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# CO EMISSION FROM SUPERNOVA REMNANTS

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## ABSTRACT

In a search for molecular gas associated with supernova remnants, we have observed the CO line in the three optical remnants: the Cygnus Loop, IC 443, and Cas A. In both the Cygnus Loop and IC 443, CO molecules are detected from dense clouds of mass $\sim 100\ M_{\odot}$, probably located at the edge of the expanding remnants. These are locations of particularly bright optical filaments and strong radio continuum emission. The foreground emission seen in Cas A exhibits changes on a small scale compared with the radio continuum, implying a low filling factor for molecular absorption lines in Cas A.

*Subject headings:* interstellar: molecules — nebulae: supernovae remnants

## I. INTRODUCTION

The interaction between an expanding supernova remnant (SNR) and the surrounding interstellar medium is still a subject of active analysis and debate. There does not appear to be general agreement on basic problems of hydrodynamics and energetics (Woltjer 1972; Pacini and Salvati 1973; Mansfield and Salpeter 1974; Solinger *et al.* 1975; Chevalier 1975; Falle 1975), the source of energetic electrons and magnetic field for the radio continuum (Gull 1973; Cowie 1975; Scott and Chevalier 1975), or the relation of the optical filaments to the supernova ejecta and shock wave (McKee and Cowie 1975; Sgro 1975; Bychkov and Pikel'ner 1975).

There are two circumstances in which one might find dense molecular gas physically associated with supernovae. Current theoretical models predict the existence of a shell of cold neutral gas behind the expanding shock of old remnants ($\tau \gtrsim 2 \times 10^4$ yr [Chevalier 1974; Straka 1974; Mansfield and Salpeter 1974]); possible H I shells have been detected for two distant SNR, W44 and HB 21 (Knapp and Kerr 1974; Sato 1974; Assousa and Erkes 1973). Whether such a shell will become sufficiently dense and self-shielding to permit a buildup of molecular abundances on a time scale of $10^4$ yr is doubtful. Though the models, calculated at an ambient density $n_0 \sim 1\ \text{cm}^{-3}$, indicate a density greater than $10^3\ \text{cm}^{-3}$ for a thin portion of this shell, the total column density of the neutral gas remains low ($\sim$few times $10^{19}\ \text{cm}^{-2}$), implying a visual extinction by grains of only $10^{-2}$ mag. A second opportunity to observe molecular gas associated with SNR will occur when the expanding shell encounters an adjacent molecular cloud which was able to survive the initial flash of UV photons. This might be the same cloud out of which the massive supernova star originally condensed or, alternatively, a cloud caught by chance in the vicinity.

We report here observations of three supernova remnants in the 2.6 mm line of carbon monoxide. In two of these regions, the Cygnus Loop and IC 443, the observed molecular emission arises from high-density clouds abutting the optical remnant. In the third source, Cas A, which has been previously observed in the CO line by Wilson *et al.* (1974), the emission is probably produced in clouds along the line of sight which are unrelated to Cas A itself.

The CO observations were made in 1976 March on the 5 m antenna (half-power beam width [HPBW] = 2′) of the Millimeter Wave Observatory[1] at the University of Texas. The observed antenna temperatures $T_A^*$ have been corrected for atmospheric extinction and beam efficiency using measurements of the sky opacity about twice daily. CO emission features were initially found using a broad low-resolution spectrometer spanning 210 km s$^{-1}$ at a resolution of 0.6 km s$^{-1}$. In addition to the results described in the next section, a brief unsuccessful search for CO emission was conducted in the Monoceros remnant (see Table 1). Emission was also detected in S147, but time did not permit a full mapping.

## II. RESULTS

The CO line was detected in the vicinity of the Cygnus Loop, IC 443, and Cas A. In all regions, it is relatively weak ($T_A^* = 2$–$8$ K) as compared with the same line observed in galactic H II region sources (Lizst 1973). The line widths and radial velocities as summarized in Table 1 are quite typical of quiescent dark nebulae and show no obvious dynamic effects of the associated supernovae.

