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A Massive H I Cloud Surrounding Some Compact H II Regions

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Observations of 21-cm line emission from an area of sky surrounding the radio continuum sources near the nebulae K3−50 and NGC 6857 have revealed an extensive neutral-hydrogen cloud centered on these sources. The mean radial velocity of the cloud coincides with that of the H 109α and H 137β recombination lines from this region. The 21-cm absorption spectrum of the radio-continuum complex has also been derived. The neutral-hydrogen cloud contains between 100 000 and 250 000 $M_\odot$ and has a mean spin temperature of 55°K. The cloud is rotating and may also be contracting. It is suggested that the region may be an early stage in the formation of a star cluster.

I. INTRODUCTION

RECENTLY presented evidence by Rubin and Turner (1969) and Wynn-Williams (1969) shows that the emission nebula K3−50, which together with NGC 6857 and two other radio-continuum sources lies within the boundary of the extended thermal radio source NRAO 621, is a dense H II region of the class described by Mezger (1968). The sources in this complex are of considerable interest as a number of radio spectral lines have been observed in their direction. OH emission has been reported by Elldér *et al.* (1969), Turner (1969), and Downes (1970). Zuckerman *et al.* (1970) have observed the 4830-MHz transition of formaldehyde in absorption against the continuum radiation from the complex at a velocity near that of the H 109α and H 137β recombination lines from the region (Rubin and Turner 1969). Thompson *et al.* (1969) have suggested that a 21-cm line-emission feature in a profile obtained by Westerhout (1966) at a position 38 arc min from the continuum sources may also be related to them. We have studied the distribution of neutral hydrogen in this area of sky using the 300-ft transit telescope at the National Radio Astronomy Observatory (operated by Associated Universities, Inc., under contract with the National Science Foundation) and the 85-ft telescope at the Dominion Radio Astrophysical Observatory.

II. OBSERVATIONS

The observations at the NRAO were made with the 300-ft transit telescope and the 100-channel autocorrelation receiver (Weinreb 1963) with a system noise temperature of ∼200°K, a channel bandwidth of 6.25 kHz, and an effective integration time of 10 sec. The beamwidth of the telescope at 1420 MHz is close to 10 arc min.

As there is considerable structure in the H I emission from the area of sky surrounding K3−50, it was necessary to determine line profiles throughout this area in order to assess the effects of Galactic confusion. The observations were made by taking line profiles at 10-sec intervals during drift scans of length 20 min centered on the right ascension of K3−50 ($\alpha_{1950} = 19^h59^m50\overset{s}{.}2$, $\delta_{1950} = 33°24'19''$). Six such drift curves were taken at $\delta_{1950} = 33°26'$, and four in the same range of right ascension at adjacent declinations between $\delta_{1950} = 33°06'$ and $33°41'$.

Figure 1 shows a typical drift curve reduced to contours of equal antenna temperature in the α_{1950}–V_{LSR} plane by the procedure used in the *Maryland–*

