THE ASTROPHYSICAL JOURNAL, **204**:781–788, 1976 March 15

CARBON RECOMBINATION LINE OBSERVATIONS OF THE SHARPLESS 140 REGION

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Received 1975 July 28

ABSTRACT

Carbon recombination line emission has been detected at two frequencies from a dark cloud contiguous with the small H II region Sharpless 140. The observations show the dark cloud to be of unusually low temperature and to have a markedly inhomogeneous density distribution, with localized regions of high density surrounding one or more embedded stars. The carbon is probably ionized by photons from both the exciting star of S140 and the embedded stars. The dark cloud and S140 apparently represent two stages of star formation which have occurred over a period of at least 5×10^5 years in adjacent regions of the same dark cloud.

Subject headings: nebulae: individual — radio sources: lines — star formation

I. INTRODUCTION

Recently, we have begun an investigation of the properties of regions of ionized carbon (C II Strömgren spheres) surrounding early-type stars embedded in dark clouds, using observations of radio-frequency recombination lines (Brown *et al.* 1974; Knapp, Brown, and Kuiper 1975; hereafter Papers I and II, respectively). In these papers, we showed that the average physical properties of such regions may be derived from observations at several frequencies of the carbon recombination line emission. In the present paper, we discuss a C II region in the dark cloud L1204 (Lynds 1962), a few arc minutes northeast of the emission nebula Sharpless 140 (Sharpless 1959).

S140 is a small H II region excited by the stars HD 211880 (BD +62°2061, spectral type B0 V) and BD +62°2060 (B2 V) (Hiltner 1956; Crampton and Fisher 1974), and is ionization-bounded on its northeastern edge by the dark cloud L1204. Blair and Vanden Bout (private communication, and 1974) have recently found a CO "hot spot" and a strong 2 μ infrared source in this cloud at $\alpha(1950) = 22^h17^m.6$, $\delta(1950) = +63°04'$ ($l = 106°.8$, $b = +5°.3$), about 9′ north of HD 211880. Since the infrared object is likely to be an embedded early-type star, we have searched at this position for carbon recombination line emission. This was found at two frequencies (2.27 and 1.43 GHz), and the analysis suggests that this dark cloud is of unusually low temperature, with strong density fluctuations. A reproduction of part of the red print of this region from the Palomar Observatory–National Geographic Society Sky Survey, with the telescope beamwidth used for the observations, is presented in Figure 1. We have also carried out observations of the 6 cm H_2CO line and the 2.6 mm CO line at this position, as well as of the H 166α line for S140.

* Operated by Associated Universities, Inc., under contract with the National Science Foundation.

II. OBSERVATIONS

As we showed in Papers I and II, observations of carbon recombination lines at different frequencies using telescopes with the same beamwidth allow us to derive a set of physical parameters (n_e, the electron density in cm^{-3}, and T_e, the electron temperature in kelvins) of the C II region. The observations to be described below were made of the C 142α and C 166α lines with telescopes of the same beamwidth; a search for C 110α emission using higher spatial resolution was also made.

a) C 142α *Observations*

Observations of the C 142α line at 2.27 GHz (13 cm) were made in 1974 October with the 26 m Venus antenna of the NASA Deep Space Network at Goldstone, California. The zenith system temperature was ~18 K, the beam efficiency (η_B) ≈65 percent, and the beamwidth ≈21′. The spectral line observations were made using a 64-channel one-bit autocorrelation receiver with a total bandwidth of 0.5 MHz (~1.3 km s^{-1} per channel). The total-power method of observing was used, with a total observing time of ~12 hours.

TABLE 1

RECOMBINATION LINE OBSERVATIONS OF S140

Line	ν(GHz)	Ω_B (arcmin)	T_A (K)	V_{LSR} (km s^{-1})	Δv (km s^{-1})	P_L (K × kHz)
C 142α............	2.273	21.0	0.010 ± 0.006	−9.0 ± 0.7	1.8 ± 0.7	0.30 ± 0.10*
C 166α............	1.425	22.5	0.050 ± 0.015	−9.0 ± 0.7	2.6 ± 0.7	0.80 ± 0.30
C 110α............	4.88	6.0	< 0.02	...	...	< 1.2
^{12}CO.............	115.3	2.5	22.0	−9.0	...	...
Hα(S140)..........	...	...	...	−12.9[1]	...	...
BD +62°2060.......	...	...	...	−13.7 (stellar)[2] −1.0 (interstellar)[2]	...	...
HD 211880.........	...	...	...	−7.4 (stellar)[2] −6.5 (interstellar)[2]	...	...
†H 166α...........	1.42	21.0	0.018	−4 ± 2	22 ± 2	...