Maps of the CO emission in the Cygnus Loop and IC 443 are shown in Figures 1 and 2. Contours of the

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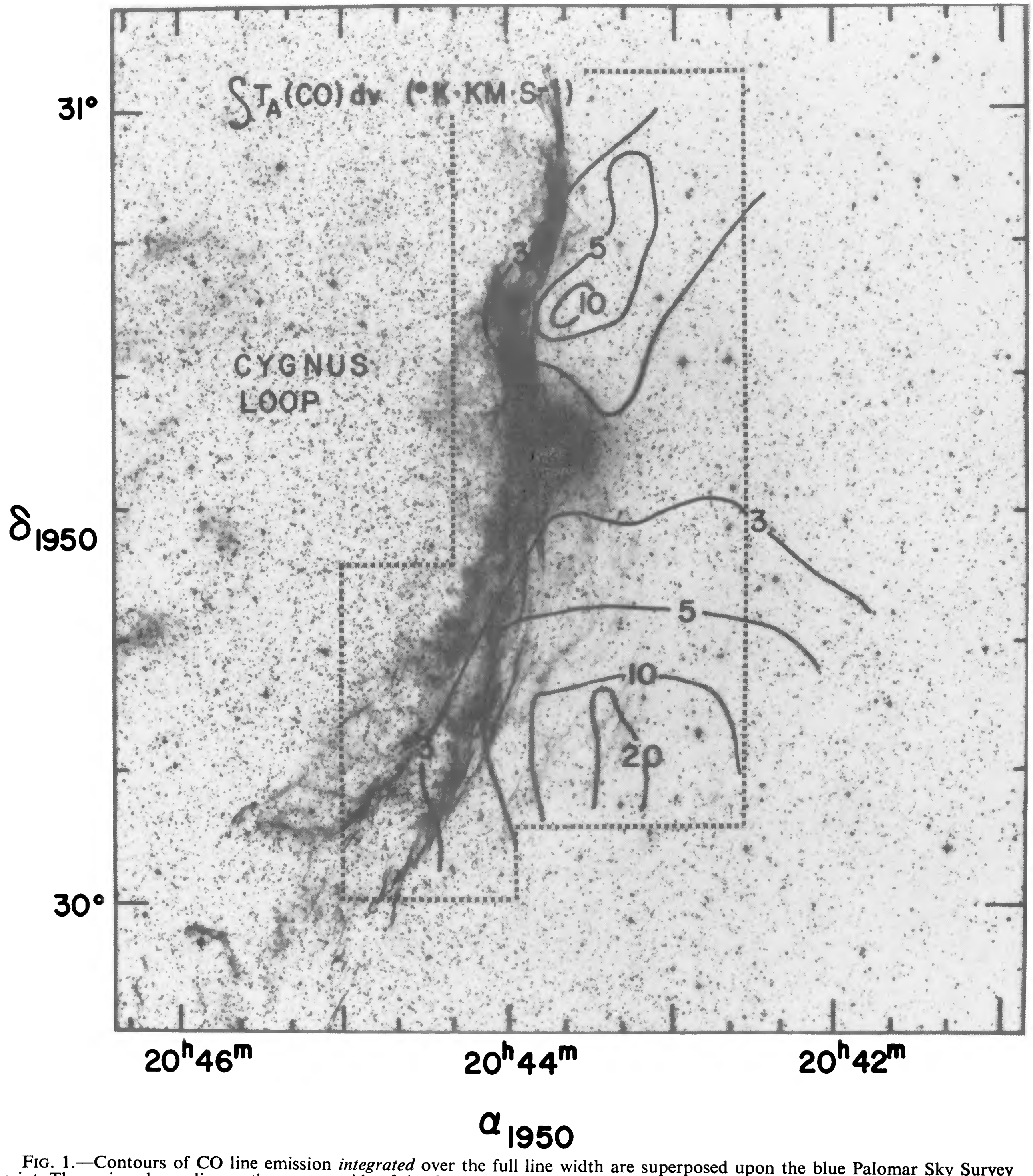

FIG. 1.—Contours of CO line emission *integrated* over the full line width are superposed upon the blue Palomar Sky Survey print. The region shown lies on the western side of the Cygnus Loop. All antenna temperatures have been corrected for beam efficiency and atmospheric extinction. The observed region lies within the dashed line.

