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# RECOMBINATION LINES FROM THE INTERFACE BETWEEN THE ORION MOLECULAR CLOUD AND THE H II REGION NGC 1977

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## ABSTRACT

We report observations of the C110α and H110α lines at 6 cm wavelength and the C76α line at 2 cm wavelength from the vicinity of the H II region NGC 1977. The favorable viewing angle in this source allows a direct study of the transition from the H II region to the molecular cloud to be made. The observations confirm that the carbon lines arise from a distinct boundary region at the edge of the molecular cloud. The $C^+$ emission zone penetrates about 0.3 pc into the molecular cloud and has a derived electron density of about 1 $cm^{-3}$. It appears that the shock front preceding the expanding ionization front may be responsible for an extended heated region just inside the molecular cloud.

*Subject headings:* interstellar: molecules — nebulae: individual — nebulae: Orion Nebula — radio sources: lines

## I. INTRODUCTION

A star that is forming within a molecular cloud can play an important role in the evolution of that cloud. One way in which the star can interact with the cloud is via the formation of a compact H II region which then expands into the cloud. This expansion can affect the future of star formation within the cloud. If it is sufficiently disruptive, it may end the star-forming era in that part of the cloud. However, under the right conditions it may initiate further star formation (e.g., Elmegreen and Lada 1977). In order to learn more about these possibilities, it is important to study the interface zone between the H II region and the molecular cloud.

Important information about this interface region can be provided by observations of narrow carbon recombination lines. These have been best studied in the case of the Orion Nebula and its associated molecular cloud. In the generally accepted model for that source, the molecular cloud passes behind the H II region. The H II region is assumed to be ionization bounded and expanding into the molecular cloud. As suggested by Zuckerman and Palmer (1968), the observed carbon recombination lines apparently come from the transition zone between the H II region and the molecular cloud. However, the particular geometry of this source, with the H II region lying in front of the dense cloud, makes it difficult to confirm this generally accepted picture.

In this paper we report observations of recombination lines from a region in which the geometry is much more favorable for studying the location of the C II zone with respect to the molecular cloud and the H II region. Our observations are of the small H II region NGC 1977 which appears as the northern star in the Sword of Orion. These observations were suggested by the molecular observations reported by Kutner, Evans, and Tucker (1976, hereafter KET).

Before describing the new observations, we briefly review the molecular observations. Studies of CO, $^{13}CO$, and 2 mm and 2 cm $H_2CO$ lines revealed a dense (molecular hydrogen density $n_H \approx 10^4$ $cm^{-3}$) molecular cloud running north from the Kleinmann-Low nebula, through OMC-2, and another quarter degree north to an abrupt end at NGC 1977. As shown in Figure 1, there is a sharp falloff in the molecular emission at the edge of the H II region (as can also be seen in the photograph in KET). There is an extended region in the molecular cloud, close to the edge, in which the CO brightness temperature is about 30 K. It was suggested in KET that a shock front preceding

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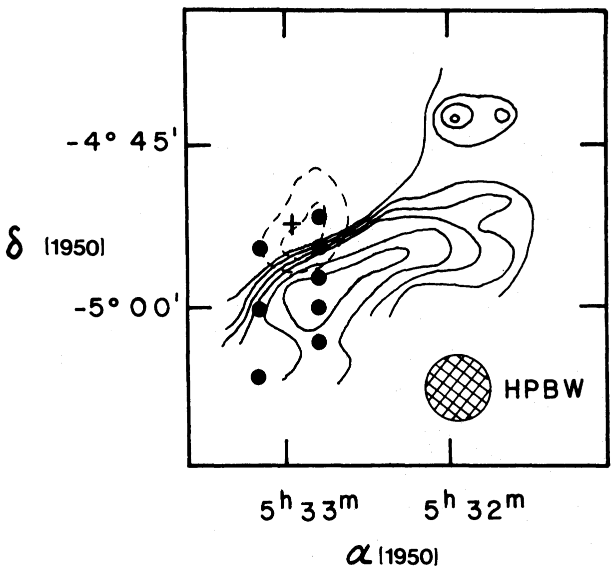