* P_{142} calculated assuming $\Delta v = 2.5$ km s^{-1} for C 142α line.

† Continuum temperature = 0.9 K.

REFERENCES.—[1] Courtès *et al.* 1968. [2] Crampton and Fisher 1974.

b) C 166α *Observations*

Observations of the C 166α line at 1.43 GHz (21 cm) were made in 1974 October with the 40 m telescope at the Owens Valley Radio Observatory. The telescope beamwidth was 22′.5 at this frequency, the beam efficiency was ~75 percent, and the system temperature ~80 K. The observations were performed with a 100-channel autocorrelation receiver, using a total bandwidth of 625 kHz (~1.3 km s^{-1} per channel). The frequency-switching mode was used, with a total integration time of ~15 hours. The resultant C 142α and C 166α profiles are presented in Figure 2.

c) 6 *Centimeter Observations*

The 6 cm C 110α line at 4.88 GHz was observed in 1975 February using the NRAO 43 m telescope and the dual-channel cooled paramp. The beam efficiency of the telescope in its Cassegrain configuration is ~65 percent, the beamwidth ~6′, and the system temperature ~55 K. A total bandwidth of 5 MHz (≡1.6 km s^{-1} per channel) was used. A total integration time of 3 hours was used; no line was detected.

The results of the above observations are summarized in Table 1, which gives the observed line; its frequency; the telescope beamwidth; the peak antenna temperature in the line, T_A(K); the velocity relative to the local standard of rest, v_{LSR} in km s^{-1}; the velocity half-width Δv in km s^{-1}; and the power in the line, P_L, defined as

$$P_L = \frac{T_A \Delta \nu}{\eta_B} \text{ K} \times \text{kHz} . \quad (1)$$

The quoted errors in Table 1 are 2 σ. Also given in Table 1 are the CO velocity (see below), the Hα velocity of S140 (Courtès *et al.* 1968), the velocities of HD 211880 and BD +62°2060 (Crampton and Fisher 1974), and the H 166α parameters for S140 (see below).

d) *Observations of the* H_2CO, CO, *and* H 166α *Lines*

To help in our understanding of the region, we have also carried out observations of the above lines. The 6 cm H_2CO line and the 2.6 mm CO line were both observed at the position of the infrared source; the H 166α line at the position of HD 211880. The H_2CO observation was made in 1975 May with the 26 m telescope (of the University of California, Berkeley) at Hat Creek, California; the beamwidth was 11′ and the velocity resolution 0.15 km s^{-1}. No emission or absorption greater than 0.08 K was detected. The observation of the ^{12}CO line was made in 1975 May with the 4.6 m antenna of the Aerospace Corporation, El Segundo, California. The beamwidth was 2′.5 and the velocity resolution 0.65 km s^{-1}. The observed profile is shown in Figure 3. The H 166α line was observed in 1975 June with the NRAO 43 m telescope. The beamwidth was 21′ and the velocity resolution 2.8 km s^{-1}. The observed parameters for the H 166α line are given in Table 1. No emission in the C 166α line was detected at the position of S140 itself.

The observed carbon recombination lines are all extremely narrow, as are those observed in other dark clouds (cf. Papers I and II), and the closeness of their central velocities to that of the CO line (rather than to that of the H II region) suggests that they arise from C II transitions in the dark cloud itself, and not in S140. The observations described above will now be used to investigate the physical parameters of the S140 C II region.

III. PHYSICAL PARAMETERS OF THE S140 C II REGION

a) *Electron Temperature and Density of the Region*

In Papers I and II, we showed how sets of values of n_e and T_e can be calculated from the ratios of the powers in two lines at different frequencies observed with the same telescope beamwidth, using values of the non–LTE departure coefficients b_n, and their slopes, S_n, which for the following analysis we have taken from Dupree (1972). In the present case, the ratio of the powers in the C 142α and C 166α lines, P_{142}/P_{166}, is 0.38. Viable solutions to the transfer equation give $T = 10$ K, $n_e = 0.05$ or 0.15 cm^{-3}. In fact, the low value of P_{142}/P_{166} suggests that $T < 10$ K, so that this C II region probably has a fairly low