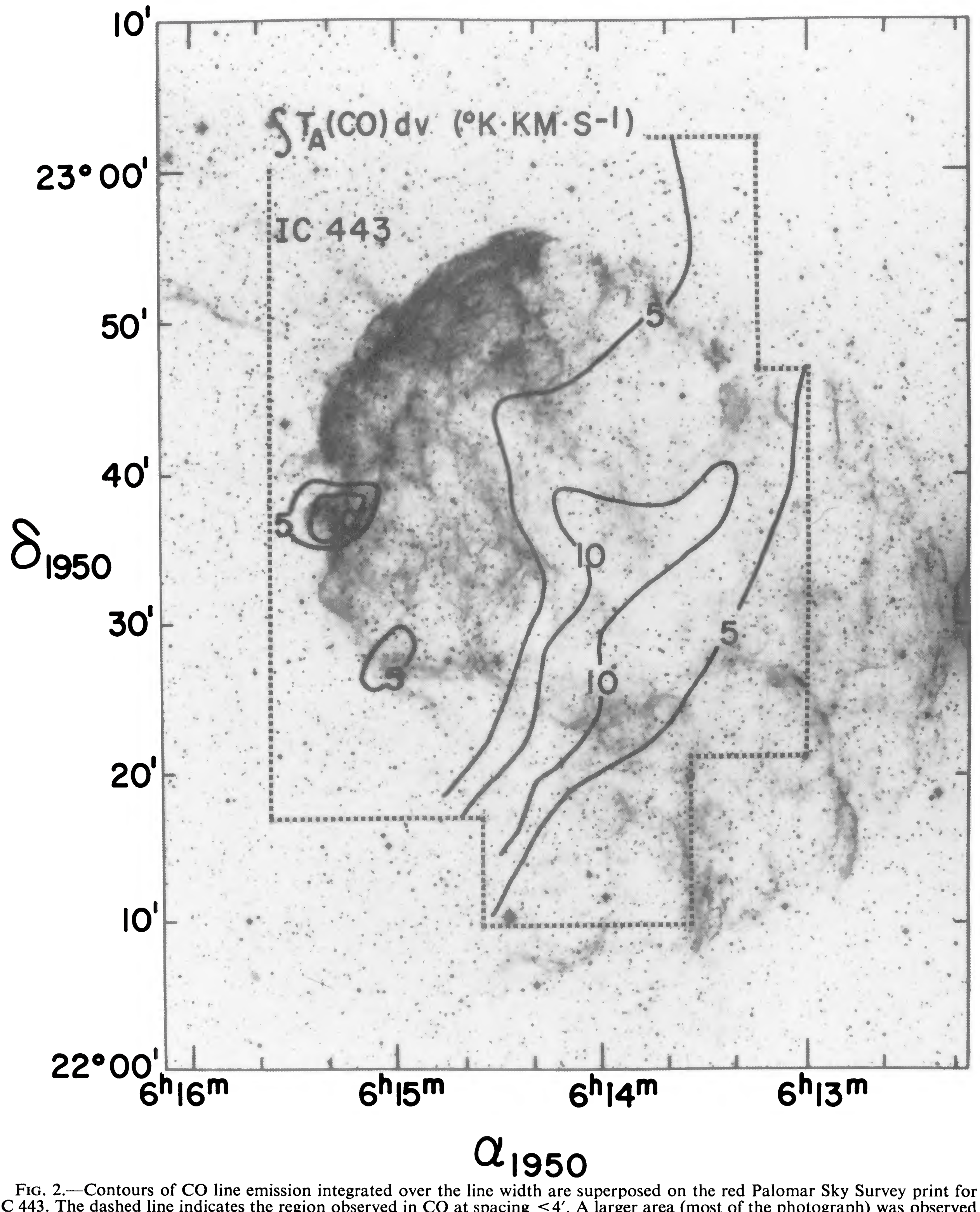

FIG. 2.—Contours of CO line emission integrated over the line width are superposed on the red Palomar Sky Survey print for IC 443. The dashed line indicates the region observed in CO at spacing ≤4′. A larger area (most of the photograph) was observed at coarser spacing.