FIG. 1.—Sketch of the molecular cloud–H II region interface in NGC 1977. Solid lines are CO emission contours (from KET) in 5 K steps. Dashed lines are 6 cm continuum contours (Goss and Shaver 1970). The plus indicates position of the exciting star for the H II region. Filled circles indicate positions of C110α observations (listed in Table 1). The indicated HPBW is for the 6 cm observations.

the ionization front into the cloud may be responsible for this heated region. It was also pointed out that carbon recombination lines from the interface region should be detectable.

## II. OBSERVATIONS AND RESULTS

The observations were of the C110α and H110α lines at 6 cm and the C76α line at 2 cm. All observations were done on the NRAO[1] 43 m telescope with the 384-channel autocorrelator spectrometer. The 6 cm observations were done in 1976 June and 1977 April. The half-power beamwidth (HPBW) was 6.′6, and the main beam efficiency was 80%. All observations were taken with frequency switching of the first local oscillator, with the line falling in the spectrometer passband in both halves of the switching cycle. Receiver system temperatures were about 60–70 K. For the 1977 observations both linear polarizations were detected and the results combined. Two positions were repeated in order to check for consistency between the two runs.

The 2 cm observations were done in 1977 November. The HPBW was 2′; the beam efficiency at the zenith, for sources of the size discussed below, was 60%, with considerable falloff at large hour angles (Knapp, Loren, and Evans 1979). An elevation-dependent correction was made for beam efficiency. Two polarizations were observed, and frequency switching, as above, was employed. Receiver system temperatures were about 120–130 K.

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

The results of these observations are summarized in Table 1. Most of the points are in a north-south strip running across the interface between the H II region and the molecular cloud. Sample 6 cm spectra are shown in Figure 2. The noise level was comparable in all of the 6 cm spectra.

All the carbon lines are relatively narrow (1–2 km $s^{-1}$) features at a local standard of rest velocity of about 12 km $s^{-1}$, the same as that of the CO lines in this region. The distribution of C110α intensity with declination is shown in Figure 3. In this figure we have plotted the distribution of both peak line brightness temperature and integrated intensity. There is a definite peaked distribution in both quantities, with the intensity increasing as the pointing position moves southward from the H II region, then decreasing as the position moves farther into the molecular cloud. The width of this distribution is comparable to the HPBW, suggesting a source that is beam diluted in one dimension. This would be expected if the emission were coming from a source that was extended in one dimension, along the ionization front. Our limited east-west mapping leads us to believe that we have not yet found the full east-west extent of the emission.

The relationship between the C110α emitting region and the molecular cloud can also be seen in Figure 3. In the lower half we have indicated the declination distribution of 2.6 mm CO and $^{13}CO$ and 2 mm $H_2CO$ emission (all the data are taken from KET). The C110α peak occurs just at the edge of the CO peak and falls off by the time the $^{13}CO$ emission reaches its peak value and just before the 2 mm $H_2CO$ peak.

The C76α observations were undertaken in order to achieve the better angular resolution needed for determination of how severely beam diluted the 6 cm lines are. The 2 cm line was detected at three positions near the peak of the 6 cm intensity. Two of the positions are 2′ apart in the north-south strip of the 6 cm observations. The third position is between the other two in declination and $10^s$ west. Negative results were obtained at all other positions. The 2 cm lines have much poorer signal-to-noise ratios than do the 6 cm lines, but it appears that the 2 cm emission has a width of 2′–3′ (uncorrected for the beamwidth).

The H110α distribution is shown in Figure 4. It appears that two different types of lines are present. There is the broad line, normal for H II regions, whose integrated intensity falls off as the pointing position moves southward, out of the H II region. At the position of the strongest carbon line there also appears to be a narrow hydrogen line, whose center velocity and width agree to within 0.1 km $s^{-1}$ with those of the carbon line (see the lower left spectrum in Fig. 2).