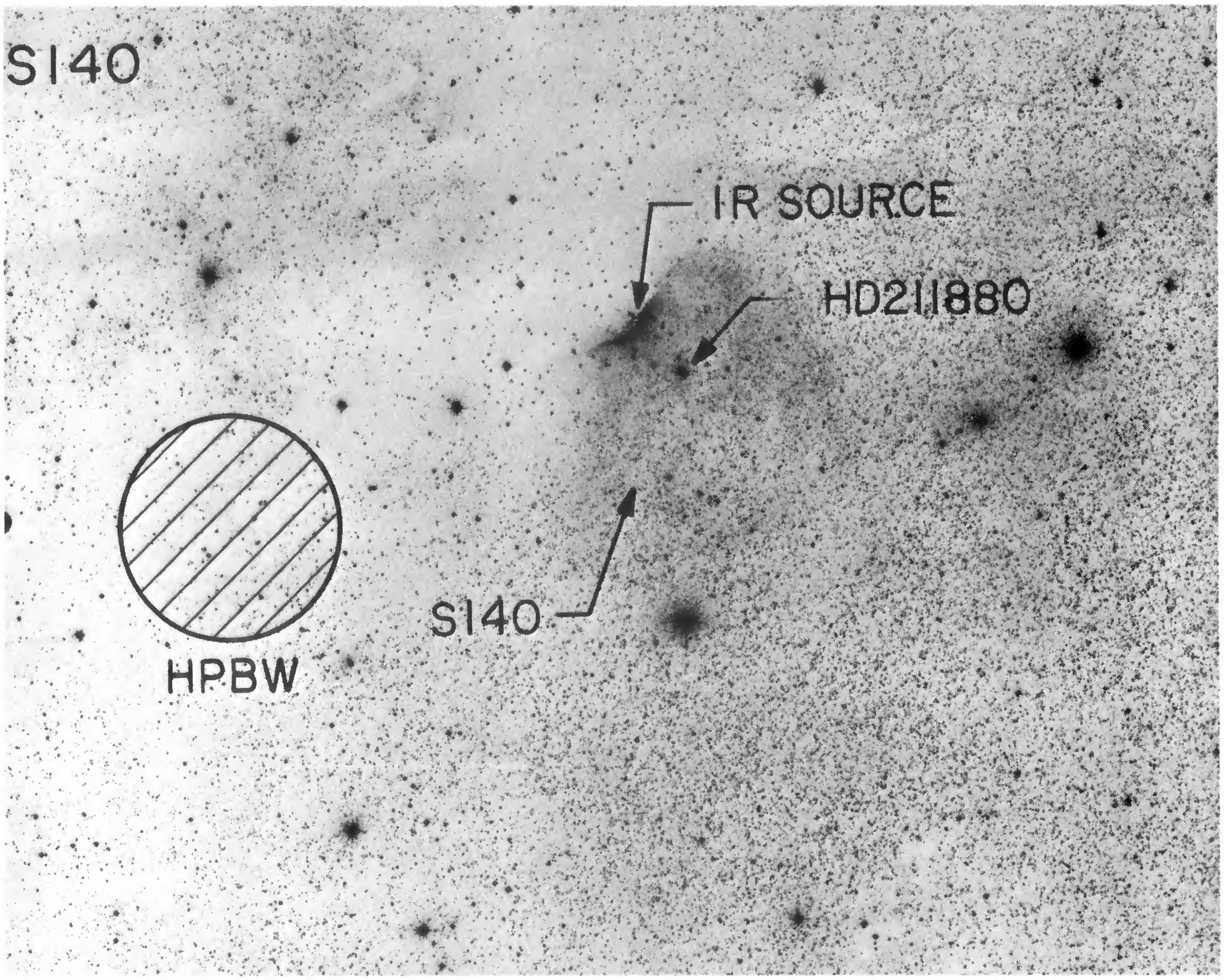

FIG. 1.—The region around Sharpless 140, reproduced from the Palomar Observatory–Sky Survey E-print. The positions of S140, its exciting star HD 211880, and the size of the telescope beam used to make the carbon-line observations, are indicated. (Copyright by the National Geographic Society–Palomar Observatory Sky Survey; reproduced by permission from the Hale Observatories.)

