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INFRARED PHOTOMETRY IN THE R CrA ASSOCIATION

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SUMMARY

JHKL photometry of 44 stars in the area of the R CrA association is reported. No previously undiscovered cases of dust emission were found but several highly reddened stars are identified. These show the dark cloud to have a visual absorption of ~ 8 mag. The ratio E_{J-H}/E_{H-K} is suspected to be higher in the cloud than predicted by traditional reddening laws. Detailed comments on several stars in the region are given.

1. INTRODUCTION

The R CrA association is a nearby (~ 150 pc) region of star formation. Superposed on a dark cloud are found a group of young variable stars with associated nebulosities. Recent infrared studies by Knacke *et al.* (1973—*q.v.* for a brief review of knowledge about the association) and Strom *et al.* (1974a) have confirmed that the variable stars in this region possess strong infrared excesses and found a new infrared source not associated with any visible star. There are only a few certain members of this association and attempts to find more have been based on searches for variables (Knox-Shaw 1920; Hardy & Mendoza 1968) and an Hα emission survey (Knacke *et al.* 1973). In this paper we report on a *JHKL* photometric survey of stars in and around the dark cloud with the joint aim of finding new members of the association and of exploring the link between variability and infrared excess discovered in the Orion Nebula cluster (Penston 1973; Penston, Hunter & O'Neill 1975) but not found among the field RW Aurigae stars (Glass & Penston 1974).

2. OBSERVATIONS

Most of the *JHKL* photometry was performed at the 74-in. telescope of the Radcliffe Observatory, Pretoria, using the photometer described by Glass (1973). The data were reduced to the system defined by the southern standards of Glass (1974). The stars to be observed were picked to lie in or near the dark nebulosity and were bright enough to be easily found in the 74-in. telescope (i.e. $m_V \lesssim 16$). They are identified on Plate I. Observations of the four stars R, S, T and TY CrA were reported earlier (Glass & Penston 1974): they are repeated here for completeness.

The resulting magnitudes and colours are listed in Table I, together with the Allen type, spectral type and comments including other designations for each star. Errors are given where they exceed 0·05 mag. The Allen type is defined by Allen (1973) and refers to the nature of the infrared emission as deduced from the *JHKL* colours. X denotes ordinary hot star colours and R these after the effects

TABLE I

Photometry in the R CrA association

Name	Date	*K*	*J–H*	*H–K*	*K–L*	Allen type	Comments
R CrA	1972 June 27	3·43	2·15	1·64	1·65	D	CoD −37° 13027, Sp type A5pe
S CrA	1972 June 27	6·23	1·25	0·91	1·10	D	Sp type Cont+e
T CrA	1972 June 27	6·34	1·38	1·18	1·33	D	Sp type Foe
TY CrA	1972 June 27	6·57	0·53	0·26	0·47	F	CoD −37° 13024, KS 70, Sp type B9e
VV CrA	1973 Sept. 1	5·87	1·71	1·51	1·86	D	Hα em^{n} (Knacke *et al.* 1973)
DG CrA	1973 Sept. 1	8·61	1·30±0·15	1·26±0·14	1·1±0·3	D	
a	1973 Aug. 29	6·77	>2·4	3·12	2·20	R	See Strom *et al.* (1974a)
b	1973 Aug. 30	10·3±0·3		>0·9			
c	1973 Aug. 30	9·07	0·38	0·03			CoD −37° 13013
d	1973 Aug. 30	7·50	1·55±0·16	0·73	0·21±0·16	R	
e	1973 Aug. 30	10·9±0·2		>0·1			
f	1973 Aug. 30	10·01±0·11	1·1±0·4	−0·1±0·2			
g	1973 Aug. 30	8·55	0·70	0·18	<1·0		
h	1973 Aug. 30	>9·7	>0·9	<0·3			
i	1973 Aug. 30	8·30±0·10	1·55±0·16	0·69±0·14	<1·4	R	Hα em^{n} (Knacke *et al.* 1973)
j	1973 Aug. 30	6·22	1·07	0·32	0·15±0·15	R	KS 22
k	1973 Aug. 31	6·23	0·02	−0·01	−0·07±0·15	X	HR 7170, CoD −37° 13018 HD 176270, Sp type B8
l	1973 Aug. 31	6·66	−0·01	−0·03	−0·16±0·18	X	HR 7169, CoD −37° 13017 HD 17269, Sp type B8
m	1973 Aug. 31	11·0±0·3		>0·1			KS 18

