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ON THE DISTANCE AND MEMBERSHIP OF THE R CrA T ASSOCIATION

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ABSTRACT

Photoelectric photometry and some spectroscopy of suspected members of the R CrA T association are presented. From *uvby*, β photometry of three lightly reddened early-type stars associated with the R CrA dark cloud, we derive a mean distance of 129 pc. The confirmed late-type young stars occupy the expected band from one to three magnitudes above the main sequence in the plot of V magnitude against $V-I$ color. A red objective-prism survey has revealed seven additional stars which appear to have Hα emission. Our observations cast some doubt on the pre-main-sequence nature of some of the faint Hα-emission stars noted by Knacke *et al.* (1973).

I. INTRODUCTION

The R CrA dark cloud [$\alpha(1950) = 19^h00^m$, $\delta(1950) = -37°$] is a nearby region of star formation which has been rather well studied by a variety of observational techniques. Knacke *et al.* (1973) obtained optical and infrared photometry of known young stars in the region and suggested that the unusually large infrared excesses in some of the R CrA stars might indicate extreme youth. They also noted ten Hα-emission objects which seemed likely to be associated young stars. Additional *JHKL* photometry by Glass and Penston (1975) of a number of stars in the central part of the cloud failed to reveal any previously unknown young stars showing evidence of circumstellar dust shells. The presence of several Herbig–Haro objects and an associated infrared source in the R CrA dark cloud (Strom, Strom, and Grasdalen 1974; Vrba, Strom, and Strom 1975) is further evidence of very recent star formation. Vrba, Strom, and Strom (1976a) have mapped much of the dark cloud at a wavelength of 2 μ but found only a few additional objects, which may be embedded young stars. Their observations imply that the efficiency of star formation in this region is unusually low. However, Brown and Zuckerman (1975) did find two compact H II regions in the central part of the cloud from continuum radio observations.

The magnetic field structure in the R CrA dark cloud has been traced out via linear polarization measurements of background stars by Vrba, Strom, and Strom (1976b). The resulting picture (Vrba 1977) is that the magnetic field appears to be hindering the cloud collapse and that star formation is occurring in a "magnetic well" at the point closest to the galactic plane. An extensive study of the R CrA molecular cloud at radio wavelengths by Loren (1979) confirms this basic picture and suggests a nonhomologous collapse along the magnetic field lines with little associated rotation. The wavelength dependence of optical polarization of stars reddened by the R CrA dark cloud (Marraco 1978; Vrba, Coyne, and Tapia 1978, 1980) provides compelling evidence for anomalous interstellar extinction throughout the cloud.

In this paper we present the results of a survey for additional Hα-emission stars in the R CrA dark cloud, as well as photometric and spectroscopic observations of a number of the fainter suspected members of the T association. We also derive the distance to the R CrA dark cloud from *uvby*, β photometry of several associated early-type stars.

II. OBSERVATIONS

a) *Survey for Hα-Emission Stars*

A search for Hα-emission stars in the R CrA dark cloud has been made using eight objective-prism plates taken with the Curtis Schmidt telescope on Cerro Tololo during September 1974 and July 1976. The exposure times ranged from 9 to 90 min on type 098-04 emulsion; either the 4° or 10° prism was used. We list in Table I the ten stars identified by Knacke *et al.* (1973) as Hα-emission objects (denoted Hα 1 to Hα 10) and seven additional stars with Hα emission which we have noted in our survey (denoted Hα 11 to Hα 17). The stars Hα 11 to Hα 17 are also identified on finding charts in Fig. 1. The columns in Table I give the 1950.0 coordinates of each star, an estimate of the observed Hα-emission strength, and any pertinent remarks. In addition, we note that Hα emission was clearly seen in the stars R CrA, S CrA, T CrA, DG CrA, and VV CrA; we did not see

