STAR FORMATION AT A FRONT: G 134.2+0.8

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ABSTRACT

The Westerbork Synthesis Radio Telescope has been used at λ 6 cm to obtain higher-resolution maps (7″.9×9″.0) of the H II region G 134.2+0.8. The H II region is produced by a young B0.5 star which has formed in the dense region ahead of a shock front which is being driven by stellar winds, and which is moving into a molecular cloud. The front has passed over the star which is now situated in the ionized shell behind the front. The resulting drop in ambient density probably accounts for the anomalously low electron density of the H II region. The parameters of the region are determined.

I. INTRODUCTION

The general problem of how and where stars of various types form is somewhat complex. Some progress has been made observationally in the case of early-type stars which seem to form toward the outside of clouds, disperse their surrounding gas comparatively quickly, and appear optically together with their associated H II regions. B-type stars are often embedded in dark molecular clouds, but can be detected by observing both the radio emission from their optically obscured H II regions, and the associated infrared emission. More progress has been made on the theoretical side. In a large number of cases, external pressure from a shock wave appears necessary to initiate the self-gravitational collapse of part of a cloud. In one mechanism Woodward (1976) has shown theoretically how condensations can form on the ouside of a cloud owing to the passage of the shock associated with a galactic spiral density wave. In other mechanisms, induced star formation could be produced by cloud-cloud collisions (Loren 1976), by the expansion of both supernovae remnants (Wootten 1977; Herbst and Assousa 1977) and H II regions (Elmegreen and Lada 1977), or in ionization fronts (Chevalier and Theys 1975; Giuliani 1980).

Recently, Hughes and Vallée (1978) have demonstrated that for a number of sources the infrared luminosity near λ 100 μm (Fazio *et al.* 1975) is nearly equal to the total luminosity of the star required to excite the radio H II region. This near equality suggests that most of the radiation from the star is absorbed by the surrounding dust, and implies that the physical parameters of the exciting star—spectral type, mass, and luminosity—can be inferred with some certainty even though the star is optically obscured.

One source of particular interest is that designated IRS 5 by Fazio *et al.* or as infrared source AFGL 333 by Price and Walker (1976). In this paper it is referred to as G 134.2+0.8. It shows evidence for the formation of an isolated B0.5 star (Vallée and Hughes 1978) as a result of the influence of the shock front centered on the OB association within IC 1805 (Vallée, Hughes, and Viner 1979, hereafter referred to as VHV). The OB association appears to have formed about 10^6 yr ago and to have dispersed its surrounding gas either by the continuous action of stellar winds or by a single supernova event early in its history.

Further infrared measurements at λ 50 and λ 100 μm by Thronson, Harvey, and Gatley (1979) essentially confirmed that the infrared luminosity indicated a spectral type for the exciting star which was similar to that deduced from the radio results. But they pointed out that the star appeared to be young and thus could be assumed to have condensed out from a molecular cloud with density $> 10^7$ cm^{-3}, yet the electron density of the H II region was less than 1000 cm^{-3}. A number of possible explanations were given, namely, that the star condensed from a low-density region, that the star could be very much older, that the star has moved from its place of birth, or that the stellar formation efficiency is low. Since the detailed mechanisms of star formation are of considerable importance, the region has been reexamined with the greater angular resolution (about 9″) of the Westerbork Synthesis Radio Telescope at λ 6 cm. The observations and results are described in Secs. II and III and discussed in Sec. IV. It is concluded that the star probably formed in the dense region ahead of the shock front, but that this shock has now moved across the star and is being maintained by stellar winds from the OB association in IC 1805. Parameters for the region are derived.