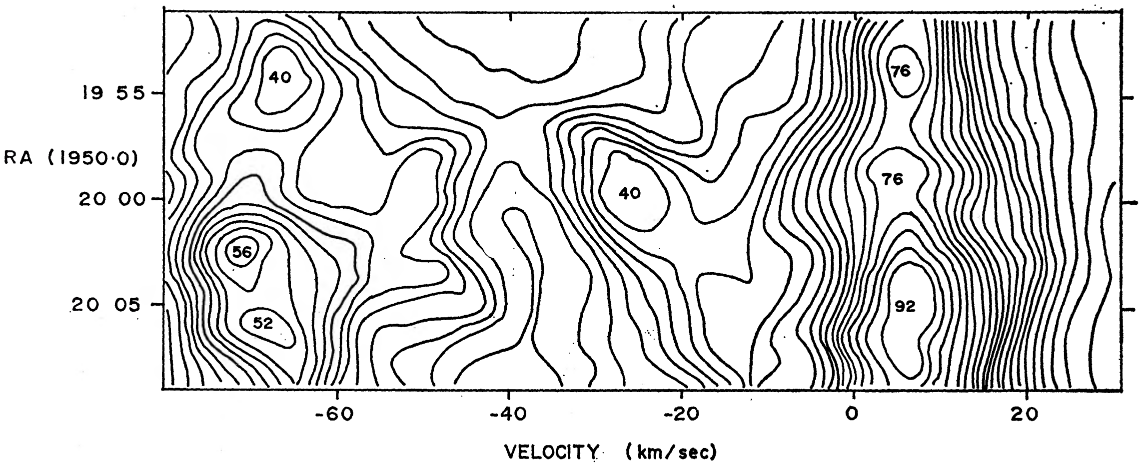

FIG. 1. Contour map of antenna temperature as a function of velocity and right ascension (1950.0), at Dec. 33°26′: The velocity is with respect to the local standard of rest. The contour unit is 5°K.

Green Bank Galactic 21-cm Line Survey (Westerhout 1969). It was evident from such contours that a localized line-emission feature is centered on $\alpha_{1950} \sim 19^h 59^m 40^s \pm 10^s$, $\delta_{1950} \sim 33°26' \pm 10'$ and $V_{\rm LSR} \sim -26$ km/sec. The angular width of the feature between half-temperature points in right ascension is ~70 arc sec.

The NRAO observations do not delineate the H I cloud completely in declination, so additional observations were made for this purpose with the 85-ft telescope at the DRAO, Penticton (Locke *et al.* 1965). These observations were made with a system noise temperature of 215°K and a 100-channel filter spectrometer with a channel bandwidth of 10 kHz and an effective integration time of 2 min. The beamwidth of the telescope at 1420 MHz is close to 35 arc min. Line profiles were recorded at points 30 arc min apart in declination between Dec. 2°30′ north and 2°30′ south of the position of K3−50. The feature was found to be asymmetric in declination, the peak brightness temperature occurring at $\delta_{1950} = 33°35' \pm 10'$ and the declination width of the main peak between half-temperature points being $65' \pm 10'$. The DRAO observations were also used to determine the brightness temperature of the slowly varying component of the Galactic emission in the region surrounding the continuum sources; this enabled us to check that correct allowance was made for the effect of the error beam of the 300-ft telescope in the reduction of the NRAO observations.

The extended emission feature is centered on a position close to that of the continuum emission near K3−50; its central velocity is also close to the velocity of -24.2 ± 0.6 km/sec found for the H 109α and H 137β radio recombination lines from the region by Rubin and Turner (1969). We suggest that these coincidences in position and velocity imply a physical association between the H I emission feature and the continuum complex. Our observations show that other interstellar clouds appear in emission within a few degrees of this region and at similar radial velocities, but a coincidence in all three parameters seems unlikely unless the H I cloud and the source of the recombination lines are physically related. We therefore suggest that the region contains a complex of relatively compact H II regions within an extensive neutral-hydrogen cloud; the extended source NRAO 621 (Westerhout 58) may be part of the same association.

III. DERIVATION OF THE BRIGHTNESS DISTRIBUTION ACROSS THE CLOUD

In order to separate the emission of the cloud from that of the general interstellar medium at the same radial velocities, allowance must be made for the finite optical depth of both the cloud and the interstellar medium, and for possible differences in spin temperature between them. The brightness temperature T_1 observed in the direction of the cloud is made up of three components as shown in Fig. 2. These are: the brightness contributed by the cloud, by the foreground (gas between the cloud and the observer), and by the background (gas beyond the cloud). As a first step in calculating the brightness contributed by the cloud at each velocity, the brightness temperature T_2 observed on either side of the cloud at this velocity was estimated, and a baseline (denoted by "a" in Fig. 2) was interpolated through the position of the cloud. The cloud is of finite optical depth, however, and will absorb the emission from the background. The true baseline therefore lies below the interpolated directly, as shown by "b" in Fig. 2. In addition, the foreground may absorb the emission from the cloud, as shown by "c" in Fig. 2, and from the background.