TABLE 1

CO EMISSION IN SUPERNOVA REMNANTS

| Remnant | $\alpha_{1950}$ | $\delta_{1950}$ | $T_{\rm max}$* (K) | $V$ km s$^{-1}$ | $\Delta V$† km s$^{-1}$ | Remarks |
|---|---|---|---|---|---|---|
| S147 | $5^{\rm h}40^{\rm m}20^{\rm s}$ | 26°24′00″ | 2.0 | −2.5 | 3.0 | 6.0 K emission detected at $\Delta\alpha = -36'$, $\Delta\delta = +5'$ |
| IC 443 | 6 14 06 | 22 37 12 | 5.2 | −3.5 | 2.5 | |
| Monoceros | 6 35 00 | 6 30 00 | < 0.5 | ... | ... | |
| Cygnus Loop | 20 43 20 | 30 10 00 | 4.7 | 11 | 4.9 | Southern peak |
| | 20 43 40 | 30 45 00 | 2.7 | 12 | 3.5 | Northern peak |
| | 20 44 00 | 30 15 00 | 4.7 | 9.2 | 2.1 | Edge of optical filament |
| $^{13}$CO | 20 44 00 | 30 15 00 | 0.8 | 9 | 1.5 | |
| Cas A | 23 21 10 | 58 32 24 | 2.0 | −42 | 12.0 | Stronger emission 2′ SE |

* $T_{\rm max}$ is peak Rayleigh-Jeans brightness temperature in excess of the cosmic background corrected for atmospheric extinction and beam efficiency.

† $\Delta V$ is the full width to half-maximum intensity.

CO intensity integrated over the full line width are superposed on optical photographs. The data on Cas A are displayed in the form of spectra (Fig. 3) because of the complex profile variations.

### *a*) *Cygnus Loop*

The observed area shown in Figure 1 lies on the western periphery of the Cygnus Loop and covers about 1° in declination. This particular spot was chosen after inspection of the optical photograph revealed heavy obscuration of the background star light. The responsible dust is apparently immediately outside the expanding supernova shell since noticeable obscuration is only apparent outside the optical filaments.

The CO data shown in Figure 1 show an extremely good correlation with the obscuration. For both of the CO emission regions shown in the figure, the intensity falls to less than 10% of the peak values at points located +10′ east of the optical filament. We also find a deep minimum of the molecules in the direction of the bright star located midway between the two peaks. To determine the full extent of the molecular cloud we observed several isolated points 1° farther west and 2° to the northwest where there is evident optical obscuration. Emission was detected at all of these points with $T_A{}^* \sim 2$–4 K and $\Delta V \approx 2$ km s$^{-1}$, characteristics similar to the lines observed in Figure 1. An additional spectrum taken just outside the bright optical filament on the northeastern side of the Cygnus Loop showed no emission with $T_A{}^*$ greater than 0.5 K.

A single point where the eastern edge of the cloud abuts the optical filament was observed in the rare $^{13}$CO isotope in order to estimate the opacity of the observed CO emission. At this location the Rayleigh-Jeans brightness temperatures of CO and $^{13}$CO emission were 4.7 and 0.8 K (see Table 1). Converting the observed 4.7 K excess above the cosmic background to a Planck brightness temperature, we find an excitation temperature of 8 K for the $J = 1 \rightarrow 0$ transition here since the CO is optically thick. Assuming that $^{13}$CO has an identical excitation temperature, we then deduce a $^{13}$CO optical depth of 0.2 and CO optical depth of 7.5 at line center if the CO:$^{13}$CO abundance ratio is 40:1 (Wannier *et al.* 1976). And if all the CO rotation levels have this same excitation temperature, the total CO column density integrated over the line profile is $5 \times 10^{16}$ cm$^{-2}$. (A full discussion of these calculations is presented by Scoville, Solomon, and Penzias 1975.)

### *b*) *IC 443*

Most of the CO emission in IC 443 appears as a lane crossing the center of the optical remnant (Fig. 2). This CO ridge at −5 km s$^{-1}$ corresponds in position and velocity to a 21 cm hydrogen absorption feature (Dickel 1973), suggesting that the CO gas, like the H I gas, is in front of the SNR. This conclusion is reinforced by the anticorrelation of CO emission with optical emission which indicates optical extinction by dust. Conclusive evidence could come from observations of molecular absorption lines like $H_2CO$ and OH. We were able to trace the lane of CO emission as a narrow ridge extending over 2° to the south of IC 443. This southern extension of the cloud includes an optical emission nebula at $\alpha_{1950} = 6^{\rm h}07^{\rm m}00^{\rm s}$, $\delta_{1950} = 20°30'00''$ where the CO exhibits a local peak of 17 K.