n	1973 Aug. 31	9·8±0·2	1·04±0·15	0·0±0·2			KS 19
o	1973 Aug. 31	10·8±0·3	0·7±0·4	−0·2±0·4			KS 17
p	1973 Aug. 31	6·58	0·06	0·04	0·10	X	CoD −37° 13023, HD 176386, Sp type Ao
q	1973 Aug. 31	8·05	1·37	0·44	0·3±0·3	R	
r	1973 Aug. 31	8·13	1·17	0·37	0·7±0·2	D/F	
s	1973 Aug. 31	>10·5					Hα em^{n} (Knacke *et al.* 1973)
t	1973 Aug. 31	9·8±0·3	>0·6	0·8±0·3			
u	1973 Aug. 31	7·34	1·03±0·14	0·35	−0·1±0·3	R?	KS 2
v	1973 Aug. 31	9·32±0·11	1·03±0·19	0·16±0·17			
w	1973 Aug. 31	9·03	0·59±0·14	0·29±0·14			KS 14
x	1973 Sept. 1	8·51	0·31	0·29	<0·8	D?	CoD −37° 13028
y	1973 Sept. 1	6·78	1·01	0·31	0·3±0·2		
z	1973 Sept. 1	8·26	1·58	0·51	(−1·8±0·2)	R	Hα em^{n} (Knacke *et al.* 1973)
a2	1973 Sept. 1	8·25	0·40	0·06	<0·2		KS 20, CoD −37° 13029
b2	1973 Sept. 1	9·07±0·14	0·5±0·2	0·4±0·3			KS 21
c2	1973 Sept. 1	9·16	0·89±0·15	0·32			KS 23
d2	1973 Sept. 1	7·97	1·12	0·46	0·4±0·3	R?	KS 68
e2	1973 Sept. 1	9·7±0·2	0·5±0·4	0·5±0·3			
f2	1973 Sept. 1	8·33	0·82±0·14	0·36	<0·3		
g2	1973 Sept. 3	9·4±0·2	>0·9	0·4±0·3			
h2	1973 Sept. 3	6·85	1·00	0·35	−0·2±0·2	R?	
i2	1973 Aug. 30	7·63	0·65	0·25	−0·3±0·3	R?	Anon 1 of Knacke *et al.* 1973), KS16, CoD −37° 13022
j2	1973 Aug. 30	7·06	1·31	0·51	0·28±0·16	R	Anon 2 of Knacke *et al.* (1973)
k2	1973 Aug. 31	7·82	1·03	0·32	0·69±0·16	D/F	KS 15
l2	1973 Sept. 3	>10·8					KS 9

of appreciable reddening, while D and F are applied where the colours show the infrared emission to arise from dust reradiation or hot free–free emission respectively. Other stellar designations given in the Comments column of Table I are from the *Bright star catalogue* (HR), the *Cordoba Durchmusterung* (CoD), the *Henry Draper catalogue* (HD), Knox-Shaw (1920—KS) and from Knacke *et al.* (1973).

Infrared searches to a limiting magnitude $K \sim 8$ were made of three areas each 2 arcmin square centred on HD 176386, R CrA and Anon 1 of Knacke *et al.* (1973). In this way we independently discovered the source reported by Strom *et al.* (1974a)—here denoted as star *a*. We find this source to lie 42 ± 6 arcsec west and 66 ± 6 arcsec south of R CrA itself.

