2 indicates the synthesized region in Figure 5. *Middle* – The 15 GHz (1.95-cm) map of W3 by Schraml and Mezger (1969) with a HPBW ~ 2′. The scale is the same as that on the left. *Right* – The 0.4-GHz (73.5-cm) synthesis map of the southern extension of G133.7 + 1.2 seen at 15 GHz by Wynn-Williams (1971) with a resolution of ~90″.

(b) OBSERVATIONS OF W3

Figures 4 to 6 contain some of the radio data on W3. Figure 4 shows the Mezger and Henderson (1967) 5-GHz map (HPBW ~ 6′) and at the same scale the Schraml and Mezger (1969) 15-GHz map (HPBW ~ 2′).

The rectangle on the 5-GHz map indicates approximately the synthesized area at 2.7, 5.0 and 8.1 GHz. The 0.4-GHz map by Wynn-Williams (1971) resolves the southern extension seen at 15 GHz into at least 3 and perhaps 4 separate components. Figure 5 shows synthesis maps at 2.7 and 8.1 GHz by Wink (1973) with effective resolutions of 6″ × 7″ and 3″ × 3″ respectively, at 5 GHz by Wynn-Williams (1971) with a resolution of 6.5″ × 7.4″, and a synthesis map of H_2CO absorption at 4.83 GHz in front of W3 *A* and *B* by Fomalont and Weliachew (1972) with a resolution of 40″ × 60″.

The high-resolution continuum synthesis maps all show the four components designated *A*, *B*, *C* and *D* by Wynn-Williams (1971). The strongest component, W3 *A*, is apparently a ring or shell with some local density fluctuations. At the highest resolution shown (3″), component *B* appears to have even smaller structure; Wink (1973) had to use five gaussian components to fit the observed brightness distribution.

A recent synthesis map at 1.4 GHz has been made by Sullivan and Downes (1973) with a resolution of 25″ × 28″ and is shown in Figure 6.

The maps by Wynn-Williams *et al.* (1972) at 2.2 and 20 μm (diaphragm ~ 10″) are shown in Figure 7. The 1720-MHz OH emission source (Wynn-Williams *et al.*, 1973) has been added for comparison with the H_2O, IR and radio continuum positions.

Several points of interest are: (1) components *A* and *B* have IR counterparts at both 2.2 and 20 μm; (2) component *C* has only a 20 μm counterpart; (3) IRS2 coincides with the hole in component *A* and is thought to be the highly reddened radiation from the ionizing star of component *A*; (4) IRS5, IRS6, and IRS7 have no radio counterparts, although H_2O emission appears to be coincident with IRS5; and (5) neither radio continuum nor IR radiation comes from the 1720-MHz OH source.

(c) IONIZATION OF COMPACT COMPONENTS

Are the compact components in H II regions ionized from outside or from inside? Are they simply density fluctuations in the diffuse ionized gas or are they newly formed, hot stars surrounded by the ionized remnant of the cloud out of which they formed? Obviously the answer to this question is critical to our understanding of the nature of small-scale structure in H II regions.

Mezger and Henderson (1967) give for the flux density and size of G133.7 + 1.2 (the main component of W3 with spatial resolutions $\gtrsim 2'$) at 5 GHz, $S_{5\,\mathrm{GHz}} = 76.5$ Jy and $\theta_s \simeq 4\overset{'}{.}3$. This implies an excitation parameter of 124 pc cm^{-2} and a stellar L_c-photon flux of $N_c \gtrsim 7.3 \times 10^{49}$ s^{-1}, which corresponds to a star of spectral type O5 (ZAMS) or earlier (Churchwell and Walmsley, 1973). To see whether a single O5 star can account for the ionization of components *A*, *B*, *C*, and *D* in W3 three cases are considered:

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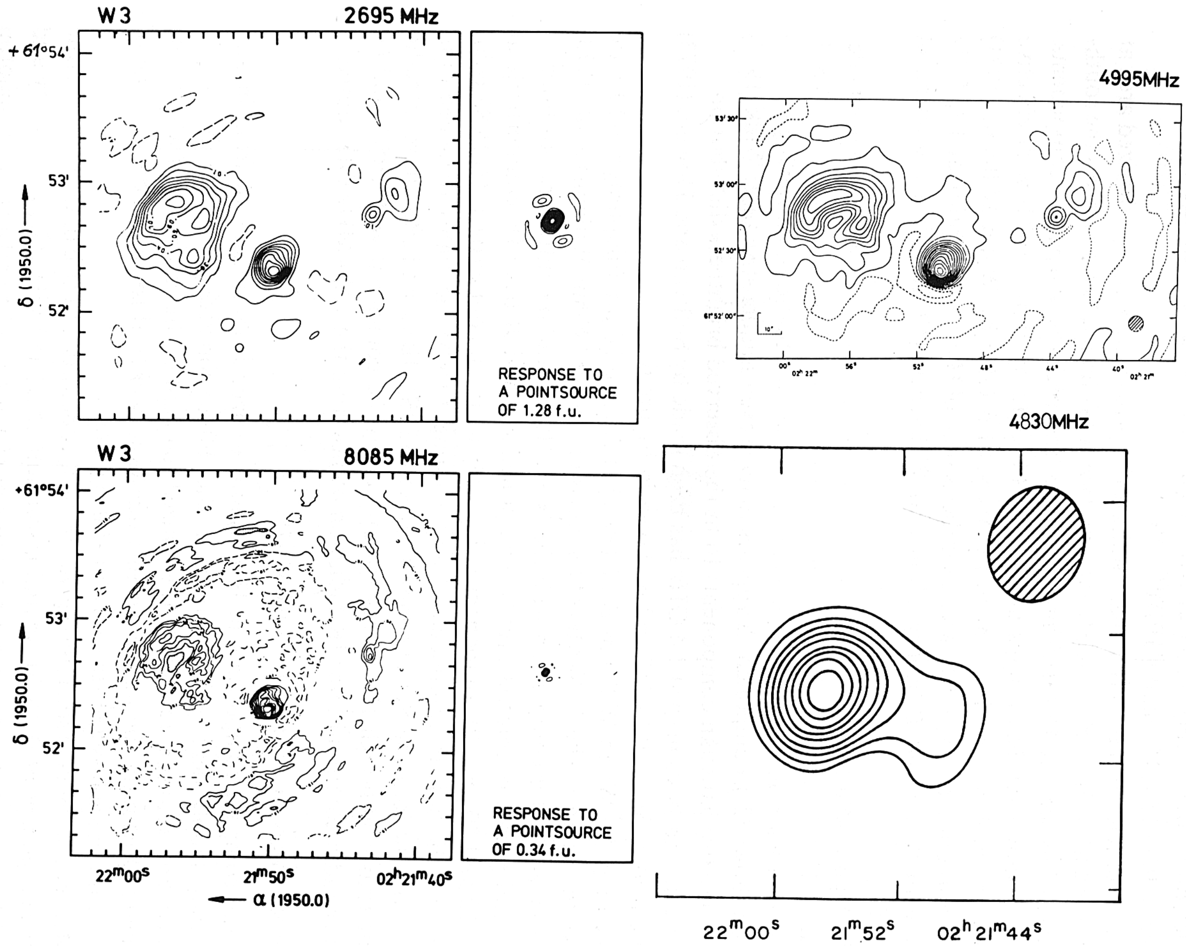