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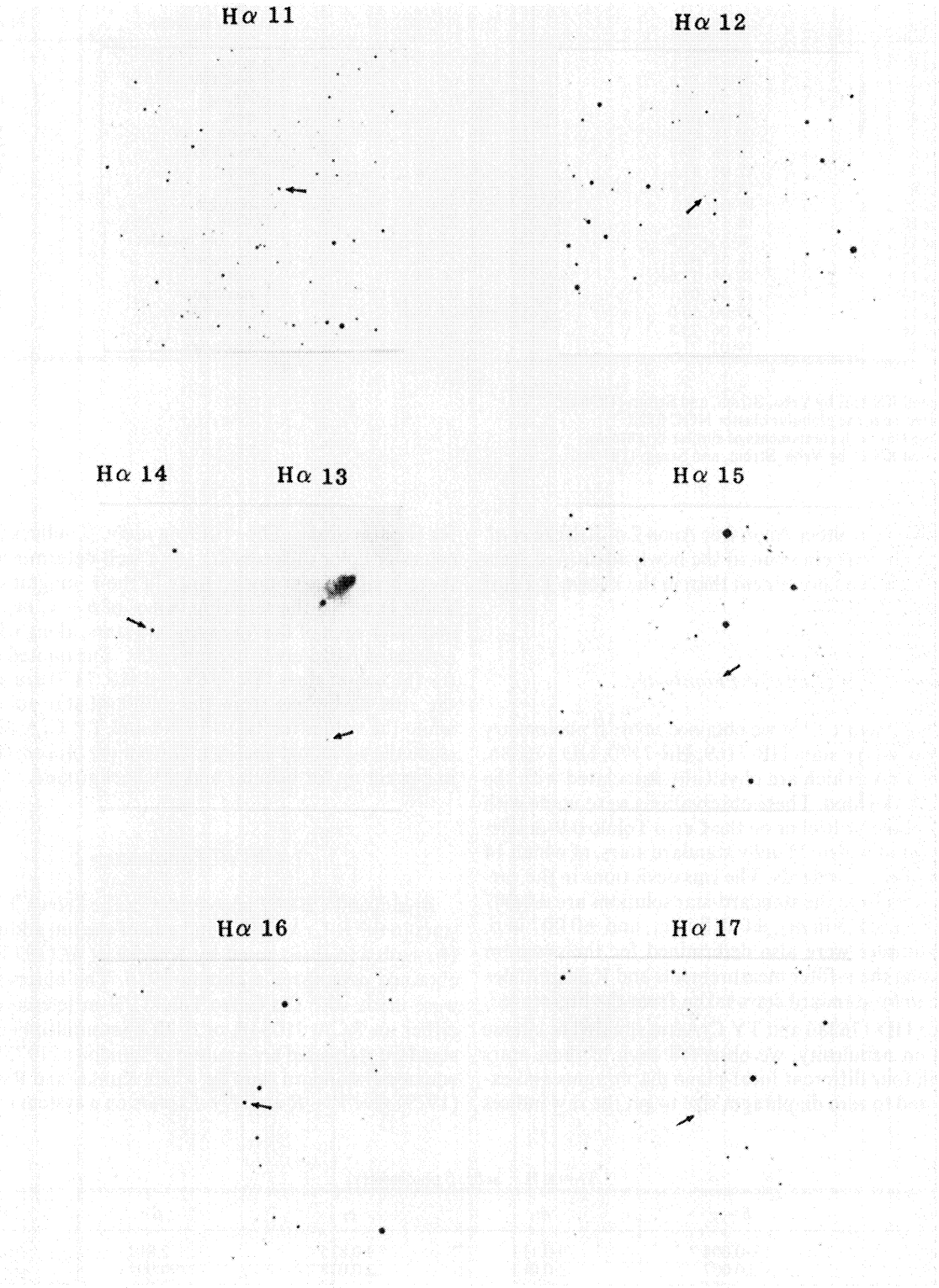

FIG. 1. Finding charts for the stars Hα 11 through Hα 17. These are from a 15-min *V* plate (IIa-D + GG 14) taken with the Curtis Schmidt telescope. North is up and east to the left; each chart is 10 arcmin on a side.

TABLE I. Results of Hα objective-prism survey.