3. DISCUSSION

Two-colour *J–H/H–K* and *H–K/K–L* diagrams for the stars observed are presented in Figs 1 and 2 respectively. The positions of the points in these diagrams can be used to determine the nature of the infrared emission from the corresponding stars. The use of the *H–K/K–L* diagram was discussed by Allen (1973): some similar conclusions can be drawn from the *J–H/H–K* diagram. In this way the Allen types of Table I were assigned.

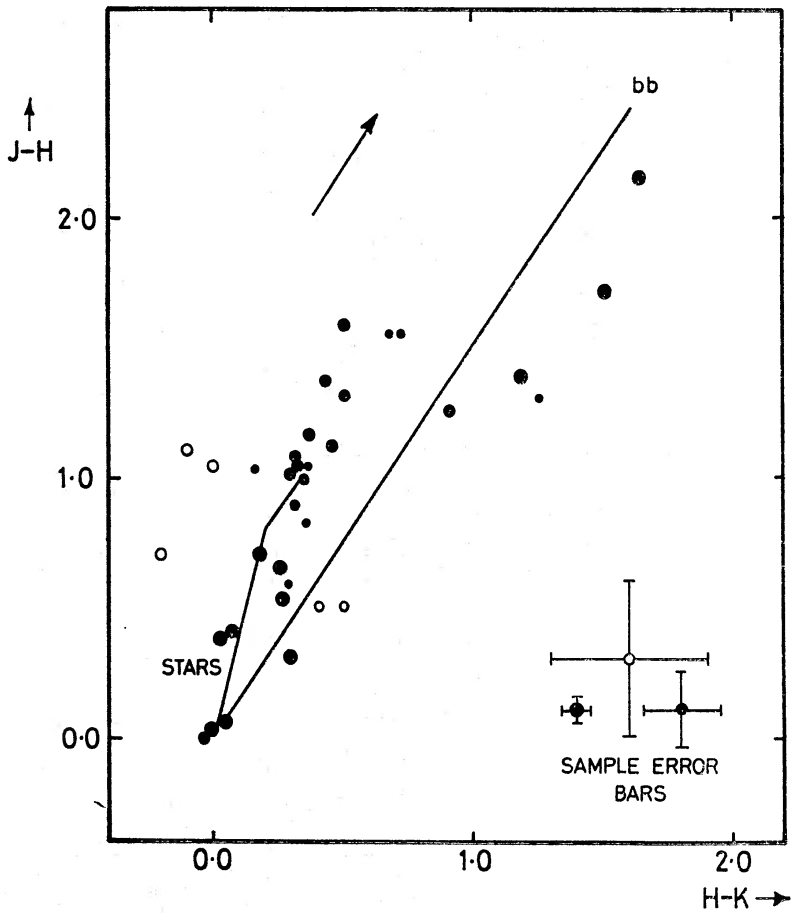

FIG. 1. *The two-colour J–H/H–K diagram of the R CrA association. Large and small filled circles denote JHK photometry more accurate than 0·05 and 0·15 mag respectively, open circles less accurate results. The lines represent the loci of normal stars and blackbodies. The arrow points in the direction of the reddening vector.*