The quantity estimated on the baseline interpolation is the difference $\Delta T = T_1 - T_2$. This is related to the brightness temperature $T_{\rm C}$ which would be observed for the cloud in isolation by the equation,

$$\Delta T = T_{\rm C} e^{-\tau_{\rm FG}} \left(1 - \frac{T_{\rm BG}}{\mathcal{T}_{\rm C}}\right). \qquad (1)$$

Here $T_{\rm BG}$ is the brightness temperature which would be observed for the background in isolation, $\mathcal{T}_{\rm C}$ is the spin temperature of the cloud, and $\tau_{\rm FG}$ is the optical

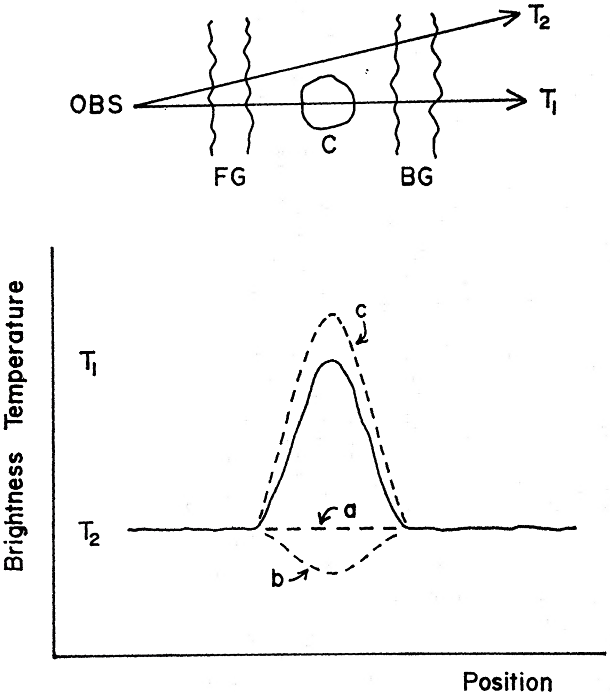

FIG. 2. Diagram illustrating the effect of finite optical depth on the emission profile at one velocity: The *upper* diagram represents the distribution of gas in the foreground (FG), the cloud (C), and the background (BG). The *lower* diagram shows the observed drift curve (*full line*), the initial interpolated baseline (a), absorption of the background emission by the cloud (b), and absorption of the cloud emission by the foreground (c).

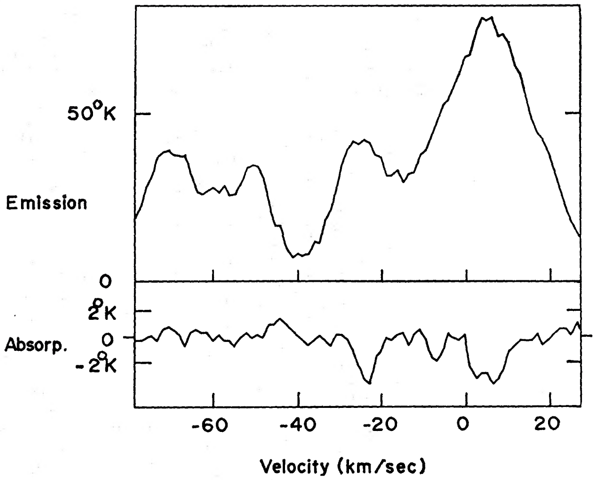

FIG. 3. Interpolated emission profile and absorption profile at the position of K3−50.

depth of the foreground material. In order to derive T_C from the observed values of ΔT, it is therefore necessary to estimate τ_{FG}, T_{BG}, and a characteristic value of $\mathcal{T}_C$. These parameters cannot be derived from the observed emission profiles alone; the additional information required is provided by the H I absorption profile of the continuum sources. Figure 3 shows this absorption profile, derived from the mean of the six drift curves at $\delta_{1950}=33°26'$, together with the interpolated emission profile at the position of the continuum complex.

The absorption at each velocity was obtained by analyzing the mean drift curve at that velocity. If the radiation from the source is absorbed, there is a decrease in brightness centered on the source position; the shape of this decrease in right ascension is determined by the antenna response if the source is not appreciably resolved.

The drift curve at each velocity was fitted with a polynomial baseline and a superimposed antenna response centered on the source position. No constraint was imposed on the sign of the antenna response in this fit: either absorption or emission, centered on the source position, could have been indicated. Figure 3 shows that only absorption was found. The magnitude of the fitted antenna response was used to estimate the absorption.