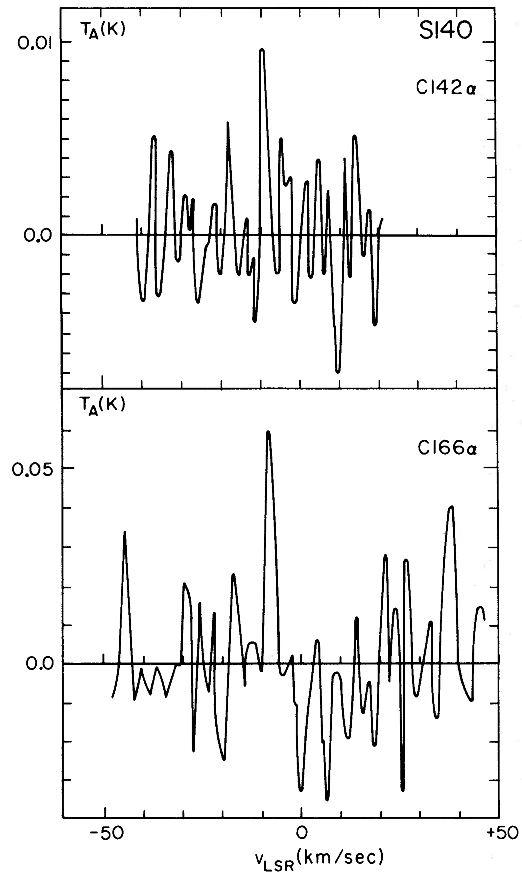

FIG. 2.—C 142α (2.27 GHz) and C 166α (1.43 GHz) lines observed in the direction of the infrared source near S140.

temperature, close to that usually found in dark clouds not associated with regions of star formation (cf. Heiles 1972).

We can decide between the two possible values of the electron density by considering the physical size of the C II region. The power emitted in the C 166α line is:

$$P_L = 1.14 \times 10^4 \frac{f_n b_n}{n}\left(1 - \frac{T_0 \beta}{T_e}\right) T_e^{-3/2} n_e^2 l \times \exp\left(\frac{1.579 \times 10^5}{n^2 T_e}\right), \quad (2)$$

where $n = 166$, T_0 is the background temperature, $n_e^2 l$ is the emission measure in cm^{-6} pc, and the rest of the symbols have their usual meanings (see Gordon 1973). The background temperature is difficult to estimate, because S140 is close to a region of confused emission (see Felli and Churchwell 1972), but we estimate T_0(total) = 4.4 K at 1.4 GHz.

Taking $T_e = 10$ K, we find that if $n_e = 0.05\ \mathrm{cm}^{-3}$, $l \geq 14$ pc; if $n_e = 0.15\ \mathrm{cm}^{-3}$, $l \geq 2.1$ pc (where the inequality holds because we do not know whether or not the C II region fills the beam).

Examination of the Palomar Observatory Sky Survey prints of this region (see Fig. 1) shows an

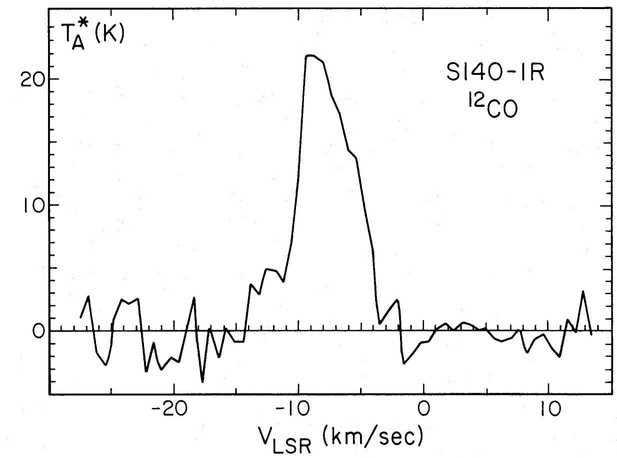

FIG. 3.—^{12}CO line observed at the position of the S140 infrared source. The ordinate is line temperature expressed in units of equivalent brightness temperature.

ionization front between S140 and the dark cloud L1204 (suggesting interaction between the objects), and many foreground stars visible over the face of L1204, indicating a fairly large distance for the cloud. The distance to HD 211880 is 910 pc (Crampton and Fisher 1974), and hence L1204 and the C II region are at this distance. The projected diameter of L1204 is then ~5 pc, and thus the higher value of the electron density (0.15 cm^{-3}, which corresponds to a linear size of ~2 pc) is more likely.