II. OBSERVATIONS

The observations were made with the Westerbork Synthesis Radio Telescope (WSRT) at λ 6 cm (4.995 GHz) on 1980 February 10. The source was observed for a total of 12 hr with the two movable telescopes posi-

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tioned 36 and 108 m beyond the westernmost telescope of the fixed array; a total of 18 interferometers was used with spacings of 36–1260 m in steps in 72 m. A more detailed description of the WSRT has been published elsewhere (Baars *et al.* 1973; Högbom and Brouw 1974; van Someren Gréve 1974). The data were Fourier transformed (Weiler 1973), the CLEAN procedure used (Högbom 1974), and the map restored using a beam in the form of the synthesized beam between first zeros. The map thus contains a spectrum of angular frequencies for the area from the highest frequency, which corresponds to the synthesized beam of 7″.9×9″.0, to the lowest, which corresponds to the minimum spacing or about 3′. This means that, for example, a Gaussian source with a half-power beamwidth of 2′ will have a visibility of only 0.6. The instrumental data are summarized in Table I.

TABLE I. Equipment parameters.

Observing wavelength	6 cm	
Single-dish beam pattern HPW	11′	
No. of spacings	18	
Minimum baseline	36 m	599.9λ
Maximum baseline	1259.9 m	20 992.4λ
Incremental spacing	72 m	
Highest resolution (R.A.×Dec.)	7″.9×9″.0	
Radius of first grating response (R.A.×Dec.)	2′.9×3′.3	
Observing time	12^h	
rms noise at field center	0.1 mJy	
Field center, R.A.×Dec. (1950)	$2^h24^m35^s$	61°15′00″

III. RESULTS

The basic results are shown in the map of the area covering 9′×9′ (R.A.× Dec.) in Fig. 1, and the enlarged map of the area covering 2′.5×2′.5 in Fig. 2. In addition, a further map was produced but convolved with an antenna beam 23″×26″, which is the same resolution as that of the λ 21-cm map obtained by VHV also using the WSRT. However, apart from minor variations in the lowest contour levels, it was identical to the λ 21-cm map and is not shown here.

The map of Fig. 1 shows the isolated H II region G 134.2+0.8 together with some low-level contours to the north and south of it. Some of the emission at a distance of about 3′ from the H II region could be the result of the first-order grating response, the second-order grating response being seen in the southeast corner of the map. However, the emission within 3′ from the H II region appears to be real and exists also in the λ 21-cm map, where the first-grating response is at a radius of 20′. The ridge at λ 6 cm is less extended than at λ 21 cm, principally as a consequence of the virtual rejection of angular components greater in extent than about 3′. There is also a small decrease with distance from the center of the map since no correction was applied for the fall off in the