The absorption profile has also been observed interferometrically by Thompson *et al.* (1969). There is good agreement between the main features of the absorption profiles obtained by us and by Thompson *et al.*, suggesting that both groups have correctly allowed for the effects of confusion.

Absorption is evident at velocities between +12 and −10 km/sec, suggesting that the continuum sources are beyond most of the material of the local arm. The magnitude of the absorption implies that the entire continuum complex observed by Wynn-Williams lies beyond the absorbing material. There is no absorption in the velocity range −45 to −80 km/sec corresponding to material in the Perseus arm. It is therefore probable that the continuum sources lie between the near side of the Perseus arm and the far side of the local arm.

Both our profile and that presented by Thompson *et al.* show appreciable absorption at the radial velocities of the cloud material. In our profile, this absorption is confined to the velocity range −20 to −28 km/sec, whereas the interferometric profile indicates absorption at all velocities exhibited by the cloud. This difference is within the experimental uncertainties of the two profiles; if the form of our profile were confirmed, it would reinforce our suggestion that the entire continuum complex is embedded in the H I cloud. Both profiles indicate that the material of the cloud has an optical depth $\tau_C\sim 1$ in absorption in the velocity range −22 to −27 km/sec. For the purpose of assigning a characteristic spin temperature $\mathcal{T}_C$ to the cloud for use in Eq. (1) we put $\tau_C=1$ for the emission and assume the cloud to be located between the Perseus arm and the Local arm. The spin temperature so derived will represent a weighted mean of the temperature distribution within the cloud.

There is evidence that the temperature of the interstellar hydrogen between the spiral arms is considerably greater than the 125°K adopted in early studies of the Galactic H I. Hjellming *et al.* (1969), Mebold (1969), Radhakrishnan and Murray (1969), and Hughes and Routledge (1970) have suggested that the intercloud medium has a spin temperature which may be >1000°K. This is in agreement with studies of low-frequency interstellar free–free absorption (Bridle and Venugopal 1969) and theoretical investigations of heating of the interstellar gas by low-energy cosmic rays (Field *et al.* 1969; Spitzer and Scott 1969; Goldsmith *et al.* 1969). We therefore neglect absorption of radiation from the cloud by the foreground material at its velocity.

The distance of the cloud is unknown. If we assume it to be on the far side of the local arm, so that it absorbs all of the emission from the interstellar gas at its radial velocity, the observed values of ΔT give $\mathcal{T}_C=70$°K. If, however, we assume it to be on the near side of the Perseus arm, so that it absorbs none of the emission from the gas at its velocity, we find $\mathcal{T}_C=40$°K. In what follows, we have adopted a spin temperature $\mathcal{T}_C=55$°K, and have further assumed that $T_{FG}=T_{BG}$. The values of T_C derived from Eq. (1) are insensitive to the particular assumption made at this point.

The effect of the error beam of the 300-ft telescope was allowed for by a procedure analogous to that described by Westerhout (1969), using parameters of the main beam and of the error beam deduced by Heiles and Hoffman (1968). The values obtained for the brightness temperature of large-scale structure in the region surrounding the cloud were within 10% of those observed with the DRAO 85-ft telescope, indicating that the effect of the error beam was adequately allowed for by our analysis.

The values of T_2 near the position of the cloud were estimated by interpolation of the surrounding brightness temperatures in both right ascension and velocity. Figure 4(a)–(e) shows contours of constant T_C in the α_{1950}–V_{LSR} plane derived using Eq. (1) and the parameters estimated above.

IV. PARAMETERS OF THE H I CLOUD

A. Refined Position and Radial Velocity

Our method of reduction eliminated emission features of width $>3°$ in right ascension or >15 km/sec in radial velocity. The maps shown in Fig. 4 contain a number of features of small angular and velocity scale which were not eliminated by this process but which are probably unrelated to the continuum complex. These are: feature (B) at $\alpha \sim 20^h04^m$, $\delta \sim 33°36'$ and centered on $V_{LSR} \sim -15.5$ km/sec [Fig. 4(c)–(d)], and feature (C) at $\alpha < 19^h54^m$, $\delta < 33°06'$ and $V_{LSR} \sim -18$ km/sec [Fig. 4 (a) and (b)]. We consider only feature (A) in what follows.