b) Total Particle Density of the C II *Region*

We can obtain a firm lower limit to the average particle density in the C II region by assuming that the carbon is undepleted and that all of it is singly ionized. Then, using the cosmic abundance of carbon ([C/H] = 3×10^{-4}) and our estimate of the electron density ($n_e = n[\mathrm{C}^+] = 0.15\ \mathrm{cm}^{-3}$), we find the total hydrogen density $n = n(\mathrm{H}) + 2n(\mathrm{H}_2) \gtrsim 500\ \mathrm{cm}^{-3}$. This average particle density (corresponding to an H_2 density of 250 cm^{-3}) is strikingly low compared with the usual densities seen in dark clouds (10^3 to $10^4\ \mathrm{cm}^{-3}$). We note, however, that it is quite consistent with the large value for the linear diameter of ~2 pc derived for the region in § III*a*, since the size of a C II region is determined by the mean free path for carbon-ionizing photons, which is inversely proportional to the density (see Papers I and II).

c) Source of Ionization

The obvious candidates for providing the radiation between λλ912–1100 which ionizes the carbon in L1204 are either the embedded star or stars seen at 2 μ, or HD 211880, the exciting star of S140 (the contribution of BD +62°2060 is negligible, owing to its relatively late spectral type). The carbon line observations described in this paper are not of sufficient angular definition to allow a direct determination of the source of ionization, so that we must rely on indirect arguments.

Using the values of n_e(0.15 cm^{-3}), T_e(10 K), and r (1 pc) derived in § III*a*, we can estimate the minimum number of carbon-ionizing photons needed to give the observed emission from

$$\mathscr{L}_C \geqslant \int \alpha(C) n_e n(C^+) dV \, s^{-1} , \qquad (3)$$

where $\mathscr{L}_C$ is the number of carbon-ionizing photons, α(C) is the recombination coefficient for carbon, V is the volume of the region, and we take $n_e = n(C^+)$. The inequality in equation (3) holds because we consider only the absorption by carbon atoms of the stellar radiation between λλ912–1100 and ignore absorption of the radiation by grains and by photodissociation of H_2 and other molecules. Then, if we assume that the region is of uniform density and temperature, we have $\mathscr{L}_C \geqslant 6 \times 10^{45}$ photons s^{-1}.

The star HD 211880 is of spectral type B0 V; the total number of carbon-ionizing photons emitted by this star can be calculated from Panagia's (1973) average stellar parameters and the model atmospheres of Van Citters and Morton (1970). If we assume that the carbon-ionizing photons are unattenuated before they reach L1204, and that the boundary of L1204 subtends a cone of angle ~30° at the star (see Fig. 1), we have $\mathscr{L}_C = 2 \times 10^{46}$ photons per second impinging on the dark cloud, more than enough to produce the observed large-scale carbon ionization. Thus it is plausible that a significant part of the observed ionization in L1204 is due to HD 211880; further recombination line mapping of the region, particularly with small telescope beams at low frequencies, is obviously desirable.

We can also evaluate the possible contribution of the other potential source of ionization, the embedded stars. For an embedded star at the position of the infrared source, surrounded by gas at constant temperature and density, the coolest star which can produce the required ionization is of type B2 V. Such a star will also be surrounded by a small H II region (~20″ in size and of flux ~20 mJy).

Recently, continuum aperture synthesis observations of the S140 region at 2.7 GHz (Gilmore *et al.* 1976) have shown the presence of a small continuum source close to the infrared object, of strength 25 mJy and diameter 10″. If this source is a small H II region at the distance of the S140 complex, its derived flux, excitation parameter, etc., correspond to a compact H II region of radius 0.02 pc and electron density 3×10^3 cm^{-3}, with an exciting star of spectral type near B1 V. However, it is unlikely that this star contributes greatly to the ionization of the dust cloud, for the following reason. The relatively high particle density (3×10^3) presumably reflects local density inhomogeneities near the star, so that it is surrounded by enough interstellar matter that carbon-ionizing photons cannot escape into the cloud. This is supported by the observations of Beckwith and Evans (1975), who find a deep 10 μ silicate absorption feature in the source, implying the presence of obscuration in the vicinity of the source.