Fig. 5. Aperture synthesis maps of W3. *Upper left* – 2.7-GHz map by Wink (1973) with a resolution of 6 × 7″. *Lower left* – 8.1-GHz map by Wink (1973) with a resolution of 3″ × 3″. *Upper right* – 5.0-GHz map by Wynn-Williams (1971) with a resolution of 6.5″ × 7.4″. *Lower right* – map of H_2CO absorption at 4.83 GHz by Fomalont and Weliachew (1972) with a resolution of 40″ × 60″.

(1) an O5 (ZAMS) star at the center of W3 *A* (ring or shell structure);
(2) an O5 (ZAMS) star at the center of component *B*;
(3) an O5 (ZAMS) star at the geometrical center between components *A*, *B*, *C*, and *D*.

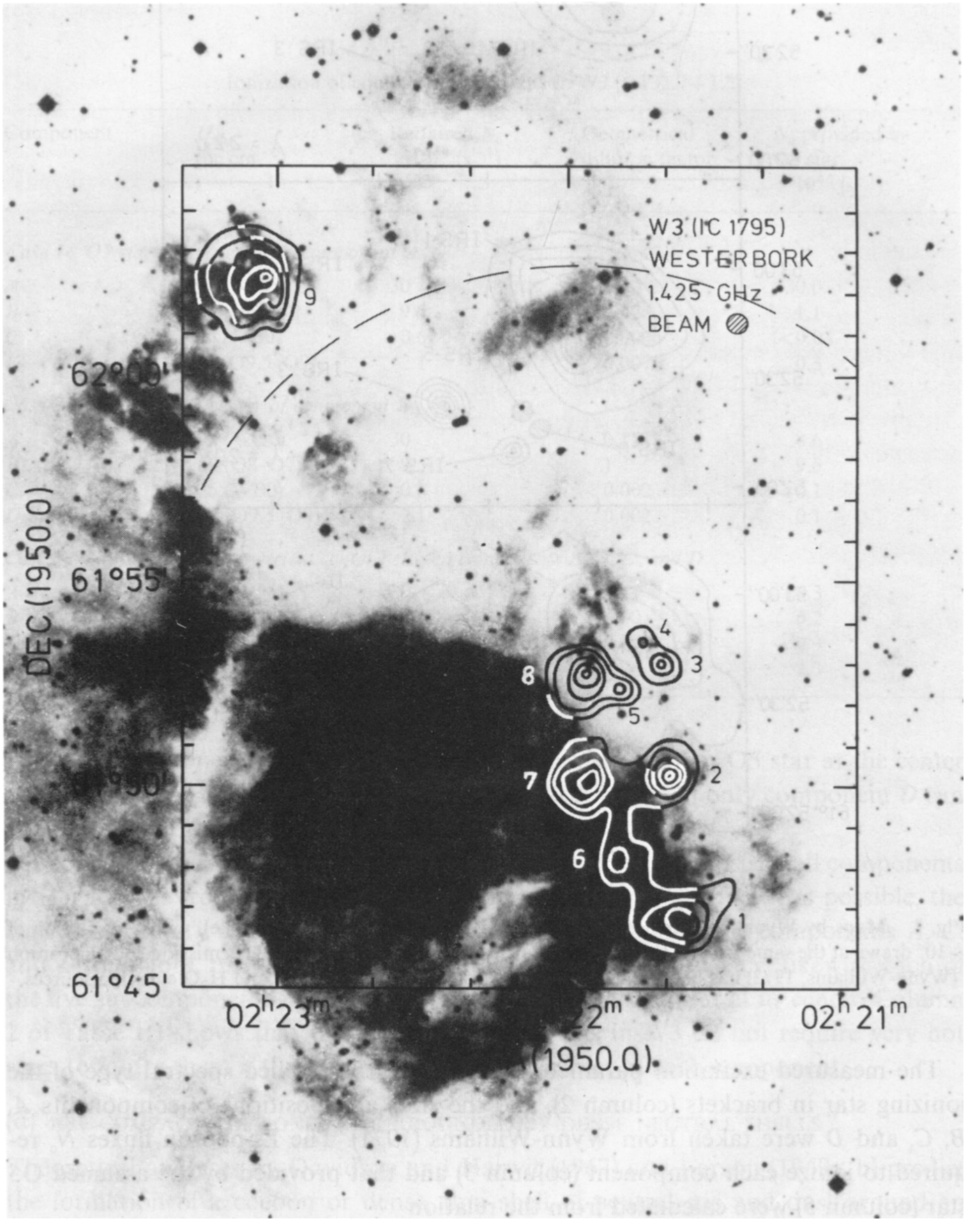

Fig. 6. Aperture-synthesis map of W3 by Sullivan and Downes (1973) at 1.4 GHz (continuum) with a resolution of 25″ × 28″. (Copyright by National Geographic Society – Palomar Observatory Sky Survey. Reproduced by permission from the Hale Observatories.)

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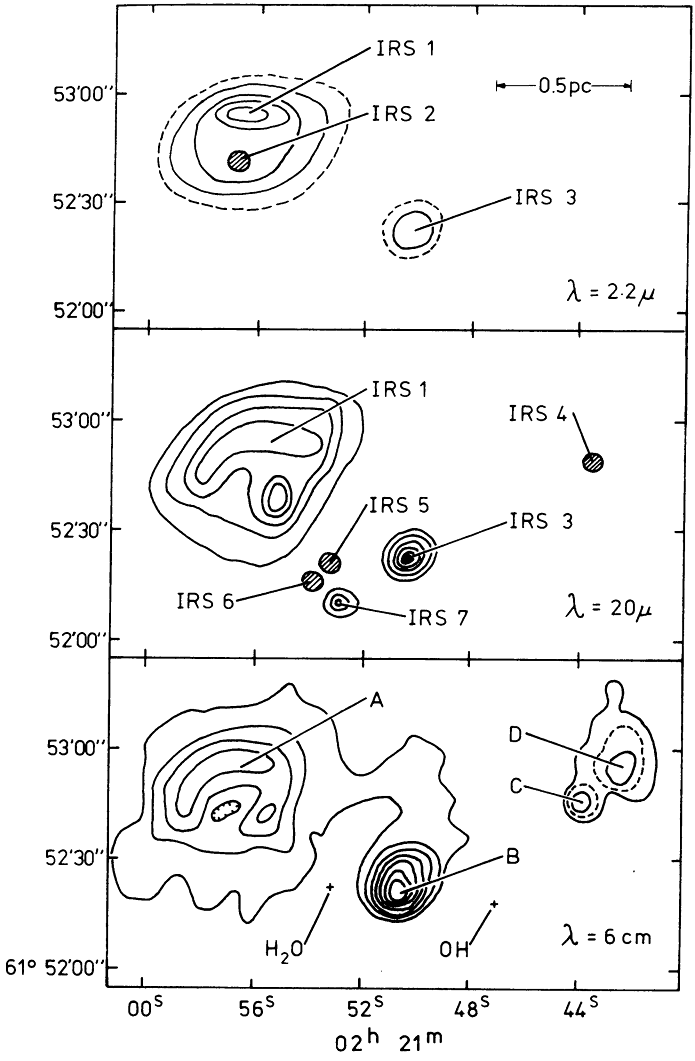

Fig. 7. Maps by Wynn-Williams *et al.* (1972) at 2.2 μm (top) and 20 μm (middle), with a resolution of ~10″ drawn at the same scale as the 5.0-GHz map (bottom). The 1720-MHz OH emission source position (Wynn-Williams, 1973) has been added for comparison with the IR, radio, and H_2O emission sources.

The measured excitation parameters, U_{obs}, with the implied spectral type of the ionizing star in brackets (column 2), and the sizes and positions of components *A*, *B*, *C*, and *D* were taken from Wynn-Williams (1971). The L_c-photon fluxes N_c required to ionize each component (column 3) and that provided by the assumed O5 star (column 5) were calculated from the relation