In addition to the lane crossing the center of IC 443, we have found several smaller knots of emission on the east and northeast periphery of the remnant. This is the same side where the optical filaments are particularly bright. A minimum density of at least 100 cm$^{-3}$ is required to produce the observed $J = 1 \rightarrow 0$ excitation above the cosmic background temperature of 2.7 K (e.g., Scoville and Solomon 1974). The fact that the molecular knots are found ringing the bright side of the optical remnant suggests a physical association between the two, as opposed to merely a line-of-sight coincidence. There is evidence from 21 cm observations by deNoyer (1976) of a larger H I cloud to the northeast with possible densities of 10–20 cm$^{-3}$.

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### *c*) *Cas A*

Many of our ideas concerning "typical" spiral arm H I and $H_2$ clouds are based upon analysis of absorbing (H I, OH, $H_2CO$) or weakly masing (CH) spectral features observed against this strong continuum source. Both Orion and Perseus arm features are observed (e.g., Rydbeck *et al.* 1976; Davies and Matthews 1972; Troland and Heiles 1974). Measurements of molecular abundances and excitation temperatures for these species have normally been made on the assumption that the clouds are homogeneous on a scale equal to the source diameter.

CO spectra for each point in a grid with 2′ spacing in the direction of Cas A are shown in Figure 3. Several distinct CO clouds may be seen at velocities of $-38$, $-43$, and $-48$ km s$^{-1}$, corresponding to features present in the CH, $H_2CO$, and OH spectra (all of which have significantly poorer spatial resolution). It is very clear that the clouds have dimensions $\leq 2'$, in agreement with the $\sim 1'$ scale size found by Greisen (1973) from 21 cm H I interferometry and the inference from the $H_2CO$ map of Troland and Heiles (1974) that the structure exists on scales $\leq 4'$. Comparison of the spectra with radio continuum maps (Rosenberg 1970; Strom and Duin 1973) shows no correlation between the two. Thus the molecule emission in Cas A is probably produced in clouds along the line of sight which have no physical connection with the supernova.

An accurate estimation of the fraction of the continuum source covered by the molecular clouds will