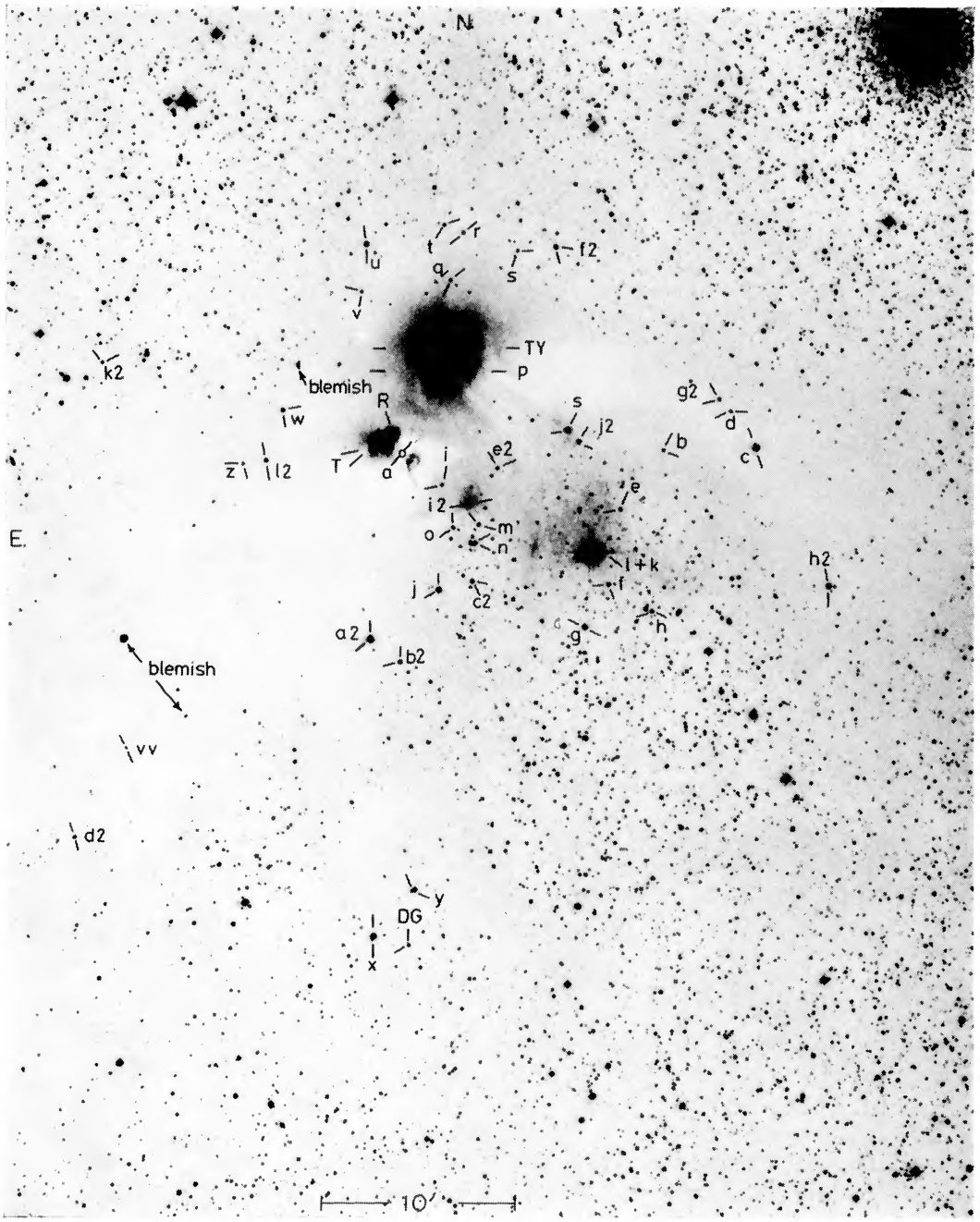

PLATE I. *Finding chart of the R CrA association reproduced from the Whiteoak Extension of the Palomar Observatory Sky Survey (i.e. a red plate). Stars observed in this work are identified—capital letters denote known variable stars (i.e. R denotes R CrA), small letters stars named here (for other designations see Table I).*