$$\left[\frac{N_c}{s^{-1}}\right] = 3.806 \times 10^{43} \left[\frac{U}{\text{pc cm}^{-2}}\right]^3,$$

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where it is assumed that $T_e = 8000$ K. The effect of dust is ignored in all cases.

In no case can the O5 star account for the ionization of all components (which make up no more than 50% of the total radio emission from G133.7+1.2). Component *A* can be easily ionized with an O5 or even an O6 star at its center, but then

TABLE III

Ionization of compact components in W3 (G133.7+1.2)

Component	U_{obs} (pc cm^{-2})	Required N_c $\times 10^{48}$ (s^{-1})	Geometrical dilution factor	N_c provided by O5 star $\times 10^{48}$ (s^{-1})
Case 1: O5 star at the center of component A				
A	92 (~O6)	30	1	30.0
B	63 (O8–O7)	9.5	0.026	1.1
C	25 (~B0)	0.6	<0.0006	<0.03
D	38 (O9.5–O9)	2.1	0.0075	0.3
Case 2: O5 star at the center of component B				
A	92 (~O6)	30	0.15	8.6
B	63 (O8–O7)	9.5	1	9.5
C	25 (~B0)	0.6	<0.002	<0.1
D	38 (O9.5–O9)	2.1	0.002	0.1
Case 3: O5 star at the geometrical center between components A, B, C, and D				
A	92 (~O6)	30	0.11	6.3
B	63 (O8–O7)	9.5	0.09	5.2
C	25 (~B0)	0.6	<0.006	<0.3
D	38 (O9.5–O9)	2.1	0.04	2.3

the other components could not be ionized. Similarly with an O5 star at the center of component *B*, only component *B* can be ionized. In case 3 only component *D* can be accounted for.