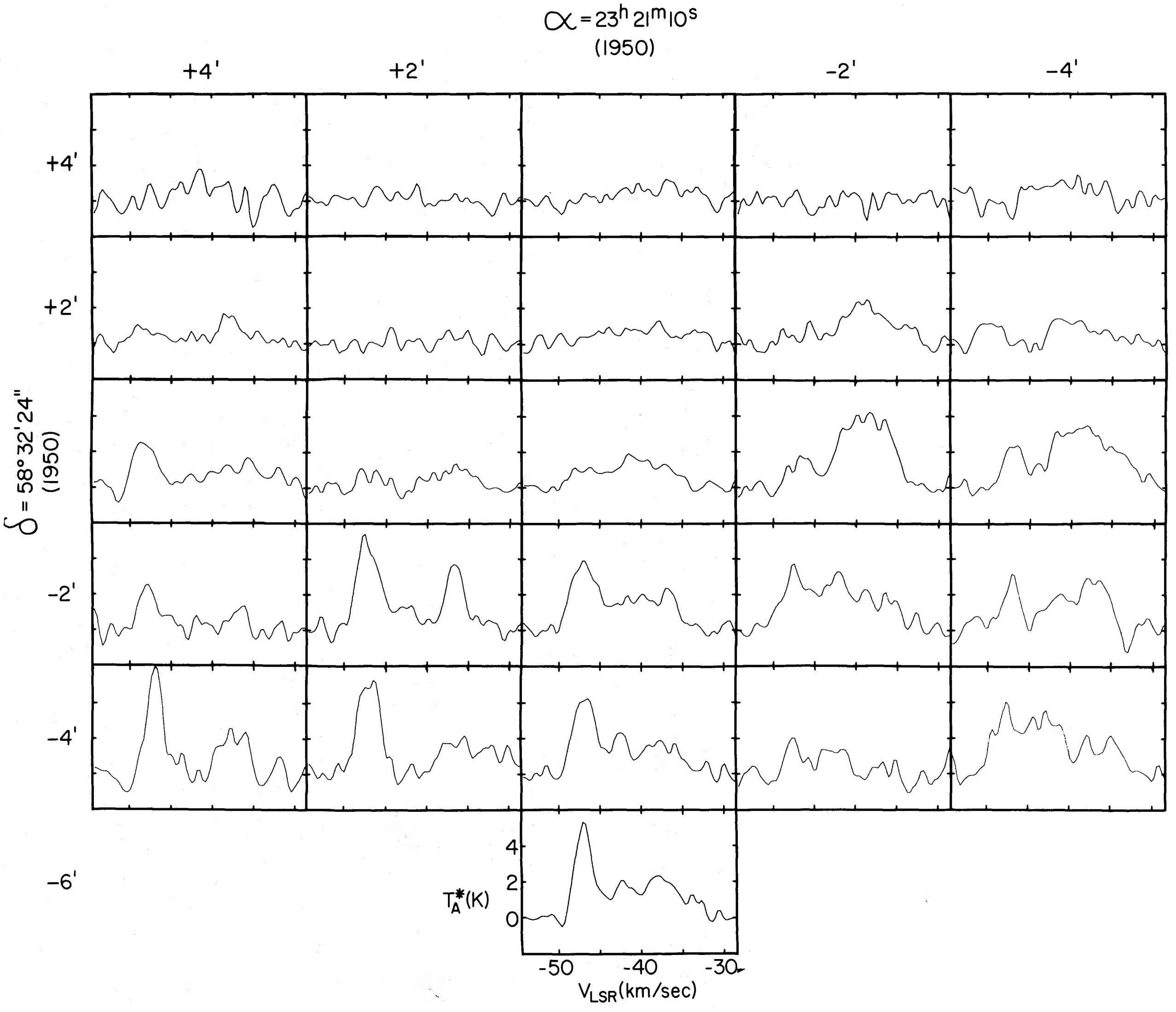

FIG. 3.—CO spectra are shown over a grid of spacing 2′ in the direction of Cas A (diameter = 3′). The profiles show sharp variations on the scale of 2′. The right ascension scale has been set with $\Delta\alpha = 1'$ in right ascension corresponding to (4/cos δ) s.

require even higher resolution CO observations, since the radio continuum originates from a shell not much larger than our 2′ beam. However, it is already clear from the abrupt changes we observe in the line profiles over 2′ that the filling factor appropriate to analysis of $H_2CO$ and OH absorption line data is quite likely $\leqslant 0.1$, not unity as is often assumed.

## III. DISCUSSION

The Cygnus Loop is the prototype old SNR and is at a fairly well-defined distance of 0.8 kpc (Woltjer 1972; Ilovaisky and Lequeux 1972). A similar incomplete shell structure is shown by the optical (van den Bergh, Marscher, and Terzian 1973), continuum radio (Keen *et al.* 1973; Kundu and Becker 1972; Moffat 1971; Colla *et al.* 1971), and X-ray emissions (Seward *et al.* 1976; Gronenschild *et al.* 1976). Estimates of the age of the SNR vary between 20,000 yr and 70,000 yr, depending upon the interpretation of the velocities measured for the optical filaments (Hogg 1974; Clark and Culhane 1976). There is much greater uncertainty regarding both the distance and evolutionary stage of IC 443 (e.g., Duin and van der Laan 1975). Distance estimates include values of 0.55 kpc, based upon a possible spatial coincidence with the H II region S249 and its possible illuminating star HD 43836 which lie to the NE of IC 443, of less than 2.2 kpc on kinematic grounds from 21 cm spectra (Dickel 1973), and of 3 kpc on the assumption that the expansion velocity of the nebula is the traditional $65 \mathrm{~km~s}^{-1}$, that the SNR is in the momentum-conserving stage of its evolution (Phase III; Woltjer 1972), and that it has the same age as the pulsar PSR 0611+22 (located 0°.7 from the center of the remnant). The pulsar age estimated from $P/\dot{P}$ is 65,000 yr. Morphologically, IC 443 is similar to the Cygnus Loop. As in the Cygnus Loop, there is a system of optical filaments forming a nearly circular ring, brightest on the northeast side where we have detected knots of molecular gas.