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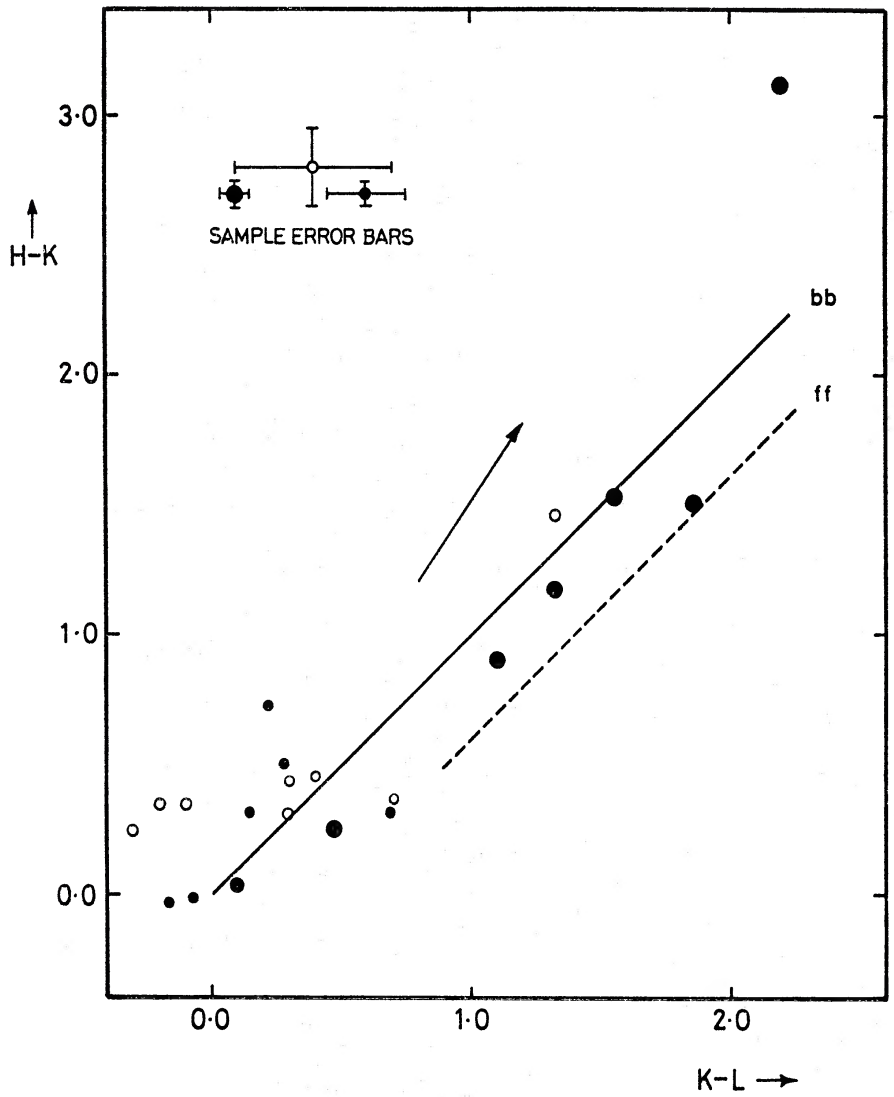

FIG. 2. *The two-colour H–K/K–L diagram of the R CrA association. Large and small filled circles represent HK photometry more accurate than* 0·05 *mag and L photometry more accurate than* 0·05 *and* 0·15 *mag respectively, open circles are less accurate results. The solid and dashed lines represent the blackbody and free–free lines respectively. The arrow points in the direction of the reddening vector.*

Fig. 1 clearly shows that only a few stars in the sample studied have infrared excesses caused by dust emission. The only stars with strong dust excesses are the variables R CrA, S CrA, T CrA, VV CrA and DG CrA—all these excesses were earlier reported by Knacke *et al.* (1973).

Several other stars are quite red however, particularly in $J–H$—these are probably reddened heavily by material in the dark cloud. Stars in this category include *d*, *i*, *j*, *g*, *z* and *j2* all of which lie within the confines of the cloud. The $J–H$ values of these stars range as high as 1·6 mag, compared with the range of 0·0 to 1·0 mag for normal stars. Thus the stars lie in or behind the dark cloud and limits to the extinction therein of $0{\cdot}6 < E_{J-H} < 1{\cdot}6$ can be set. This E_{J-H} corresponds to a visual absorption A_V between 6 and 16 mag. However, the absorption cannot be as high as the latter number since the $V-K$ of these stars cannot easily exceed 8–10 mag: the visual light of the 74-in. is $\sim$16 and the 2·2-μ mag of these stars

fall in the range 6–8. Thus we deduce (since $A_V \lesssim V-K$) that the visual absorption in the cloud is about 8 ± 2 mag. This compares with an estimate of 3 mag by Gaposchkin & Greenstein (1936). It is a remarkable fact that the visual absorption in front of the globular cluster NGC 6723 which lies only 20 arcmin from the dark cloud is less than 0·1 mag (e.g. van den Bergh 1967). Setting a limit of $A_V < 10$ implies $E_{J-H} < 1{\cdot}0$ and shows that the reddened stars referred to are K stars or later: they are probably background giants.