I conclude from Table III that it is very difficult to ionize dense small components in H II regions from the outside, even with very hot stars. When it is possible, the star must be very close to the compact component. Each of the components *A*, *C*, and *D*, therefore, probably has a single ionizing star at its center; likewise each of the five subcomponents in *B* probably has a single ionizing star at its center. Column 2 of Table III shows that the compact components in W3 do not require very hot stars to ionize them if the star is located at the center of each component.

(d) ARE COMPACT COMPONENTS SURROUNDED BY DENSE NEUTRAL SHELLS?

Theoretical analyses by Davidson and Harwit (1967) and Larson (1969a, b) predict the formation of a cocoon or dense, thin shell of neutral gas and dust around an inner sphere of gas ionized by a newly formed star. Interferometric observations of small bright OH and H_2O emission-line sources (Burke *et al.*, 1970; Johnston *et al.*, 1972; Hills *et al.*, 1972) have shown that such sources tend to be closely associated both in position and velocity with compact H II regions. Since OH and H_2O can only exist for reasonable times in neutral gas clouds (Hesser and Lutz, 1970; Stief *et al.*, 1972) it is believed by some that compact H II regions are surrounded by neutral shells. An alternative interpretation is that the OH/H_2O maser sources are themselves protostar clouds which lie in the neighborhood of a slightly more evolved star with its own compact H II region.

The best observational evidence for a dense neutral shell is the appearance of OH emission sources around the edge of W3 (OH) (Baldwin *et al.*, 1973; Wink *et al.*, 1973). The VLBI OH positions are only relative, however, and the apparent clustering of OH sources around the edge of W3 (OH) has yet to be confirmed by accurate measurements. From a comparison of the IR and radio observations of W3, Wynn-Williams *et al.* (1972) conclude that the extinction varies from component to component; on the basis of this they argue that each condensation is associated, at least in part, with its own obscuring matter. From their synthesis of the 21-cm hydrogen line toward W3, Sullivan and Downes (1973) find no variation of the absorption over the whole of W3 (G133.7 + 1.2). They indicate that one possible way to reconcile the IR and hydrogen line data is for the compact H II components to be surrounded by a considerable mass of H_2.

W3 *B* has the largest visual extinction of all the components in W3; also, OH and H_2O emission sources appear in projection on opposite sides of it. However, the H_2O source apparently originates from IRS5 and not from component *B*. Also, according to Wink (1973), component *B* is composed of at least five subcomponents. Thus no simple neutral shell model for W3 *B* can be supported by the present data.

In my opinion the data support both the neutral shell and separate-protostar models of OH and H_2O emission. The best case for the former is W3(OH) and for the latter is W3 *B*.

(e) THE MASS DISTRIBUTION IN GIANT H II COMPLEXES

Let us first consider the large-scale mass distribution in W3. Mezger and Henderson (1967) derive:

$$\text{total } M_{\mathrm{H\,II}} \simeq 4.2 \times 10^2 \ M_\odot .$$

In section IIIc, we found that for W3(G133.7 + 1.2) $N_c^* \gtrsim 7.3 \times 10^{49}\ \mathrm{s}^{-1}$. The average integrated Lyman continuum flux-to-mass ratio for O star clusters is: $\langle N_c \rangle / \langle M \rangle \simeq 2 \times \times 10^{46}\ \mathrm{s}^{-1}\ M_\odot^{-1}$ (Mezger *et al.*, 1974). We, therefore, infer a stellar mass in W3 of:

$$\text{total } M_* = N_c^* / (\langle N_c \rangle / \langle M \rangle) \simeq 4 \times 10^3 \ M_\odot .$$

From the column density of $14 \times 10^{13}\ \mathrm{cm}^{-2}$ for H_2S toward W3 (Thaddeus *et al.*, 1972) and an assumed ratio of $N_{\mathrm{H_2S}}/N_{\mathrm{H_2}} \simeq 3 \times 10^{-9}$, as in Orion A (Thaddeus *et al.*, 1972), we infer a column density of H_2 toward W3 of $\simeq 5 \times 10^{22}\ \mathrm{cm}^{-2}$. If we further assume that the H_2 cloud has the same extent as the H_2CO cloud toward W3 (about $14' \times 5'$, see Dickel (1973), then the mass of the extended molecular cloud is

$$M_{\mathrm{mol}} \simeq 2 \times 10^5 \ M_\odot .$$

Thus the large scale distribution of mass in the W3 region goes approximately as

$$M_{\text{mol}} \gtrsim 10\ M_*,$$

and

$$M_* \gtrsim 10\ M_{\text{H II}}.$$

Similar analyses for Orion A and W49A yield approximately the same results (Mezger, 1973). An obvious and not new conclusion indicated by these numbers is that very massive clouds are required for star formation to occur at least for large O star clusters. The ratio of M_*-to-$M_{\text{H II}}$ has been used to infer that the efficiency of star formation is very high; however, such a ratio probably overestimates the efficiency because the low mass stars may be embedded in neutral gas.