## III. DISCUSSION

The general distributions shown in Figures 3 and 4 clearly show that the carbon recombination lines arise from a distinct zone sandwiched between the H II region and the molecular cloud. The strongest carbon recombination emission comes from the very edge of the molecular cloud. The peaked distribution of this

TABLE 1

Recombination Line Parameters—NGC 1977

| Line | α (1950) | δ (1950) | $T_L$* (K) | $v_{LSR}$ (km s$^{-1}$) | Δ$v$ (km s$^{-1}$) | ∫ $Tdv$ (K km s$^{-1}$) |
|---|---|---|---|---|---|---|
| C110α....... | 5h32m47s | −5°03′30″ | 0.036 | 13.0 | 0.06 | 0.015 |
| | 5 32 47 | −5 00 30 | {0.036<br>0.041} | {11.5<br>12.3} | 1.6 | 0.094 |
| | 5 32 47 | −4 57 30 | 0.086 | 12.1 | 1.2 | 0.125 |
| | 5 32 47 | −4 54 30 | 0.055 | 11.9 | 1.8 | 0.085 |
| | 5 32 47 | −4 51 30 | < 0.03 | ... | ... | ... |
| | 5 33 11 | −5 06 30 | < 0.04 | ... | ... | ... |
| | 5 33 11 | −5 00 30 | 0.043 | 12.0 | 1.1 | 0.032 |
| | 5 33 11 | −4 54 30 | < 0.03 | ... | ... | ... |
| H110α...... | 5 32 47 | −5 00 30 | {0.034<br>0.031} | {10.5<br>13.7} | 9.6 | 0.55 |
| | 5 32 47 | −4 57 30 | 0.029 | 12.1 | 1.3 | 0.63 |
| | 5 32 47 | −4 54 30 | {0.024<br>0.049} | {6.0<br>13.7} | 18.5<br>4.3 | 0.30<br>0.20 |
| | 5 32 47 | −4 51 30 | 0.024 | 9.3 | 22.4 | 0.63 |
| | 5 33 11 | −5 00 30 | < 0.03 | ... | ... | ... |
| C76α........ | 5 32 37 | −4 56 15 | 0.073 | 12.7 | 2.0 | 0.142 |
| | 5 32 47 | −5 01 30 | < 0.07 | ... | ... | ... |
| | 5 32 47 | −4 59 30 | < 0.04 | ... | ... | ... |
| | 5 32 47 | −4 57 30 | 0.053 | 12.2 | 2.2 | 0.114 |
| | 5 32 47 | −4 55 30 | 0.043 | 11.6 | 2.0 | 0.088 |
| | 5 32 47 | −4 53 30 | < 0.06 | ... | ... | ... |
| | 5 32 57 | −4 58 45 | < 0.05 | ... | ... | ... |
| | 5 31 11 | −5 00 00 | < 0.06 | ... | ... | ... |

* Line brightness temperature. For positions with detected lines, typical uncertainties (1 σ) are 0.01 K for C110α and H110α and 0.02 K for C76α. Upper limits are half the peak-to-peak noise level.