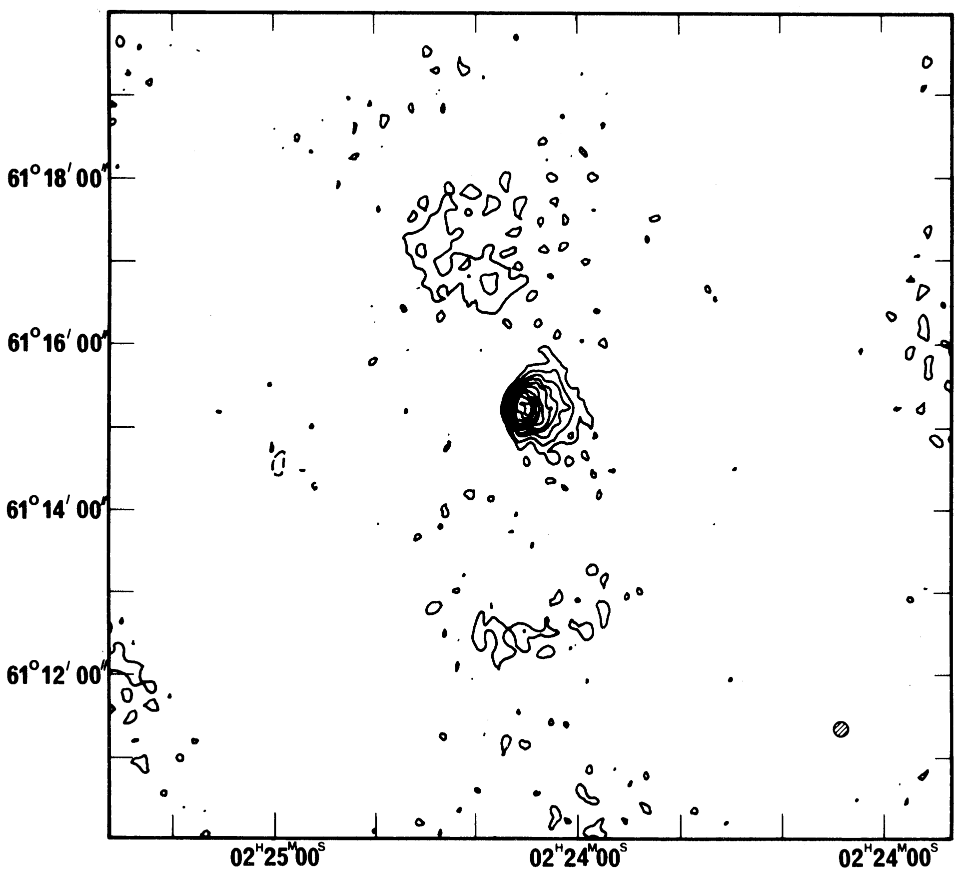

FIG. 1. A map of the area 9′×9′ at λ 6 cm centered on the H II region G 134+0.8. Contour levels are at 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 mJy/beam area. The size of the antenna beam, 7″.9×9″.0, is shown by the shaded area in the bottom right-hand corner.

primary beam. The fact that the emission breaks up into a large number of small regions could indicate small blobs or instabilities, but more likely they are the peaks of noise fluctuations on top of a ridge of low-level emission running north-south. This is discussed further in Sec. IV.

In the enlargement of the central region, as shown in Fig. 2, the H II region is lacking in structure except for the distinct compression of the contours to the east. In Sec. V we attribute this to the stellar wind produced by the OB association which has driven a shock front from east to west across the map.

Thus, qualitatively, the present λ 6-cm results, when combined with the previous λ 21-cm results (VHV), show a simple H II region which has been identified with a B0.5V star both by VHV, and by Thronson *et al.* (1979) in the infrared. The H II region is situated near a weak ridge of emission which runs approximately from north to south, and which is attributed to ionized gas. The λ 4.6-cm map obtained at the Algonquin Radio Observatory (ARO) with a resolution of 4'.6 (VHV), also shows a ridge but somewhat to the east of the WSRT one. It will be shown in Sec. IV b that both are produced by the same ionized shell.

IV. ANALYSIS

a) The H II Region G 134.2+0.8

The total flux density of the H II region G 134.2+0.8 at λ 6 cm was determined by integrating over the surrounding region of size 1'.1 × 1'.1. The result was 173 mJy. However, there appears to be a low-level plateau at 0.5 mJy/beam area which could be associated with either the H II region or, quite possibly, the ridge of emission. If we correct for the latter, the flux density is 154 mJy, compared with the value of 146 ± 10 mJy obtained at λ 21 cm. The results are consistent with the fact that the H II region is thermal and optically thin, shows no obvious complications, and is the result of the presence of a single early-type star situated at its center. If we adopt a distance to the H II region of 2.3 kpc (Georgelin and Georgelin 1976), then its radius is approximately 0.15 pc, or 31 000 AU. A simple analysis can then be carried out to determine the type of star responsible for the ionization.

It can easily be shown that for an ideal spherical and optically thin H II region, the flux density is given by

$$S = 3.88 \times 10^{6}[17.7 + \ln(T^{3/2}/\nu)]T^{-1/2}U^{3}D^{-2}, \quad (1)$$