Table I gives the right ascensions $\bar{\alpha}$ and radial velocities $\bar{V}_{LSR}$ of the centroids of the optical depth distributions corresponding to each of the maps shown in Fig. 4. The spin temperature has been taken as 55°K in this computation. The values of $\int\int \tau(\alpha, V_{LSR}) d\alpha dV_{LSR}$ for feature (A) at each declination are also given. Gaussian interpolation in declination shows that this quantity would have its maximum at

$$\delta_{1950} = 33°21' \pm 3'.$$

The values of $\bar{\alpha}$ and $\bar{V}_{LSR}$ show a systematic progression with declination. Interpolation to $\delta = 33°21'$ gives

$$\bar{\alpha}_{1950} = 19^h59^m43^s \pm 3^s,$$
$$\bar{V}_{LSR} = -26.2 \pm 0.5 \text{ km/sec},$$

close to the corresponding values for the source of the recombination lines. The right ascension half-width of the emission from the cloud is 75±5 arc min at the mean declination. The declination half-width estimated from the Gaussian interpolation is 50±5 arc min, in fair agreement with that estimated from the observations at the DRAO.

B. Mass

The number of hydrogen atoms within the cloud was calculated from

$$N_H = 1.736 \times 10^{61} D^2 T_C \int\int\int \tau(\alpha,\delta,V) d\alpha d\delta dV, \quad (2)$$

where D is the distance to the cloud in kiloparsecs and the integral is evaluated over the cloud. A Gaussian distribution of the optical depth in declination was again assumed when evaluating the integral. Taking the spin temperature to be 55°K, we find the mass of neutral hydrogen to be $\sim 3000 D^2 M_\odot$, and the mean density $n_H \sim 36 D^{-1}$ atoms/cm^3. These estimates are insensitive to the exact form of the temperature distribution in the cloud, as τ is nowhere $\gg 1$ across the cloud.

TABLE I. Parameters of the observed optical depth distributions.

δ_{1950}	$\bar{\alpha}_{1950}$	$\bar{V}_{LSR}$ (km/sec)	$\int\int \tau(\alpha,V) d\alpha dV$ (min arc km/sec)
33°06′	$19^h59^m54^s$	−25.2	701
33 16	19 59 50	−26.6	881
33 26	19 59 30	−26.4	820
33 36	19 59 14	−27.0	758
33 41	19 58 52	−28.2	454

Using the Contopoulos–Strömgren Galactic rotation curve (Mihalas and Routly 1968), the radial velocity of −26.2 km/sec derived above implies a distance of 9 kpc for the H I cloud. This is similar to the distance suggested by Thompson *et al.* (1969). At this kinematic distance ($D=9$), the derived mass of neutral hydrogen would be $\sim 250\,000 M_\odot$. This mass would be unusually large for a Galactic H I association, although it is similar to that found for the I Mon association by Girnstein and Rohlfs (1964) and by Raimond (1966) and for the Orion region by Menon (1958). It is 5 times greater than the masses found in II Mon by Raimond (1966), and around λ′ Orionis by Wade (1958).

In view of the uncertainties in the detailed kinematics of Galactic material (e.g., Kerr 1969), an interpretation based solely on the kinematic distance must, however, be treated with caution. Peculiar velocities of order ~25 km/sec with respect to the general Galactic rotation are commonly observed; if the cloud had a peculiar velocity of this order, the corresponding error in its distance would be ±2 kpc. As a cloud or cloud complex of large mass is unlikely to be formed far from the spiral arms, and would be strongly attracted to them, we suggest that the smallest distance compatible with the absorption profile of the continuum sources should be adopted. If the cloud were assumed to be on the further edge of the local arm, i.e., at a distance $D \sim 6$, the contours presented in Fig. 4 would not be significantly altered, but the estimated neutral-hydrogen mass would become $\sim 110\,000 M_\odot$ and the mean density ~6 atoms/cm^3.