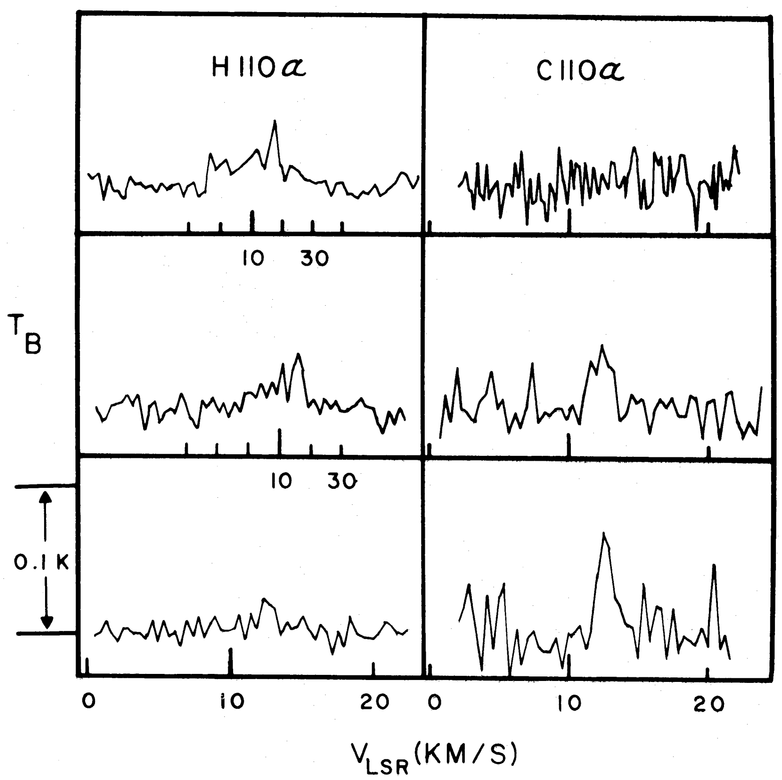


Fig. 2.—Sample 6 cm recombination line spectra in NGC 1977. The three positions are in a north-south strip at declinations (1950) (*from top to bottom*) of −4°51′30″, −4°54′30″, and −4°57′30″. The northernmost position is in the H II region, and the southernmost position in this group is that of the strongest C110α emission. Note the different velocity scale for the two upper hydrogen spectra, where a lower resolution was used because of the broader H II region lines.

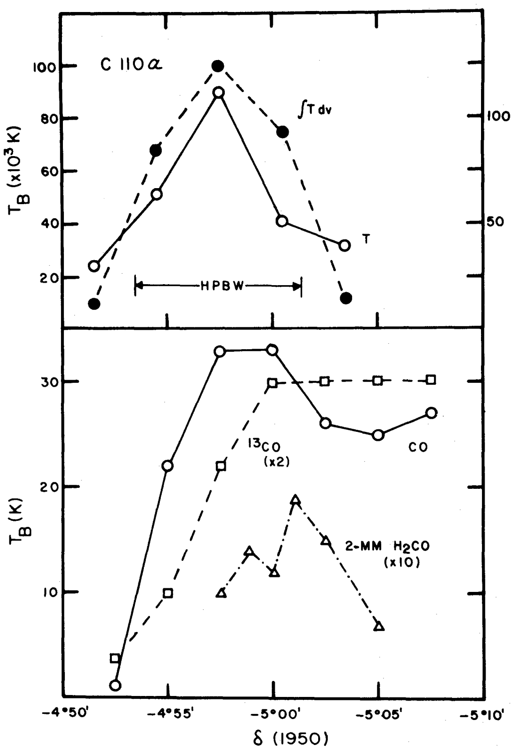


FIG. 3.—Upper part of the figure shows the distribution in declination of the C110α emission. Open circles represent peak line brightness temperatures; filled circles represent integrated intensities. All points are at α(1950) = $5^h32^m47^s$. Lower part of the figure shows, for comparison, the distribution of molecular emission in the same declination strip. The molecular data are taken from KET.