Star	R.A.(1950)	Decl.(1950)	Hα emission	Notes
Hα 1	$18^h57^m57^s.6$	−36°52′17″	none	
Hα 2	18 58 19.2	−37 04 13	possible	
Hα 3	18 59 10.7	−37 02 45	strong	1
Hα 4	19 00 03.1	−37 18 06	none	
Hα 5	18 56 40.2	−36 41 54	none	2
Hα 6	18 56 39.7	−36 41 19	moderate	2
Hα 7	19 01 47.6	−36 59 02	none	3
Hα 8	19 02 39.5	−37 13 35	none	
Hα 9	19 01 29.1	−37 32 02	possible	
Hα 10	18 55 28.7	−37 23 32	none	
Hα 11	18 55 51.9	−37 15 42	wk and variable	
Hα 12	18 56 40.1	−36 32 10	moderate	
Hα 13	18 58 37.6	−37 06 43	weak	
Hα 14	18 59 09.1	−37 02 29	moderate	4
Hα 15	19 00 55.0	−37 03 33	moderate	
Hα 16	19 06 23.8	−37 09 18	moderate	
Hα 17	19 07 21.5	−37 04 05	moderate	

Notes

1. Denoted KS 15E by Vrba, Strom, and Strom (1976a).
2. Located near the globular cluster NGC 6723.
3. Double star with components of similar brightness.
4. Denoted KS 15 by Vrba, Strom, and Strom (1976a).

Hα emission in either Anon 1 or Anon 2 of Knacke *et al.* (1973). The Hα emission in the newly identified stars is in all cases less prominent than in the known T Tauri stars.

b) *uvby, β Photometry*

During August 1976 we obtained *uvby, β* photometry of the early-type stars HR 7169, HR 7170, HD 176386, and TY CrA, which are physically associated with the R CrA dark cloud. These observations were made with a 1P21 photomultiplier on the Cerro Tololo 0.9-m telescope and included 22 *uvby* standard stars, of which 14 were also Hβ standards. The rms deviations in the various indices from the standard-star solutions are ±0.007 in $b-y$, ±0.013 in m_1, ±0.018 in c_1, and ±0.007 in β. V magnitudes were also determined for the program stars using the y-filter measurements and V magnitudes for the *uvby* standard stars taken from the literature.

Since HD 176386 and TY CrA are situated in intense reflection nebulosity, we observed each of these stars through four different focal-plane diaphragms and extrapolated to zero diaphragm size to get the raw indices for the star alone. The resulting *uvby, β* indices (being colors or color differences) seem well determined, but there is significant uncertainty in the V magnitude. In Table II we list the resulting values of $b-y$, m_1, c_1, β, and V for each of the four program stars, along with the estimated mean error in each index. The quoted errors for the bright stars HR 7169 and HR 7170 are simply the rms deviations from the standard-star solutions, while the values for HD 176386 and TY CrA also include the estimated uncertainty from the procedure used in correcting for nebular and sky background.

c) *UBVRI Photometry*

Broadband *UBVRI* photometry of the known T Tauri stars in the R CrA dark cloud and of the ten additional Hα-emission stars noted by Knacke *et al.*(1973) was obtained over three nights in 1976. The observations were made with the Cerro Tololo 0.9-m telescope and either an RCA 31034A or S-20 photomultiplier. The standard stars used are a subset of Landolt's (1973) faint equatorial standard stars for which Kunkel and Rydgren (1979) give $V-R$ and $V-I$ colors on a system natural

TABLE II. *uvby, β* photometry.

Star	$b-y$	m_1	c_1	β	V
HR 7169	−0.004	+0.113	+0.815	2.812	6.75
	±0.007	±0.013	±0.018	±0.007	±0.02
HR 7170	+0.004	+0.126	+0.637	2.802	6.47
	±0.007	±0.013	±0.018	±0.007	±0.02
HD 176386	+0.091	+0.115	+0.885	2.855	7.40
	±0.009	±0.014	±0.021	±0.009	±0.06
TY CrA	+0.443	+0.004	+0.726	2.807	9.73
	±0.012	±0.020	±0.027	±0.010	±0.08

TABLE III. *UBVri* photometry.