V. INTERNAL KINEMATICS OF THE H I CLOUD

The emission profiles in the region of the H I cloud are sufficiently resolved in both right ascension and velocity to permit examination of the main features of the internal kinematics of the cloud. The maps shown in Fig. 4 suggest the following interpretation.

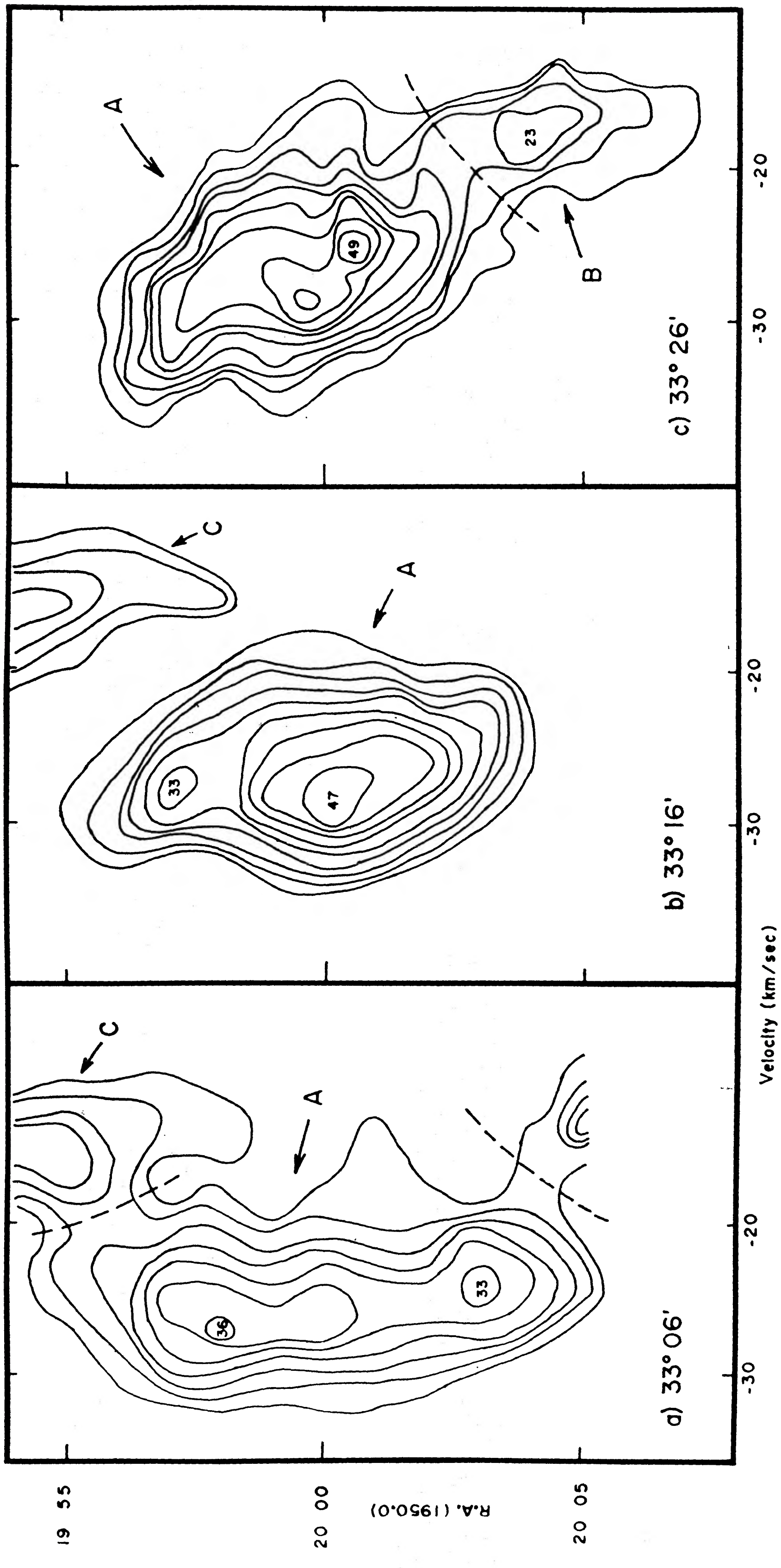

FIG. 4 (a)–(e). Contour maps of antenna temperature, corrected for absorption by the foreground material and with the Galactic background emission removed. The contour unit is 5°K.