Let us now consider what proportion of the ionized gas is in compact components. For the diffuse southern extension mapped at 15 GHz and synthesized at 0.4 GHz, Wynn-Williams (1971) gives a size of ~4.5 pc and a density $n_e \simeq 100\ \text{cm}^{-3}$, which implies a mass of $M_{\text{H II}} \simeq 120\ M_\odot$. The sum of the flux densities of components *A*, *B*, *C*, and *D* is ~42.1 Jy (Wynn-Williams, 1971), and the integrated flux density of G133.7+1.2 is 76.5 Jy (Mezger and Henderson, 1967); therefore the flux density of the *diffuse gas* in G133.7+1.2 is ~34.4 Jy. The size of G133.7+1.2 is 4.3′, which in conjunction with a flux density of 34.4 Jy implies a mass of ~400 $M_\odot$ for the diffuse ionized gas in G133.7+1.2. Excluding the southern extension, this reduces to ~280 *M*. The ionized gas in components *A*, *B*, *C*, and *D* together is ~18 $M_\odot$ (Wynn-Williams, 1971), therefore less than 10% of the ionized gas in G133.7+1.2 is in compact components.

Let us consider the ionized mass in some of the most compact H II regions. Table IV lists several of the densest H II regions observed to date, with their derived densities, masses and excitation parameters.

From Table IV we see that the more dense the sources are, the less ionized gas mass is observable, even though all these components require hot stars for their ionization. This partly reflects the fact that with increasing resolution, the smaller source

TABLE IV

Ionized gas mass in some of the most compact H II regions

Source	n_e (cm^{-3})	$M_{\text{H II}}/M_\odot$	U (pc cm^{-2})	References
W3 *C*	2.5×10^4	0.09	27	Wink (1973)
NGC 7538 *C*	8.8×10^4	0.002	12	Wink (1973)
W3 B_5	4.6×10^4	0.006	14	Wink (1973)
W3 (OH) *A*	1.8×10^5	0.084	54	Wink *et al.* (1973)
M17 *A*	1.5×10^5	0.0008	13	Wink (1973)
ON-1[a]	$(0.9–8.8) \times 10^5$	0.00003–0.03	4.9–31	Winnberg *et al.* (1973)
IRS 5			>30	Wynn-Williams *et al.* (1972)

[a] Distance ambiguity

sizes which are being resolved have lower masses and higher densities because they depend on the source size to the $+1.5$ and -1.5 power respectively. Also with the high emission measures found in these sources (typically $\sim 10^8$ pc cm^{-6}), they are optically thick at frequencies of 5 GHz and lower, hence detection becomes a limitation. A third factor which limits the amount of ionized gas in dense components is the presence of dust. At high electron densities Mezger *et al.* (1974) have shown that the dust competes with the gas for L_c-photons, and in the densest regions it may even absorb the major portion of the available L_c-flux. In this regard it should be emphasized that the excitation parameters listed in Table IV are only lower limits.

IV. Radio Recombination-Line Observations in H II Regions: Helium Abundances

In the past three years observations of radio recombination lines have been most active in the following areas: (1) the detection and interpretation of H recombination lines in the diffuse interstellar gas (see for example Gottesman and Gordon, 1970; Jackson and Kerr, 1971; Gordon and Cato, 1972; Davies *et al.*, 1972); (2) the observation of recombination lines of carbon and heavier atoms (with ionization potentials < 13.6 eV) which are believed to originate from cold and dense H I clouds associated with H II regions (see for example Palmer *et al.*, 1967; Zuckerman and Palmer, 1970; Simpson, 1970; Pedlar, 1970; Gordon and Churchwell, 1970; Ball *et al.*, 1970; Menon, 1970; Chaisson *et al.*, 1972; Chaisson, 1972; Chaisson, 1973b, c); (3) the mapping of H- and (in the brightest parts) He-line emission from a few bright H II regions (see for example Mezger and Ellis, 1968; Rubin and Mezger, 1969; Gordon, 1969; Gordon and Meeks, 1968; Chaisson, 1973a, b, c); and (4) the determination of helium abundances in galactic H II regions from observations of H and He radio recombination lines. Important progress in the identification of the spectra of several nebulae as thermal by the detection of radio recombination lines has been made by Milne *et al.* (1969), Wilson and Altenhoff (1970), Wilson and Altenhoff (1972), and Dickel and Milne (1972). Time limitations do not permit a discussion of all these areas of research. Since the first two areas are only indirectly related to H II regions and the third requires a detailed consideration of individual objects, I have chosen to restrict my my discussion to the fourth topic only.

(a) DO THE MEASURED INTENSITY RATIOS OF He- AND H-LINES REPRESENT TRUE ABUNDANCE RATIOS?

To answer this question it is necessary to consider non-LTE effects on both H and He lines, the geometry of the H II regions concerned, and the broadening of H and He lines. Goldberg (1966) first pointed out the importance of departures from LTE and the possibility of maser enhancement of radio recombination lines. A series of papers mostly by Hjellming and his coworkers (Hjellming and Churchwell, 1969; Hjellming and Davies, 1970; Hjellming and Gordon, 1971; Goldberg and Cesarsky, 1970) made the first non-LTE analyses of observed H-line intensities. Unfortunately all of these analyses assumed constant-density H II regions and ignored pressure broadening altogether. Griem (1967) found an analytical expression for pressure broadening of radio recombination lines in a plasma for given T_e and N_e values. However, when this expression was applied to H II regions, no attempt was made to include it properly in the transfer equation, and therefore it predicted much wider lines than were observed. Brocklehurst and Seaton (1972) have included in their solution of the equation of transfer non-LTE effects, a variable density model, and Griem's (1967) solution for pressure broadening. A constant electron temperature was assumed. In my opinion, this is the best theoretical treatment of the intensities of radio recombination lines to the present time. Observations of high-frequency radio recombination lines by Sorochenko and Berulis (1969), Churchwell *et al.* (1970), and Waltman and Johnston (1973) all find somewhat higher values of the line-to-continuum ratio than predicted by Brocklehurst and Seaton (1972). Whether this is due to observational difficulties or to problems with the theory remains to be seen. Batchelor (1974) has calculated the effect on the measured H- and He-line intensities when the He^+ and H^+ Strömgren spheres do not coincide. He used the Brocklehurst and Seaton (1972) model of Orion A for both LTE and non-LTE cases and varied the telescope beamsize and the relative size of the He^+ Strömgren sphere as independent variables. Among the important conclusions drawn by both Brocklehurst and Seaton (1972) and by Batchelor (1974) is that at high enough frequencies (i.e., $\nu \gtrsim 5$ GHz) the observed line intensity ratios of H and He should represent quite accurately the actual abundance ratio. In other words, at higher frequencies where the line and continuum optical depths are $\tau_L \ll \tau_c \ll 1$, the line ratios are largely insensitive to non-LTE effects, pressure broadening, and even to some extent the non-coincidence of Strömgren spheres. However, at lower frequencies where the optical depths are higher the line intensity ratios may bear almost no relation to the actual abundances.