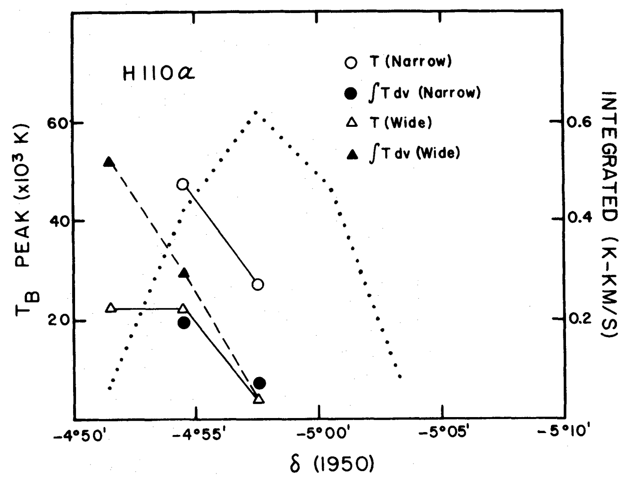


FIG. 4.—Distribution of the H110α emission for the same declination strip as in Fig. 2. The dotted line shows, for comparison, the integrated intensity distribution of the C110α line (taken from Fig. 3) on an arbitrary intensity scale. For the H110α lines, filled symbols represent integrated intensities and open symbols represent peak line brightness temperatures. Circles refer to the possible narrow line, and triangles refer to the broad line.

emission is readily explained by the competing effects of increasing total density and decreasing $C^+$ fractional abundance as one moves from the H II region to the molecular cloud.

The recombination line observations can provide information on the physical conditions in the $C^+$ zone. The intensity of one of the C$m\alpha$ lines is given by (see, e.g., Gordon 1974)

$$T_L \Delta v = \frac{3 \times 10^3}{\nu} b_m \frac{f_{mm'}}{m} n_e^2 L T_e^{3/2} \times \exp(1.579 \times 10^5 / m^2 T_e) , \quad (1)$$

where $\Delta v$ is the line width in km $s^{-1}$, $\nu$ is the frequency in GHz, $f_{mm'}$ is the oscillator strength (see, e.g., Goldwire 1969), $n_e$ is the electron density which is assumed equal to the $C^+$ density, $L$ is the thickness of the emitting region (along the line of sight) in parsecs, $T_e$ is the electron temperature, and $b_m$ is the departure coefficient for the $m$th level which depends on $n_e$ and $T_e$. We would normally expect to be able to use the ratio of C110α to C76α intensities so that such things as the emission measure ($n_e^2 L$) would cancel out, but because of incomplete mapping and beam dilution such a direct comparison is not possible. The best that we can do at this point is to estimate some of the parameters on the basis of the recombination line and molecular observations and to establish a self-consistent picture of the region.

We first estimate the width and depth of the C II zone. If we take the distance to NGC 1977 to be 500 pc, then an angular size of 1′ corresponds to 0.15 pc. The exciting star for the H II region is most likely the B2 III star HD 37018. The C II zone is about 5′, or 0.75 pc, from this star. If we account for the finite beam size at 2 cm, the width of the C II zone is about 2′, or 0.3 pc. Carbon-ionizing radiation will be expected to penetrate a distance $D$ (in parsecs) given by

$$D = \frac{250}{n_H} \ln \left( \frac{1.6 \times 10^{11}}{n_H} \right) \quad (2)$$

(Zuckerman and Palmer 1968), where $n_H$ is the hydrogen density. The molecular observations imply a density $n_H \approx 2 \times 10^4$ cm$^{-3}$, giving $D \approx 0.2$ pc, in agreement with the size estimated from the observations. We would also like to know $L$, the thickness of the C II zone along the line of sight. We first estimate the thickness of the molecular cloud. From the CO observations we derive a $^{13}CO$ column density of $10^{17}$ cm$^{-2}$. If we use Dickman's (1978) value for the $H_2$ column density of $5 \times 10^5$ times the $^{13}CO$ column density, we obtain $N_{H_2} \approx 5 \times 10^{22}$ cm$^{-2}$. Taking $N_{H_2}/n_{H_2}$ gives an estimate of 1.6 pc for the molecular cloud thickness. We can use this as an upper limit to $L$. For comparison we have some information, from the distribution of the C110α line in right ascension, about the size of the region along the front but perpendicular to the line of sight. The detection of a 0.043 K line 1 full beamwidth east of the strongest C110α line suggests an extension along the front of at least 1 pc. Therefore, a comparable extent along the line of sight is not unreasonable. For the calculation below, we will adopt $L = 1.6$ pc. Though this may be highly uncertain, we note that the electron density derived below goes roughly as $L^{1/2}$.