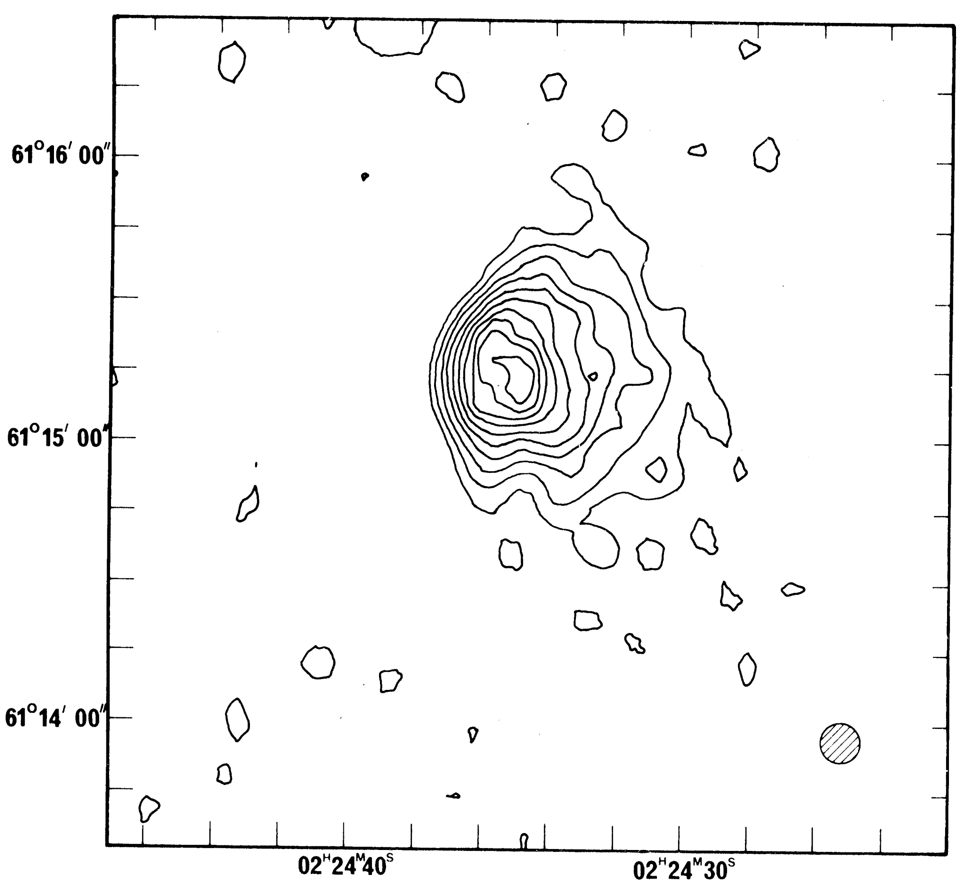

FIG. 2. Enlargement of the central 2'.5 × 2'.5 of the map in Fig. 1. Contour values are as in Fig. 1. The size of the antenna beam is shown by the shaded area in the bottom right-hand corner.

where S is in mJy, T (K) is the temperature of the H II region, U (pc cm^{-2}) is the excitation parameter, and D (pc) is the distance. Then assuming $T=10^4$ K, $D=2300$ pc, $\nu=4.995\times10^9$ Hz,

$$S=6.7\times10^{-2}U^3, \qquad (2)$$

and for $S=$ 140–157 mJy, $U=13$. The value of U is fitted to the stellar models by Panagia (1973) to determine the spectral type and total luminosity; the mass of the star is determined from the commonly assumed relationship that $\log(L/L_\odot)\simeq4\log(M/M_\odot)$. Given the mass, the time taken to contract onto the main sequence is obtained from the work by Iben (1965). Parameters derived for the H II region and exciting star are shown in Table II.

The small-scale fluctuations, chiefly to the north and south of the H II region, show up at the 1-mJy level in comparison with the estimated rms noise of 0.1 mJy. However, such fluctuations could be produced by noise peaks sitting on top of a ridge of emission. If they are produced by weak H II regions, then 1 mJy corresponds to $U=2.5$ pc cm^{-2}, which in turn corresponds to a B2V star with mass of $8M_\odot$, luminosity $4.4\times10^3L_\odot$, which would take about 1.6×10^5 yr to contract onto the main sequence. The presence of such a large number of stars in the region seems unlikely.

b) The Ionized Shell

The ridge of emission running almost north-south through the H II region, shown weakly in the λ 6-cm and more strongly in the λ 21-cm results, is probably due to a shell of ionization produced by the OB association at its center, and an estimate can be made of the electron density. Since the width of the ridge is about 1$'$.5, or 1 pc, and the radius from the OB association is about 31$'$, or 21 pc, the maximum path length through the shell is 13 pc. From the maximum contour levels of about 2 mJy and the beamwidth of 7$''$.9 $\times$ 9$''$.0, the maximum brightness is 2.3×10^6 Jy sr^{-1}. The corresponding emission measure is $E=2.7\times10^4$ pc cm^{-6}, and for an electron temperature of 10 000 K, the rms electron density is $n_e=46$ cm^{-3}.