There is some evidence from the locations of the points representing reddened stars in Fig. 1 that the reddening vector is steeper than that shown. Probably $E_{J-H}/E_{H-K} \sim 2{\cdot}7$ compared to the value from the van de Hulst (1949) No. 15 law of 1·7. Spectral types and optical colours of these stars would be interesting to obtain.

The positions of the variable stars in Fig. 2 near the blackbody line and above the free–free line give no support to cool free–free as the source of the infrared emission (Dyck & Milkey 1973).

The fact that the only stars found to have strong dust emission are the variables is interesting in connection with the correlation between excess and variability found in the Orion Nebula cluster (Penston 1973; Penston *et al.* 1974). The *H–K* colour and, Δm_{pg}, the range of variation listed in the *General catalogue of variable stars* (Kukarkin *et al.* 1969) are given in Table II. There is no convincing correlation between *H–K* and Δm_{pg} among the R CrA association stars alone unless TY CrA is excluded on the grounds it does not have a dust excess. However, when this is done the other stars fit on to the Orion cluster correlation well. It is interesting too to note that the star *k2* = KS 15 which shows a weak dust excess was found to be variable by Knox-Shaw (1920). This suggests that the other stars which may also have dust excesses (*r* and *n*) should be checked for variability.

The early-type variable, TY CrA, does not have a large dust excess. This is in line with the lack of such excesses in stars earlier than Ao in the Orion Nebula cluster (Penston 1973) and NGC 2264 (Strom *et al.* 1972). It does, however, have significantly non-zero colours in the near-infrared. The *JHKL* photometry and the visual magnitude $V = 9{\cdot}43$ (Knacke *et al.* 1973) can be reconciled if TY CrA has a small hot free–free component and is reddened by $A_V \sim 1{\cdot}5$ to 2 mag as deduced on other grounds by Knacke *et al.*

Knacke *et al.* also identified several stars with Hα emission in the neighbourhood of the association. Data presented here covers four of these stars. VV CrA, which is one of these stars, shows an outstanding dust excess but of the other three, two (stars *i* and *z*) are highly reddened and the other (star *s*) was not detected at *K*. Surprisingly, Hα emission has not in this case proved to go hand-in-glove with 2-μ excess.

TABLE II

Infrared excess and range of variation

Star	*H–K*	Δm_{pg}
R CrA	1·64	3·6
S CrA	0·91	2·5
T CrA	1·18	2·1
TY CrA	0·26	3·7
VV CrA	1·51	>4·0
DG CrA	1·26 ± 0·14	2·8

Recently Strom *et al.* (1974a, b) have discussed two Herbig–Haro (H–H) nebulae in the region of R CrA. They find that both the nebulae, H–H 100, southwest of the infrared source star *a*, and H–H 101, east of star *n*, show H–H spectral characteristics. Strom *et al.* suggest that star *a* and H–H 100 are related; moreover they further report detecting 2 μ emission in a 35 arcsec beam centred on H–H 101. Their *K* magnitude for H–H 101, however, agrees with our result for star *n* which would have fallen in their beam and was therefore probably responsible for the signal they observed. Since star *n* has only a small *H–K* it is unlike other stars associated with H–H objects. Any infrared source connected with H–H 101 has yet to be detected.

The photometry presented here and that of Strom *et al.* (1974a) for star *a* agree within their expected errors. The *HKL* colours with $H-K > K-L$ indicate the existence of heavy reddening (Allen 1973). Whether star *a* is a normal star reddened by $A_V \sim 50$ mag or resembles R CrA after 15 mag of visual absorption as proposed by Strom *et al.* cannot be determined until the reddening law in the 1–10 μ region is well established. These two hypotheses are related to the two possible interpretations of Becklin's star discussed by Allen & Penston (1974).

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