With these quantities we can estimate the emission measure ($n_e^2L$) from the C110α line. We take $T_e = 30$ K, in agreement with the CO temperature. (Changing $T_e$ to 40 K would increase the $n_e$ derived below by only 15%.) Using equation (1), we find $n_e^2L = 0.11/b_{110}$ averaged over the 6'.6 beam. On the basis of the 2 cm data, we estimate the beam dilution in the 6 cm observations to be about a factor of 3, giving $n_e^2L = 0.33/b_{110}$. If the line-of-sight thickness of the emitting region $L$ is 1.6 pc, as above, $b_{110}n_e^2 \approx 0.2$. Using the $b_m(n_e, T_e)$ of R. L. Brown (1978, private communication), we find that, at $T_e = 30$ K, this is satisfied by an electron density $n_e = 1\ \mathrm{cm^{-3}}$, giving an emission measure of 1.6 pc $\mathrm{cm^{-6}}$.

To determine whether this electron density is reasonable, we note that, if all the carbon were in the form of $C^+$ and there were no depletion, then, for $n_{H_2} = 10^4\ \mathrm{cm^{-3}}$, we would expect $n_e = 6.6$. If we allow for some depletion of carbon, a value near $n_e = 1\ \mathrm{cm^{-3}}$ seems reasonable. For example, Chaisson (1975) and Knapp, Kuiper, and Brown (1976) find depletion factors of about 6 in the ρ Oph cloud. This suggests that we have achieved a generally consistent picture for the conditions at the H II region–molecular cloud interface.

Of course, given the large uncertainties in both the thickness and width of the C II zone, as well as in $T_e$, one must consider the derived quantities to be uncertain by at least a factor of 2. Some of this uncertainty can be reduced by more complete and higher-resolution mapping. One additional check on self-consistency that might be provided with such data is that, under the derived conditions, the ratio of $\int T_L dv$ for the C110α to C76α lines, corrected for beam dilution, should be about 5.

It would be interesting to compare our derived parameters with those expected for an ionization front expanding into a molecular cloud. The most detailed calculations of this nature to date appear to be those of Hill and Hollenbach (1979). However, all of their calculations are for an exciting star of spectral type O5, so a direct comparison is not meaningful. We feel that the favorable viewing angle in NGC 1977 makes it an ideal place for comparing observations and theory, and we hope that such an opportunity might stimulate further model calculations.

The geometry of the source also makes NGC 1977 an excellent place for studying the interaction between H II regions and molecular clouds, as well as the physical conditions in the transition region. We also note that this region may provide an important opportunity to test some of the predictions of ion-molecule chemistries. With 1' resolution it should be possible to see how the relative abundances of certain molecular and isotopic species vary with distance from the ionization front and thus with $C^+$ concentration. Such variations have been predicted by several authors (e.g., Langer 1977).

## IV. SUMMARY

These preliminary observations provide direct observational confirmation that the carbon recombination line emission comes from a transition zone between the H II region and the molecular cloud, with the strongest recombination emission coming from the very edge of the molecular cloud. This is consistent with the picture that has generally been proposed for the origin of the $C^+$ emission. From a preliminary analysis of our recombination line and molecular observations, we derive a self-consistent picture of a C II zone with $n_e \approx 1\ \mathrm{cm^{-3}}$, width 0.3 pc, and distance 0.75 pc from the exciting star. A more complete mapping of the region is required for a better understanding of the structure and physical conditions.

This appears to be an excellent source in which to study the effects of an expanding H II region on a molecular cloud. Additional theoretical work is necessary if one is to see to what degree the broad heated region just inside the molecular cloud can be explained by grain heating and to what degree shock heating may be important. Assessment of the effect that the H II region might have on future star formation may be facilitated by a search of the heated region for water masers and localized infrared sources.

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