A model in which the optical filaments are shocked interstellar clouds (Sgro 1975; McKee and Cowie 1975; Cox 1972), rather than remnant material moving through the intercloud medium, requires the presence of clouds with $n_0 \geqslant 6 \mathrm{~cm}^{-3}$ in the medium surrounding the supernova. From the CO observations it is clear that even greater fluctuations in the ambient density certainly exist near the Cygnus Loop and IC 443. At a distance of 0.8 kpc, the molecular gas concentrations shown in Figure 1, typically 10′, would have a linear size of 2.3 pc. The estimated CO column density of $5 \times 10^{16} \mathrm{~cm}^{-2}$ would then imply an $H_2$ volume density of $120 \mathrm{~cm}^{-3}$ if 10% of the available carbon is in CO. (This estimate is likely to be a low value for the $H_2$ density, since we have employed both $^{13}$CO observations and a size obtained at the CO half-intensity contour.) The total mass of $H_2$ in each small condensation will be $30 M_{\odot}$. We regard these density and mass estimates as lower limits, since an independent line of analysis based upon CO excitation theory (Goldreich and Kwan 1974; Scoville and Solomon 1974) suggests a more realistic density estimate is in the range $300\text{–}10^3 \mathrm{~cm}^{-3}$.

Without resorting to detailed treatment of molecular dissociation, heating and cooling processes, and hydrodynamics, it is possible to picture crudely the circumstance of an expanding supernova encountering a molecular cloud of density $100\text{–}1000 \mathrm{~cm}^{-3}$. Presumably such encounters occur quite frequently, since surveys of molecular clouds throughout the Galaxy indicate that within 8 kpc of the galactic center the fraction of space containing molecular gas is $\sim 0.5\%$ (Scoville and Solomon 1975). Moreover, since the progenitors of Type II supernovae are thought to be young Population I stars of high mass, it seems reasonable to suppose that supernovae often occur within the very same cloud out of which they formed. The initial flash of ionizing radiation from the supernova is incapable of dissociating the molecules in the cloud which are both shielded by dust and situated 25 pc from the source. The observed regions adjacent to the Cygnus Loop and IC 443 also will probably not be catastrophically disrupted. The hot shock at the edge of the expanding remnant will bypass the cold dense cloud. A more serious problem is posed by the more massive shell of neutral gas just behind the blast wave shock (Straka 1974), assuming the supernova is in the momentum-conserving stage. Even if the supernova is in the earlier adiabatic phase, the radiative losses (Cox and Tucker 1969) in a high-density molecular cloud will rapidly cool the shocked cloud material and dissipate the thermal energy so that we might expect a local snowplow effect. The momentum transferred to the cloud is approximately limited to the momentum per unit area in the SNR shell (McKee and Cowie 1975) so that the molecular cloud will be accelerated to velocity $v_c \leqslant (\rho_0/\rho_c)(r_{\mathrm{sn}}/r_c)(v_{\mathrm{sh}}/4) \approx 15 \mathrm{~km~s}^{-1}$, where we have taken the ambient and the cloud densities as $\rho_0 = 1$ and $\rho_c = 120$, the SNR and cloud dimensions as $r_{\mathrm{sn}} = 160'$ and $r_c = 10'$, and the shell velocity as $v_{\mathrm{sh}} = 450 \mathrm{~km~s}^{-1}$ (McKee and Cowie 1975). An upper limit to the final velocity of the cloud is set by the dissociation of the $H_2$ ($\sim 30 \mathrm{~km~s}^{-1}$). The lower velocities of the observed clouds indicate that they have not yet been so accelerated.

## IV. CONCLUSIONS

We have searched five optical supernova remnants for evidence of molecular line emission in the direction of optical and radio continuum features. CO emission was detected in the Cygnus Loop, IC 443, and Cas A. In the first two, there is convincing evidence of small dense clouds existing at the periphery of the SNR and clearly correlated with the optical emission. These small clouds may well survive the passage of the high-velocity gas but have not yet been appreciably accelerated. The density of the molecular gas ($\sim 300 \mathrm{~cm}^{-3}$) is much larger than generally assumed outside supernovae ($\sim 10 \mathrm{~cm}^{-3}$) but is closer to a recent determination of $\sim 50 \mathrm{~cm}^{-3}$ from X-ray observations (Malina, Lampton, and Bowyer 1976). In Cas A the

CO emission appears to arise in foreground material with small structure compared to the radio continuum emission. The low implied filling factor affects analysis of molecular line absorption data such as $H_2CO$.

Future observations of heating and acceleration of such peripheral clouds should provide valuable information about the physical conditions and gas dynamics associated with the bright optical filaments.

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