Star	Night	$U-B$	$B-V$	V	$V-r$	$V-i$
R CrA	1	+0.31	0.83	13.53	1.07	2.12
	2		0.92	12.71	0.92	1.88
S CrA	1	−0.13	0.98	11.52	0.84	1.66
	2		1.00	11.58	0.85	1.62
	3	−0.20	0.97	11.74	0.88	
T CrA	1	+0.76	1.09	13.18	0.92	1.86
	2		1.16:	13.21	0.93	1.83
VV CrA	2		1.30:	13.10	1.22	2.39
	3	−0.14	1.20	13.02	1.17	
DG CrA	2		1.54:	14.20:	1.14	2.05
	3	+0.42	1.29	13.43	1.01	
Anon 1	2		1.10	11.22	0.71	1.34
	3	+0.65	1.08	11.23	0.71	
Anon 2	2		1.93:	13.94:	1.44	2.67
	3		1.90:	13.95	1.37	
Hα 1	2		1.57::	15.52:	0.60:	1.29::
Hα 2	2			15.87::	1.25::	2.72::
Hα 3	2			16.03::	1.70::	3.12::
Hα 4	2			16.34::	1.05::	2.08::
Hα 5	2		1.29::	15.36:	0.70:	1.27::
	3		1.07:	15.12	0.60	
Hα 6	2		1.45:	13.92:	1.02	2.08:
	3		1.26	13.94	1.04	
Hα 7	2		0.76	12.29	0.49	0.97
Hα 8	2		0.62::	15.79::	0.72::	1.40::
Hα 9	2		0.82::	15.68::	0.62::	0.99::
Hα 10	2		1.25::	14.89:	0.77:	1.33:
	3		1.25	14.77	0.74	
Hα 14	2		1.76:	14.00:	1.37	2.63
	3	1.44::	1.73	13.92	1.34	

Notes

UT night code: 1 = 30 Mar 76; 2 = 26 Jul 76; 3 = 19 Aug 76.

Measurements with a formal error of 0.03 to 0.05 mag are followed by a colon (:), while measurements with a formal error from 0.06 to 0.10 mag are followed by a double colon (::).

to the RCA 31034A and the Cerro Tololo *BVRI* filter sets; the resulting colors are denoted $V-r$ and $V-i$. On the night the S-20 was used, no $V-i$ colors were measured and it is suspected that the $V-r$ colors redder than about 1.0 may not be exactly on the Kunkel–Rydgren system.

The results of our *UBVRI* photometry appear in Table III. The various columns give the star designation, a night code, and the values of $U-B$, $B-V$, V, $V-r$, and $V-i$. The observations of S CrA have previously been reported by Rydgren (1977) but are included here for completeness. Since our observations were obtained before the introduction of the Peoples Photometry data acquisition software on Cerro Tololo, we have estimated the internal error in each raw magnitude from the formal photon-counting statistics for the bulk star and sky counts. These results have been combined with the rms deviations from the standard-star solutions to give an estimate of the mean error in each color or magnitude. This formal error is shown in Table III if it is 0.03 mag or larger. For stars near $V = 15$ and fainter, the true uncertainty (especially in the V magnitude) is undoubtedly larger than this formal error. Specifically, we are not convinced that we have actually observed variability in the stars Hα 5 and Hα 10.

d) Spectroscopy

Spectroscopic observations of suspected members of the R CrA T association which are brighter than about $B = 15$ were obtained during 1976 with the Cassegrain image-tube spectrograph on the Cerro Tololo 1.0-m telescope. These spectra were taken on baked IIIa-J plates at a dispersion of either 42 or 121 Å/mm in the blue spectral region. The stars with spectroscopic observations are listed in Table IV, along with a dispersion code and a description of the spectrum.

Following are additional remarks for several stars.

DG CrA. Herbig and Rao (1972) note that some previous spectroscopic observations have failed to show any line emission. Our 1976 spectrogram shows a definite T Tauri spectrum, so this is apparently a good example of a young star with significant variations in emission-line strength.

VV CrA. Herbig and Rao (1972) assign an emission-line class of 2 to this star. Our 1976 spectrogram shows a more advanced T Tauri spectrum, including prominent Fe II emission lines. The apparent spectral energy distribution based on our *UBVri* photometry and the *JHKL* photometry of Glass and Penston (1975) and Vrba, Strom, and Strom (1976a) rises rapidly toward

TABLE IV. Spectroscopic observations.