To test whether or not a significant amount of ionization is produced by the embedded star, we searched for C 110α (6 cm) emission from the cloud. As we discussed in Paper II, the higher frequency carbon recombination lines are detected in small regions of electron density $n_e \approx 1$ cm^{-3}, while the lower frequency lines (C 142α and C 166α in this case) are preferentially detected in larger regions where $n_e \approx 0.1$–0.3 cm^{-3} (for typical dark cloud temperatures of 10–40 K). Thus our failure to detect C 110α emission from L1204 provides strong constraints on the size of regions of enhanced density in the cloud. Suppose the neutral density condensation around the embedded star is of angular diameter θ' and electron density n_e' (due to ionized carbon), while the lower density large-scale C II region has an angular diameter θ and electron density n_e. Then, the ratio of the power in the C 110α line to that in the C 166α line is (cf. Paper II):

$$\frac{P_{110}}{P_{166}} = \frac{b_{110}(n_e')}{b_{166}(n_e)} \left(\frac{n_e'}{n_e}\right)^2 \left(\frac{\theta'}{\theta}\right)^2 \left(\frac{22}{6}\right)^2 \times \exp\left[\frac{1.579 \times 10^5}{T_e} \left(\frac{1}{110^2} - \frac{1}{166^2}\right)\right] , \qquad (4)$$

where we have explicitly included the different beam sizes used to make the C 110α and C 166α observations. Now, using the fact that the density contrast between the localized condensation and the larger dark cloud must be at least comparable with the density contrast between the embedded H II regions and the dark cloud (i.e., roughly a factor of 6) we infer from equation (4) and the observational limit $P_{110}/P_{166} \leqslant 1.5$ that $\theta' \leqslant 0.06\,\theta$. The linear radius of 1 pc derived for the larger C II region corresponds to $\theta \sim 8'$, so that the size of the neutral density condensation surrounding the embedded source is no greater than $\theta' \approx 30''$. (Also we note that the limit on the C 110α line is consistent with the derived properties of the larger C II region.)

Thus the above discussion shows that in L1204 we have a dark cloud of fairly low density, with most of the carbon-ionizing photons coming from the adjacent H II region, S140. Embedded in the dark cloud are one or more stars of type ~B1 V, but these are surrounded by higher density material, so that most of their carbon-ionizing photons are unable to pass into the larger, lower density cloud.

IV. DISCUSSION

The observations described above allow us to construct a model of the star-formation region S140/L1204. One or more very young stars of early spectral type (B1 V or earlier) are embedded in small condensations of relatively high density (~3000 H atoms cm^{-3}) surrounded by a large cloud of lower density (≥500 H atoms cm^{-3}). The star-formation region is of higher temperature than the surrounding cloud (whose temperature is ~10 K) and manifests itself as a region of enhanced CO temperature.

Lines of ionized carbon seen in the directions of bright H II regions probably arise in cold, dense, neutral clouds immediately adjoining the H II region, with the appropriate heavy elements being ionized by leakage photons from the region, and the line emission being due to spontaneous transitions (Zuckerman and Ball 1974). The present situation is another such case, with the contiguous interstellar clouds being separated in angle rather than along the line of sight as is the case, for example, with the Orion nebula. The carbon in the neutral region adjoining S140 is ionized mostly by photons from the B0 V star HD 211880, and the relatively small line widths for the C^+ lines in the present case—relative to those seen, for example, in the Orion nebula—are certainly due to the fact that the exciting star is of relatively late spectral type and therefore produces little turbulence in the dark cloud.

The velocity structure of this region is particularly interesting. Examination of the velocities in Table I and of the CO profile (Fig. 3) reveals possible clues to the evolution of the region. The CO profile at the position of the infrared source is very broad ($\sim 6\,\mathrm{km\,s^{-1}}$) compared with the line widths usually seen in dark clouds. Its central velocity is the same as that of the C^+ lines, but velocity structure suggestive of a disturbance in the region, due to either turbulence or systematic motions, is evident; the velocity structure between -9 and $-14\,\mathrm{km\,s^{-1}}$ could be due to self-absorption by colder gas in front of the hot spot, moving away from the central object (this is suggested by the steepness of the line between -9.4 and $-11.2\,\mathrm{km\,s^{-1}}$). Alternatively, the structure of the CO line could be due to the presence of several velocity components, including a low-level wing on the line between -11 and $-14\,\mathrm{km\,s^{-1}}$. Water-vapor maser emission has been detected at the position of the infrared source (Morris and Knapp 1976), and it is particularly interesting that strong components occur at $\sim -15\,\mathrm{km\,s^{-1}}$, the extreme velocity of the CO; these components then may well arise in outflowing gas. The presence of H_2O maser emission also indicates the presence of small dense condensations in this cloud.