The ARO data at λ 4.6 cm, with an angular resolution of 4$'$.6 (VHV), also shows a wide ridge running north-south, but displaced to the east of the WSRT position by about 6$'$.5. However, though a thin shell will produce a peak when its rim is observed with a narrow beam—as is seen with the WSRT observations—if the beam is so large that it cannot resolve the rim, the maximum flux will be expected to occur when the antenna is pointing inside the projection of the shell. To test this, a hypothetical shell of radius 31$'$.5 and thickness 1$'$.6 was convolved with an antenna beam of diameter 4$'$.7. As expected, the maximum signal occurred with the antenna pointing inside the tip of the shell and at a point where the path length through the shell was about 40% of the maximum. Thus, if we assume that the ridge at λ 4.6 cm is due to the shell, the flux density of about 1.1 mJy per beam corresponds to a brightness of 1.12×10^6 Jy sr^{-1}, or an emission measure of $E=1.3\times10^4$ pc cm^{-4}. Since the path length is only about 40% of 13 pc, the corresponding electron density in the shell is $n_e=50$ cm^{-3}, assuming, as appears to be the case, that the electron density behind the shell is very much smaller (VHV). This is in remarkable agreement with the value determined from the WSRT data, and gives confidence that the ridges of emission seen in the data are due to a shell of ionization of thickness 1 pc with an electron density of 50 cm^{-3}, based on an electron temperature of 10 000 K.

It can be shown that, assuming no absorption behind the shell, the total Lα continuum flux, S_0, originating at the OB association and required to produce the ionization is given by

$$S_0=4\pi R^2tN^2\alpha \quad \text{(photons s}^{-1}\text{)}, \qquad (3)$$

where R is the radius of the shell, t is its thickness, N the electron density, and $\alpha\simeq2.6\times10^{-13}$ cm^{-3} s^{-1} is the recombination coefficient of hydrogen to all states but the ground state. Inserting the values for the shell, we obtain $S_0=10^{50}$ photons s^{-1}. Since the OB association contains about nine O stars, and the value of S_0 for, say, an O6V star is $S_0=1.7\times10^{49}$ s^{-1}, the ionization can clearly be produced by the OB association. These results lead to a somewhat more refined model than that postulated by VHV.

TABLE II. Parameters of H II region and exciting star.

H II region G 134.2+0.8	
Coordinates (1950.0)	R.A. = 02^{h}24^{m}35^s.26 ± 0^s.15
(of radio peak)	Dec. = +61°15$'$14$''$.1 ± 0$''$.3
Total flux density	173 mJy
Corrected for ridge	154 mJy
FWHM (R.A. × Dec.)	25$''$ × 29$''$
Linear size	0.28 × 0.32 pc
Excitation Parameter	13 pc cm^{-2}
Electron density	450 cm^{-3}
Infrared luminosity[a] ($\lambda\geqslant30$ m)	$1.4\times10^4L_\odot$
Exciting star	
Spectral type	B0.5
Mass	$13M_\odot$
Luminosity	$3.0\times10^4L_\odot$
Time to contract onto MS	5.5×10^4 yr
Ionized shell	
Thickness of shell	1 pc
Electron density	50 cm^{-3}

[a]Thronson *et al.* (1979).

V. DISCUSSION AND CONCLUSIONS

The above analysis, when combined with that by VHV, has shown in some detail the physical conditions that exist near a newly formed star. The star is identified from its excitation parameter, which in turn is determined by the radio emission from the H II region, and confirmed from infrared observations. It is situated in or close to a thin shell of ionization due to the Lα emission from an OB association. This shell is not powering the expansion but is on the inside of a larger-diameter, denser region, which is produced by a stellar wind from the OB association. That the shell is powered by stellar winds rather than by an old supernova explosion is evidenced by the compression of the H II region in the direction of the OB association. According to VHV, the present expansion velocity of the stellar wind bubble would be about 19 km/s.