Star	Code[a]	Description of spectrum
HD 176386	a	sp type ≈ A0; no line emission
TY CrA	a	sp type ≈ B8; no line emission
R CrA	a	A-type absorption spectrum with superimposed H I and metallic em lines
S CrA	a	extreme T Tauri spectrum; see Rydgren (1977) for description
VV CrA	b	extreme T Tauri spectrum; no photospheric abs features visible; numerous metallic em lines
DG CrA	b	T Tauri spectrum; mod Ca II and H I em lines over late-type photosphere
Anon 1	a	sp ≈ K2; Ca II em cores on otherwise normal absorption-line spectrum
Anon 2	b	no em lines; late-type photosphere but too weak in blue to classify
Hα 6	b	T Tauri spectrum; mod Ca II and H I em lines; v wk He I em lines; broad Ca I λ4227 abs and TiO bands indicate early M sp type
Hα 10	b	no line em; K sp type; continuum break at G band suggests giant rather than dwarf
Hα 14	b	Ca II em cores but no other line em; broad Ca I 4227 abs and TiO bands indicate early M sp type

[a] Instrument code: a = 42 Å/mm; b = 121 Å/mm.

longer wavelengths and indicates substantial interstellar or circumstellar reddening.

Anon 1. Although this star shows Ca II H and K emission cores, slit spectrograms in the red spectral region taken by A.E.R. with the Steward Observatory 2.3-m telescope in June 1973 and the Cerro Tololo 4-m telescope in June 1977 show no evidence of Hα emission. Additional photoelectric *UBV* photometry of this star by H.G.M. indicates mild variability, with an amplitude of about 0.2 mag in the *V* filter and no significant color changes.

Hα 14. This is the star denoted KS 9 by Glass and Penston (1975) and KS 15 by Vrba, Strom, and Strom (1976a). A slit spectrogram taken with the Steward Observatory 2.3-m telescope during June 1973 confirms the Hα emission and early M spectral type.

III. THE DISTANCE TO THE DARK CLOUD

The distance of 150 pc which is usually quoted for the R CrA dark cloud comes from the star counts of Gaposchkin and Greenstein (1936). In this section we estimate the distance to the dark cloud directly from *uvby, β* photometry of several associated early-type stars. The early-type stars HD 176386 and TY CrA are involved in intense reflection nebulosity and are certainly embedded in the cloud. Direct photographs of the R CrA field (e.g., Marraco 1978) also reveal faint nebulosity connecting the bright pair of B-type stars HR 7169 and HR 7170 with the dark cloud. Moreover, Loren (1979) finds clear evidence for heating of the dark cloud material by these two stars. Thus there is good reason to believe that these two stars are at the distance of the R CrA dark cloud. While HD 176386 and TY CrA are very likely recently formed stars, HR 7169 and HR 7170 could be field stars passing close to the dark cloud.

The bright stars HR 7169 and HR 7170 have previously been observed on the *uvby, β* system by Gronbech and Olsen (1976, 1977) and by Eggen (1977). Our results for these two stars are in very satisfactory agreement with the published values and we have averaged the available photometry, giving equal weight to each reported observation. Since the four stars have spectral types between B8 and A0, we have derived the interstellar reddening $E(B-V)$ for each star by the method of Crawford, Glaspey, and Perry (1970). The resulting values of $E(B-V)$ for HR 7169, HR 7170, HD 176386, and TY CrA are 0.05, 0.09, 0.17, and 0.67, respectively; the latter two values are in excellent agreement with those found previously by Marraco (1978) from *UBV* photometry.