The radial velocities of the exciting stars of S140 are quite close to that of L1204, while the H 166α and optical interstellar line velocities are closely the same. The stellar velocities are more negative than the H II region velocity, so that the H II region may be expanding toward us, possibly due to denser gas behind the region. There is no apparent explanation, however, for the discrepancy between the Hα and H 166α velocities (Table 1).

The mass of L1204 appears to be relatively small. Taking the average hydrogen density to be $500\,\mathrm{cm^{-3}}$, the diameter to be 5 pc, and the distance to be 910 pc, we find the total mass of gas in the cloud to be $\sim 10^3\,\mathfrak{M}_\odot$. This mass is much lower than that of many other star-formation regions (e.g., the Orion complex), although regions of even lower mass are known to exist (e.g., Aveni and Hunter 1972; van Till, Loren, and Davis 1975).

The lack of emission or absorption in the 6 cm formaldehyde line could be due to either the temperature of the H_2CO line being close to the background temperature, or a deficiency of formaldehyde in the cloud. At 5 GHz, the galactic background temperature is ~ 0.2 K (extrapolated from the 1.4 GHz maps of Felli and Churchwell 1972, assuming that the emission is thermal). If collisional cooling is taking place in this cloud, anomalous absorption of strength ~ -0.3 K is expected (assuming that the H_2CO abundance is similar to that in other regions [Evans *et al.* 1975], that the cloud has the density and dimensions calculated above, and that it fills half of the 11′ telescope beam [see Fig. 1]). Thus either the formaldehyde is at a temperature close to 2.9 K (which seems unlikely) or it is underabundant by at least a factor of 3. This is no doubt due to photodissociation by the ambient ultraviolet field (Stieff *et al.* 1972). Since most of the ultraviolet radiation in the cloud appears to come from HD 211880 and the geometry of the region is fairly well defined, observations of the H_2CO line with higher spatial resolution should prove very interesting.

Finally, we note that in this region, we have at least two stars of similar spectral type (B0 V and B1 V), one exciting a large diffuse H II region and the other a compact H II region. The mean density of S140 may be inferred from its angular radius ($\sim 9'.8$), and from the radio-frequency flux, taken from Felli and Churchwell (1972), and is $\sim 20\,\mathrm{cm^{-3}}$ (while the mass is $\sim 30\,\mathfrak{M}_\odot$). Thus the diffuse, low-density H II region may represent a more advanced stage in the evolution of the interstellar matter and the newly-formed star cluster in this region: for HD 211880, the primordial interstellar matter around the star has largely dissipated, owing to a combination of thermal expansion and possibly the downstream passage of a galactic shock (Woodward 1975); while the newly born star (or stars) in L1204 are still surrounded by matter of essentially the same density as that from which they formed. If the mean expansion speed of S140 is taken as $\sim 10\,\mathrm{km\,s^{-1}}$ (from the width of the H 166α line), the different observed densities in this region imply that HD 211880 is at least 5×10^5 years older than the new stars in L1204. (The alternative possibility, that HD 211880 is a high-velocity star escaped from the new-born cluster, is essentially ruled out by the closeness of its radial velocity to that of the surrounding interstellar matter (see Table 1). Thus, in this region, we may be seeing stars of very similar spectral type forming over a time scale of at least 5×10^5 years. This is very similar to the situation in the dark cloud L1630 in Orion, where the formation times for several clusters of low-mass stars differ by up to several million years (Strom *et al.* 1975).

We are indebted to Dr. N. J. Evans II for valuable discussion and comments, and to Dr. P. Vanden Bout for informing us of this region and of his CO and infrared observations, and to Dr. N. H. Dieter for the observing time on the Berkeley 26 m telescope and for carrying out the observations. We thank Drs. W. J. Wilson and E. E. Epstein for the observing time on the Aerospace antenna, and the staffs of the NRAO, the

OVRO, and the Venus-Goldstone Station of the JPL Deep Space Network for the observing time and for their help with the observations. Research at OVRO is supported by the National Science Foundation under grant GP-30400-X1, and by the Office of Naval Research under contract N00014-67-A-0094-0019. This paper presents the results of one phase of the research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS 7-100, sponsored by the National Aeronautics and Space Administration. During much of this investigation, T. B. H. K. and R. K. K. were NRC Resident Research Associates at JPL.

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