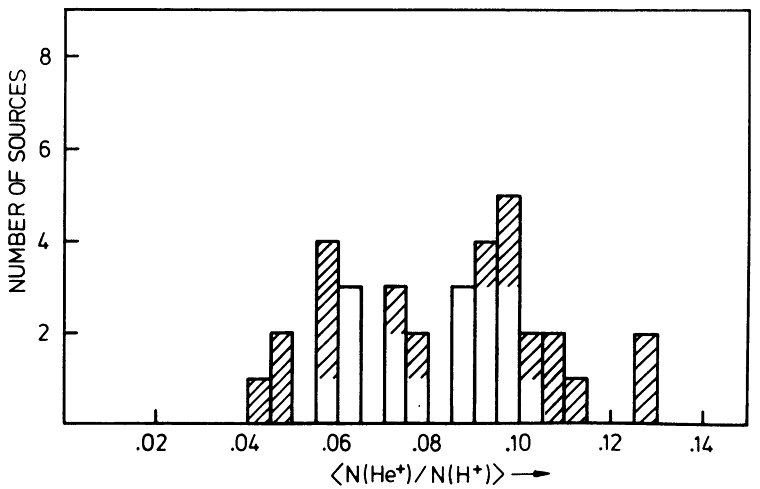

Fig. 8. Histogram showing the distribution of observed ionized He abundances (Churchwell *et al.*, 1974).

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(b) MEASURED HELIUM ABUNDANCES

Helium abundances derived from radio recombination lines have been published for only a few of the brightest H II regions (see for example Palmer *et al.*, 1969; Mezger *et al.*, 1970; Churchwell and Mezger, 1970).

Recently He- and H-line intensities have been measured at frequencies $\geqslant 5$ GHz with He-line signal-to-noise ratios $\geqslant 5$ for 39 galactic H II regions (Churchwell *et al.*, 1974). Twenty-eight of these nebulae are giant H II regions; they have intrinsic luminosities at least four times that of the Orion nebula ($N_c \geqslant 3.5 \times 10^{49}$ s^{-1}) and should therefore, have coincident He^+ and H^+ volumes. Figure 8 shows a histogram of the observed helium abundances; shaded areas indicate unconfirmed measurements (i.e., only one independent measurement is available). Three giant H II regions in the galactic center (G0.2 – 0.0, G0.5 – 0.0, and G0.7 – 0.0) are not included in this figure.

From Figure 8 we conclude that the credible range of ionized helium abundances in galactic H II regions outside the galactic center is

$$0.06 \leqslant \langle N(\mathrm{He}^+)/N(\mathrm{H}^+)\rangle \leqslant 0.10\,^*.$$

Attempts to measure the He^+ 173α line in G0.2 – 0.0, G0.7 – 0.0, W43 and W49 *A* show that

$$\langle N(\mathrm{He}^{++})/N(\mathrm{H}^+)\rangle < 0.01.$$

For the giant H II regions in the galactic center we find the limits given in Table V (Churchwell and Mezger, 1973).

The low abundance of ionized helium in the galactic center has been independently confirmed by Mezger *et al.* (1970), Chaisson (1973c), and Robinson (1973).

(c) CORRELATIONS OF MEASURED He ABUNDANCES WITH GEOMETRICAL AND PHYSICAL PARAMETERS

A check for systematic trends in the measured helium abundances with several geometrical and physical parameters was undertaken. Plots of $\langle N(\mathrm{He}^+)/N(\mathrm{H}^+)\rangle$ as a function of distance from the Sun, distance from the galactic plane, and the fraction of the nebular volume intercepted by the telescope main beam reveal no systematic trend. An apparent correlation does exist with distance from the galactic center (see Figure 9).

The abundance of ionized helium apparently increases with galactic radius to at least 7 kpc from the center; beyond 7 kpc the scatter is too large to say whether the increase continues or whether it levels off. This conclusion is based on a minimum of data and should be considered only as a tentative result until further measurements are made. It is particularly important to observe H II regions between 1 and 5 kpc from the galactic center.

No correlation is found with the H137β-to-H109α intensity ratio, which is a measure

* Angular brackets surrounding measured abundance ratios denote average values weighted by the telescope beam.