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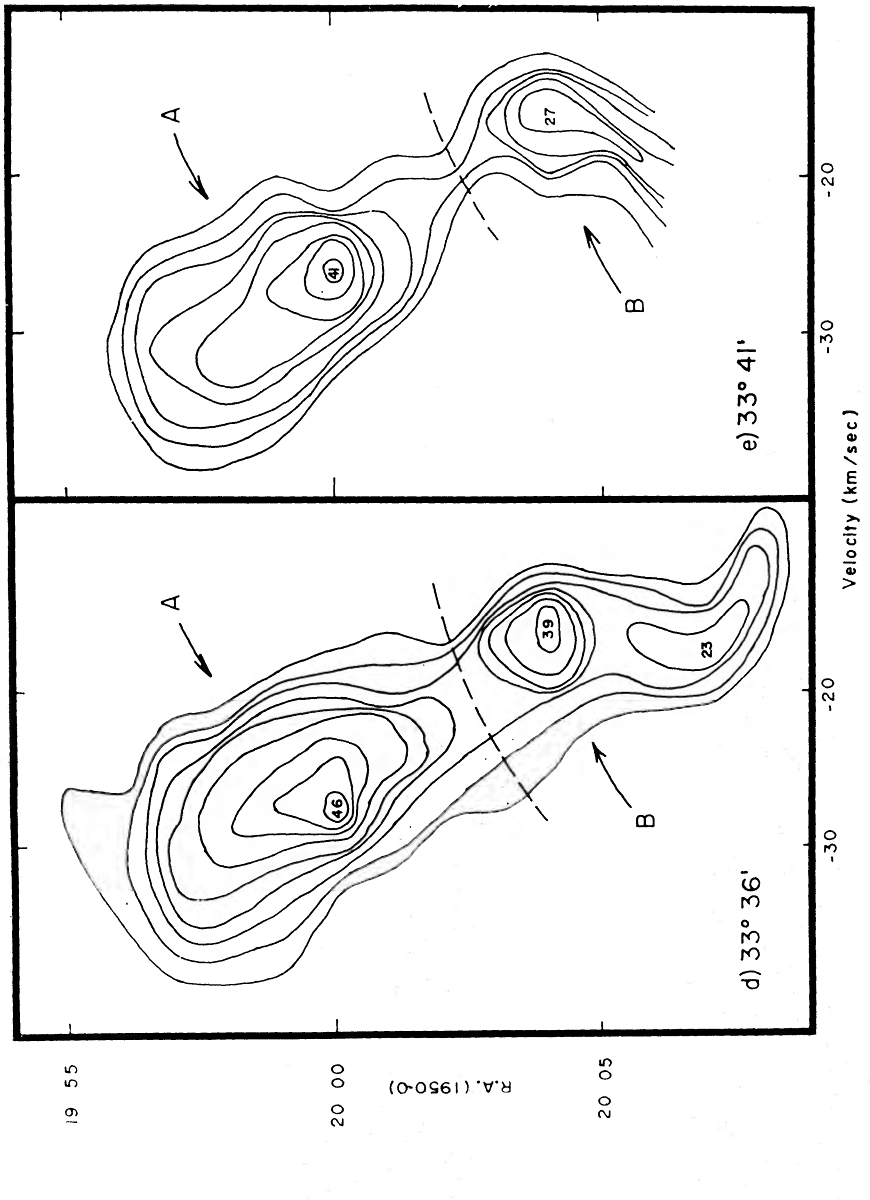

FIG. 4 (*continued*)

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The cloud is rotating. This is indicated by the inclination of the major axes of the contours shown in Fig. 4 to the lines of constant velocity. This inclination is most pronounced at $\delta=33°41'$ [Fig. 4(e)] and least pronounced at $\delta=33°16'$ [Fig. 4(b)]. The sense of this inclination is the same at all declinations; the corresponding rotation is opposed to that computed for the differential Galactic rotation. The apparent angular velocity changes with declination, suggesting that the cloud is itself in differential rotation. The angular velocity about an axis perpendicular to the line of sight is 2×10^{-15} rad/sec at the mean declination, for an assumed distance of 6 kpc. The orientation of the rotation axis cannot be determined, due to the apparent differential rotation.