Absolute visual magnitudes for the four stars have been obtained from the observed *β* indices using the recent calibration of Crawford (1978). The linear polarization measurements by Marraco (1978) clearly imply that all four stars have anomalous interstellar extinction, despite the generally small reddening values. Using the mean R value of 4.5 determined by Vrba, Coyne, and Tapia (1980) from extensive polarimetry of stars seen through the R CrA dark cloud, we find the distance moduli of the four stars to be 5.66, 5.42, 5.58, and 5.96, respectively. Since the distance modulus for TY CrA includes a large extinction correction and the *β* index could possibly be affected by a shell absorption feature (Herbig and Rao 1972), we have averaged the results for the three lightly reddened stars to obtain a mean distance modulus of 5.55. This corresponds to a distance of 129 pc and is well within the Gaposchkin and Greenstein (1936) estimate of 150 ± 50 pc. The distance modulus for TY CrA can be brought into agreement with the mean value found above by assuming $R = 5.1$, which is within the range of R values for this cloud implied by the polarimetry of Vrba, Coyne, and Tapia (1980). If we assume $R = 3.1$ for the three lightly reddened stars, we find a mean distance modulus of 5.70 and a distance of 138 pc.

IV. MEMBERSHIP IN THE T ASSOCIATION

The established members of the R CrA T association as noted in the catalog of Herbig and Rao (1972) are the embedded early-type stars HD 176386 and TY CrA, the emission-line variables R CrA and T CrA, and the T Tauri stars S CrA, VV CrA, and DG CrA. In addition, our spectra show that Hα 6 is a T Tauri star. Our detection of Ca II H and K emission cores in Anon 1 and Hα 14 indicates that they are pre-main-sequence stars with extremely weak emission. Our spectra of Anon 2 and Hα 10 show no line emission and thus provide no direct evidence that they are recently formed stars. Other than the double star Hα 7, the remaining objects on the Knacke *et al.* (1973) list of Hα-emission stars were too

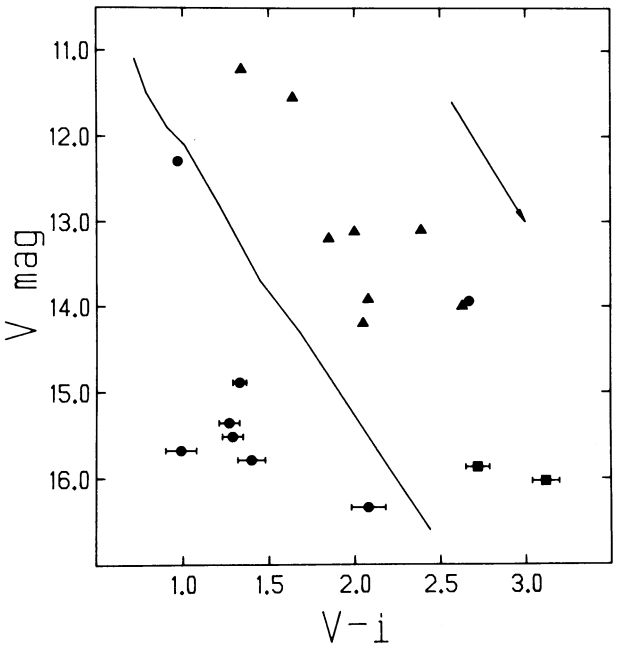

FIG. 2. Plot of mean V magnitude against mean $V - i$ color for suspected members of the R CrA T association. Triangles are confirmed young stars, while squares are other stars in which we find Hα emission, and circles are stars in which we do not see Hα emission. The main sequence at the adopted distance is sketched and the direction of interstellar reddening is indicated by an arrow.

faint for blue-region spectroscopy with the 1.0-m telescope. Our own list of additional Hα-emission stars was not compiled at the time of our spectroscopic observations, and most of these stars are also very faint in the blue spectral region.

To further explore the membership of the R CrA T association, we plot in Fig. 2 the V magnitude against $V - i$ color for the stars for which we have broadband photometry. The $V - i$ color should be less affected by line emission or spectral veiling than $B - V$ and is more accurately measured for our stars than $B - V$. Clearly established young stars are shown as triangles, additional stars in which we find Hα emission are shown as squares, and stars for which we find no Hα emission are shown as circles. The main sequence at our adopted distance modulus of 5.5 is also sketched. We see in Fig. 2 that the established young stars form the expected band from one to three magnitudes above the main sequence. In addition, the positions of Anon 2, Hα 2, and Hα 3 in the diagram are consistent with a pre-main-sequence nature. However, seven of the ten Hα-emission stars from Knacke *et al.* (1973) fall below or to the left of the main sequence.