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TABLE V

Ionized helium in the galactic center

Source	$N(He^+)/N(H^+)$	$N(He^{++})/N(H^+)$
G0.2–0.0	0.025	0.008
G0.5–0.0	0.01 [a]	
G0.7–0.0	0.021	0.005

[a] Huchtmeier and Batchelor (1973)

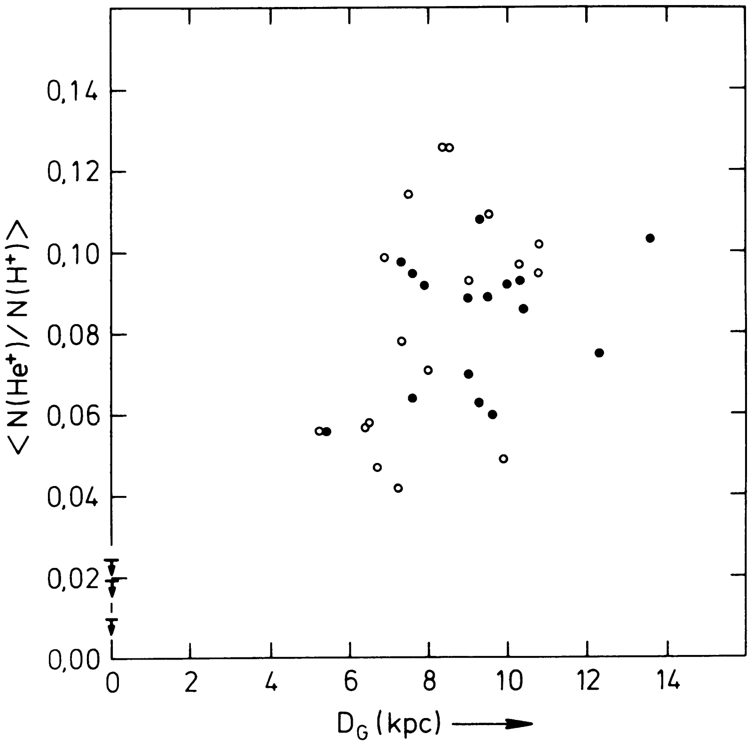

Fig. 9. Observed ionized He abundances as a function of distance from the galactic center.

of departures from LTE. This seems to confirm Brocklehurst and Seaton's (1972) prediction that the He abundance should be independent of non-LTE effects at frequencies where $\tau_L \ll \tau_c \ll 1$.

Mezger *et al.* (1974) have defined the IR excess as the difference, normalized to the Ly-α luminosity, between the integrated IR luminosity of the heated dust in H II regions and that supplied by trapped Ly-α photons. The IR excess derived from the 100 μm flux measurements of Hoffmann *et al.* (1971) is plotted against $\langle N(He^+)/N(H^+)\rangle$ in Figure 10.

The IR excess apparently increases with decreasing ionized helium abundance in

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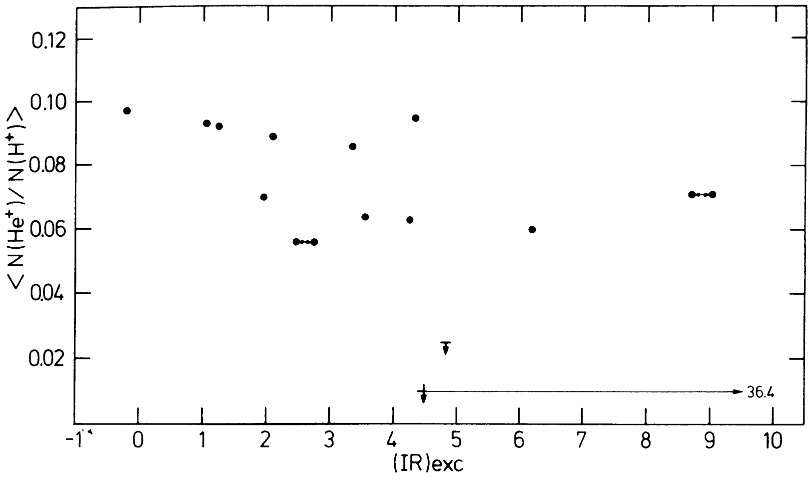

Fig. 10. Observed ionized He abundances as a function of the IR-excess radiation, i.e., IR radiation in excess of that supplied by the absorption of trapped Ly-α photons by dust in H II regions.

giant H II regions. We believe this is an indication that the dust selectively absorbs stellar photons capable of ionizing helium. Mezger *et al.* (1973) have argued that the absorption cross-section of dust must be on the average about a factor of 7 greater at wavelengths $\lambda < 504$ Å than that found at $\lambda \sim 1500$ Å by Witt and Lilley (1973).

Leibowitz (1973) has also concluded that dust selectively absorbs helium-ionizing photons; unfortunately NGC 2024, the source on which his conclusion was based, shows no ionized helium because its ionizing star is too cool and not because of selective absorption by dust.

(d) THE PROBLEM WITH LOW He^+ ABUNDANCES

More than 75% of our sample of H II regions have $\langle N(H^+)/N(H^+)\rangle < 0.10$, and $\sim 10\%$ have $\langle N(He^+)/N(H^+)\rangle < 0.065$. Doubly ionized helium is apparently negligible in all galactic H II regions. Unfortunately, no direct observational method is known for determining the neutral helium content of an H II region. Therefore it is only possible through indirect means to derive the true abundance of helium.

Churchwell *et al.* (1974) have argued that the initial helium abundance in our Galaxy was $N(He)/N(H) \sim 0.08$. Observed values of $\langle N(He^+)/N(H^+)\rangle > 0.08$ would then indicate helium enrichment in the course of galactic evolution. Present-day observations imply an average helium enrichment of ~ 0.02 by number. This value is in good agreement with that found by Talbert and Arnett (1973) for stellar evolution processes. In no case should the actual helium abundance be less than 0.08, and in general it should not be less than 0.09–0.10 after enrichment. How then can this value be reconciled with the measured He^+-abundances, which are largely less than 0.09?