The observed velocity dispersion of ±6 km/sec about the mean velocity at each right ascension could be attributed to: (i) bulk radial motions of this order, (ii) turbulence of the same order, (iii) a kinetic temperature ~3000°K or to a combination of all three. As discussed in Sec. III, the mean spin temperature of the cloud is ~55°K. This does not exclude (iii) as the origin of the line width, as T_C could vary from <55°K in an optically thick outer region responsible for the observed 21-cm absorption to ~3000°K in an optically thin inner region surrounding the H II condensations. If the temperature of 55°K were close to the true kinetic temperature of the bulk of the cloud material, the observed line width could be explained by radial motions of order ±5.5 km/sec.

If the H I cloud does indeed surround an ionized region, it is likely that there will be a temperature gradient within it. In this case the formaldehyde absorption would occur at a radial velocity characteristic of the intervening cool regions in the cloud. The formaldehyde absorption (Zuckerman *et al.* 1970) occurs at a velocity of -22.0 ± 0.5 km/sec (with a line width of 3.9 km/sec); this may be compared with the radial velocity of -26.2 ± 0.5 km/sec found by us for the peak of the H I emission. This implies that the cooler regions of the cloud are contracting onto the main mass of material with a velocity $\sim4.2\pm1$ km/sec. The absence of formaldehyde absorption at ~-30 km/sec could suggest that the continuum source is embedded in the cloud, if the latter's formaldehyde content were symmetrically distributed. Our 21-cm absorption profile would also suggest this conclusion. An absorption profile obtained with greater angular resolution and sensitivity would be desirable, however, as the marginal discrepancy between our profile and that observed by Thompson *et al.* (1969) occurs at radial velocities which are significant for this interpretation.

VI. CONCLUSIONS

Our observations have revealed an extensive H I complex centered close to the position of the continuum emission near the optical nebulosity K3−50 and at the radial velocity of the recombination lines from this region. This triple coincidence strongly suggests a physical association between a massive neutral-hydrogen cloud and an embedded complex of compact H II regions.

The magnitude of the 21-cm absorption at radial velocities near that of the emission cloud can be explained only if the main continuum components observed by Wynn-Williams (1969) are all being absorbed by this cloud. This is consistent with presuming them all to be at the same distance, in or beyond the cloud. The 480-kHz width of the H 109α recombination line from the region (Rubin and Turner 1969) suggests that it may originate from several sources with somewhat dispersed radial velocities, consistent with interpreting all the continuum sources as H II regions.

Assuming all the continuum sources to be absorbed by the cloud, the 21-cm absorption and emission profiles imply a mean spin temperature ~55°K within the cloud. The total mass of neutral hydrogen in the cloud is probably between 100 000 and 250 000$M_\odot$. The uncertainty is due mainly to the uncertainty in the distance of the cloud.

It is possible that the region may be an early stage in the formation of a massive star cluster. The ratio of H I to H II masses, assuming the H II regions to be spherical and at a kinetic temperature of 7000°K, is ~1800:1. This large ratio suggests that the H II complex may be in an early stage of formation. The observed formaldehyde absorption profile suggests that the cool outer regions of the complex may be contracting, which would also be characteristic of a young object. The gravitational potential energy of the cloud is ~20% of the total internal energy, assuming the mean molecular weight of the gas to be 1.5 and a uniform spherical distribution of material in the cloud. This suggests that the cloud is not gravitationally bound, and is consistent with theories of interstellar cloud formation based on thermal or magnetic instabilities (Goldsmith *et al.* 1969; Parker and Lerche 1969), rather than on a gravitational instability.

Further studies of the microwave continuum and line emission from the region, and observations of the nebula K3−50 at optical and infrared wavelengths, should provide further insight into the physical state of the inner regions of the cloud. Radio studies with sufficient angular resolution to distinguish the components of the continuum complex will be particularly valuable.

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