While it is not uncommon for M-type T Tauri stars to appear to the left of the main sequence in a plot of V vs $B - V$, this is not expected when the $V - i$ color is used. The uncertainties in our photometry are larger than desirable but cannot account for the observed effect. Moreover, our distance modulus for the R CrA dark cloud seems well determined and the reddening vector is nearly parallel to the main sequence. Thus the stars found below or to the left of the main sequence in Fig. 2 could be either young stars in an unexpected evolutionary phase or background stars seen through the dark cloud. We believe that the latter explanation is more likely. Our spectrum of one of these stars (Hα 10) shows no evidence that it is a recently formed star. In addition, one of us (A.E.R.) has examined two of the red objective-prism plates used in the Knacke *et al.* search for Hα-emission stars (CTIO Schmidt plate Nos. 3754 and 3884). On these two plates Hα emission was seen in Hα 2, Hα 3, and Hα 6, but not in any of the seven stars which fall below or to the left of the main sequence in Fig. 2. While additional observations of these stars would be desirable, we believe that the existing observations do not favor the view that these are pre-main-sequence stars.

Our observations support the conclusion of Vrba, Strom, and Strom (1976a) that the number of young stars in this region is surprisingly small for a star-forming cloud of this mass. In addition to the higher-mass stars HD 176386, TY CrA, R CrA, and T CrA, there are only four spectroscopically confirmed T Tauri stars in the region (S CrA, VV CrA, DG CrA, and Hα 6) and two other confirmed late-type young stars (Anon 1 and Hα 14). Additional suspected members of the T association (on the basis of Hα emission and/or position in Fig. 2) are Anon 2, Hα 2, Hα 3, Hα 11–Hα 13, and Hα 15–Hα 17. Photometric and spectroscopic observations of these suspected members should be obtained to determine if

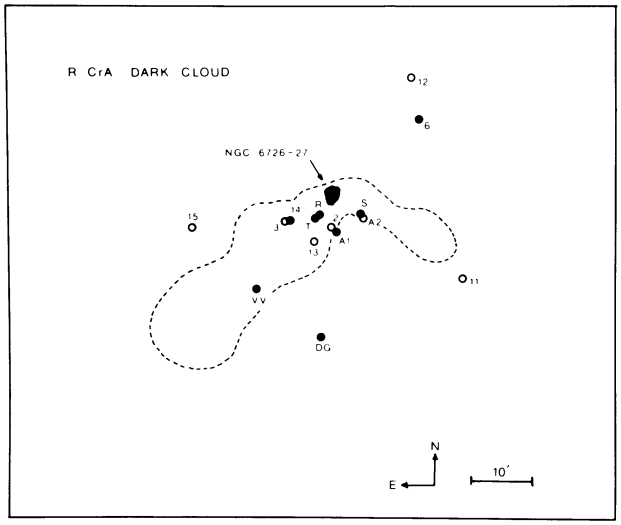

FIG. 3. Sketch of the main R CrA dark cloud. Spectroscopically confirmed young stars are shown as closed circles, while additional suspected members are indicated by open circles. The intense reflection nebulosity NGC 6726-6727 contains the stars HD 176386 and TY CrA. The dashed line shows the approximate extent of the opaque part of the dark cloud.

they actually are recently formed stars.

A sketch of the main R CrA dark cloud is shown in Fig. 3. Spectroscopically confirmed young stars are shown as closed circles, while additional suspected members are indicated by open circles. The likely association members are clearly concentrated near the bend in the dark cloud, which corresponds to the bottom of the "magnetic well" (Vrba 1977). All of the plotted points are within 25 arcmin of this point; this is equivalent to a separation of about one parsec at our adopted distance. It should be noted that the stars Hα 16 and Hα 17 are located farther east, near a smaller dark nebula denoted "cloud B" by Rossano (1978).

The observations reported above were obtained while H.G.M. was a Visiting Astronomer and A.E.R. was a Research Associate at the Cerro Tololo Inter-American Observatory, which is operated by AURA, Inc., under contract with the National Science Foundation. We thank Steve Strom for the opportunity to examine his red objective-prism plates of this region and the referee for a helpful suggestion.

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