In a previous analysis, Hughes and Vallée (1978) showed that the luminosity of the star, as derived from the parameters of the H II region, approximated the λ 100-μm luminosity as derived by Fazio *et al.* (1975). However, more recent observations by Thronson *et al.* (1979) revised the value for luminosity to $1.4\times10^4 L_\odot$ at λ 100 μm, compared with the value of $3.0\times10^4 L_\odot$ from the radio results. But they show also that the radio source is biased toward the west of the infrared source, toward denser regions of the expanding shock wave. This immediately suggests that the difference in the two luminosities could be due to leakage of the infrared radiation to the east, where the density of absorbing dust will be much smaller.

Thronson *et al.* point out that the electron density of the H II region is remarkably small if it reflects the atomic density of the region from which the supposedly young star formed. However, since the excitation parameter is known, we can use the normal physical treatment for the expansion of an H II region (e.g., Spitzer 1978) to estimate the original density if the age is known. Thus, if N is the present density, N_o the original density, U the excitation parameter, and t_4 is the age in 10^4 yr,

$$N \simeq 2.9 N_o^{3/7} U^{6/7} t_4^{-6/7}\ \mathrm{cm}^{-3}$$

$$\simeq 26 N_o^{3/7} t_4^{-6/7}\ \mathrm{cm}^{-3},$$

assuming that $U = 13$ pc cm^{-2}. If $N = 450$ cm^{-3}, and $t_4 = 6$, then $N_o = 2.8\times10^4$ cm^{-3}, or if $t_4 = 10$, then $N_o = 7.7\times10^4$ cm^{-3}. However, subsequent to triggering formation of the B0.5 star, the shock front would have moved at least 1 pc to the west, leaving the newly formed star in a lower-density region of about 50 cm^{-3}, into which it would have expanded more rapidly. Hence the above equation is not applicable, and the "problem" of the low density at the H II region has a natural explanation. Some evidence for this expanding gas may be seen around the H II region where the emission from the ridge is somewhat reduced.

The scenario for star formation in this particular case appears to be one where an expanding shock wave, produced by stellar winds from an OB association, moves into the denser region of a molecular cloud, leading to the collapse of a small region ahead of the front to form a star. The shock wave continues to move ahead and across the star, which is now situated close to the ionized shell on the inside of the expanding gas produced by the Lα radiation from the OB association. Thus it seems likely that star formation occurred at the edge of the molecular cloud where it is compressed to quite high densities by the shock wave, as shown by the fact that there is at least 12^{m} of extinction in the direction of the H II region (Vallée and Hughes 1978). It was not in the center of a molecular cloud, nor was it in an ionization front as is suggested in the mechanism by Giuliano (1980), or at a shock front with subsequent forward projection as suggested from the mechanism by Chevalier and Theys (1975). It should be noticed that only one B0.5V star appears to have formed, whereas a number of earlier-type stars appear to form when shock fronts on a larger scale occur, such as those associated with galactic spiral arms.

Two other observations of star formation in shock fronts have been reported. Loren and Wootten (1978) have observed a bright infrared source within a bright-rimmed dust cloud at the edge of the IC 1848 H II region, which they attribute to a B0.5 or B1 star. The star is associated with the position of the greatest CO excitation in a dense molecular cloud. More recently Felli, Johnston, and Churchwell (1980) have detected a radio point source in M17 which they associate with a B0 star that has been induced to form by a partially focused shock front, preceding the ionization front, which is propagating into a molecular cloud. The particular case mentioned in the present paper gives more detail of the region of star formation. Of additional interest is the fact that all three observed cases of star formation are in small-scale shock fronts, and it is stars of spectral type B0–B1 that are formed. Some stars of later type may be forming, but if so they do not have sufficient Lα output to produce a detectable H II region, and in any case they would not yet be expected to have come onto the main sequence. It would appear that stars of earlier spectral type form elsewhere, probably at larger-scale shock fronts at the leading edges of spiral arms, as has been seen in a number of cases.

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