We believe that dust may be responsible for the low He^+ abundances. Selective absorption by dust of photons with wavelengths $\lambda < 504$ Å could easily cause such an effect. The gas density may be as high as 10^4–10^5 cm^{-3} in bright compact H II regions, thus the density of grains is probably proportionally high. As is shown in Figure 10, the He^+ abundance decreases with increasing IR excess. In this regard, we note that Sgr B2 (G0.7 – 0.0) has the highest IR excess in our sample and one of the lowest upper limits on ionized helium. We have shown also that $\langle N(He^+)/N(H^+)\rangle$ appears to decrease with decreasing distance from the galactic center for $D_G < 7$ kpc (Figure 9). We therefore argue that: (1) the actual helium abundance in the Galaxy (including the nucleus) is constant with $N(He)/N(H) \simeq 0.10$; and (2) the ionized helium abundance in the giant H II regions in the galactic center is lowered by the selective absorption of He-ionizing photons by dust. Such an effect could be caused by an increase in the dust-to-gas ratio, by a change in composition, by a change in the distribution of grain sizes, or some combination of these toward the galactic center.

The observations could also be explained if H II regions toward and in the galactic center are ionized by O9 or cooler stars. We favor the dust interpretation for three reasons: (1) very large numbers of O9 stars would be required to ionize the gas in the galactic center; (2) it is questionable whether cooler stars could account for the inferred IR excess in the galactic center; and (3) the molecules in the massive molecular clouds in the galactic center probably depend on dust for their formation and subsequent protection from the intense radiation field implied by the ionized gas. It may be that the observed increase of N and O from the edge to the center in M33 and M101 by Searle (1971) and in M31 by Rubin *et al.* (1972) is also related to an increase in the dust-to-gas ratio or to a change in the properties of dust toward the nuclei in these galaxies.

It is, of course, possible that the observed variation in He^+ abundances reflects a a variation in the actual He abundance; however, this is, in my opinion, fraught with many more difficulties than the explanation which we offer here.

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E. Churchwell
Max-Planck-Institut für Radioastronomie,
Auf dem Hügel 69,
53 Bonn 1, F.R.G.

DISCUSSION

Menon: Photographs exist in the literature which show that surrounding the Orion nebula there is a highly symmetric faint H II region of extent of about 3°. This H II region can be attributed to escaped Lyman continuum photons from the density-bounded Orion nebula. The molecular clouds attributed to the CO emission are presumably within this H II region.

Habing: To some extent I agree and to some extent I disagree with your statement that star formation is not an efficient process. If one looks at the W3 map that you showed it follows that only on a large scale a lot of matter is left over after the star formation. However, on a small scale, this is not true – see, for example, the ionized hydrogen mass in W3 *B*. So it appears that in the later phases of the collapse, when the fragmentation has led to the formation of objects like W3 *B*, the stellar formation is extremely efficient.

Churchwell: This is what I meant to point out with regard to the analysis of mass in W3 *B* where $\sim 60\%$ of the ionized gas is in compact components.

Gordon: Sometimes recombination lines from H II regions have asymmetrical shapes. These have been interpreted as blends of lines from the H II region and lines from foreground H I. Could the asymmetrical shape be due entirely from the small-scale component within the H II regions now seen with interferometers?

Churchwell: I think the analysis of Brocklehurst and Seaton (1972) has shown that except at relatively high frequencies the compact components in H II regions will contribute very little to the line intensities. On this basis I would not expect large line asymmetries in recombination line profiles in H II regions due to high density components except at quite high frequencies where few line measurements have been made.

Jenkins: In support of the idea that there is an observable emission measure between known H II regions you mentioned the diffuse Hα emission recorded by Courtès and others. Is there any likelihood that interstellar dust grains have a high enough albedo and are plentiful enough to scatter or reflect Hα photons from the H II regions and produce this diffuse contribution?

Churchwell: I suspect it is possible that some of the Hα emission in the spiral arm regions of the galactic disk is due to scattered Hα photons from stars, but I have no idea how much. I believe that Peimbert and his co-workers have argued that most Hα emission seen in the disks of galaxies is largely due to re-combinations.

Monnet: There are in fact two different kinds of diffuse emission – one in the spiral arms, one between the spiral arms in the disk. It is completely impossible that the emission in the disk can come from scattered light from the classical H II regions, as the ratios of Hα/[N II], Hα/[S II], Hβ/[O II] in the disk are very different than those in the classical H II regions. On the other hand, the diffuse arm emission which has a filamentary structure with a typical size of 100 pc can be – at least partly – due to scattered light.

Guélin: The amount of scattered light has been estimated by others at between 0 and 30%. On that kind of estimation, you can be off by a factor of 3 or 4; that means that you cannot determine it.

Van Woerden: At Westerbork, Sullivan and Downes have not only measured the continuum but also looked for the recombination lines. He166α and C166α were below their detection limit. H166α was detected in one concentration (the strongest one), at a velocity agreeing with single-dish observations, with $T_b = 22 \pm 5$ K, that is, 0.4% of the continuum. The line flux in this concentration is only 1% of that measured with single-dish antennas. The latter must almost completely come from structures with scales $> 5'$. This is in agreement with the Brocklehurst and Seaton (*Monthly Notices Roy. Astron. Soc.* **157** (1972), 179) theory.

Churchwell: I point out also with regard to these measurements that with a beam of $\sim 25''$ the carbon line was not seen in absorption. Therefore one wonders about the beam dilution spoken of by Zuckerman.