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FAR-INFRARED OBSERVATIONS OF A STAR-FORMING REGION IN THE CORONA AUSTRALIS DARK CLOUD

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ABSTRACT

We have surveyed with high resolution at far-infrared (far-IR) wavelengths (40–250 μm) a 0.9 deg^2 section of the core region of the Corona Australis dark cloud that contains very young stellar objects such as T Tauri stars, Herbig Ae and Be stars, Herbig-Haro objects, and compact H II regions. Two extended far-IR sources were found, one associated with the Herbig emission-line star R CrA and the other with the irregular emission line variable star TY CrA. The two sources have substantially more far-IR radiation than could be expected from a blackbody extrapolation of their near-infrared fluxes. The total luminosities of these sources are 145 $L_\odot$ and 58 $L_\odot$, respectively, implying that the embedded objects are of intermediate or low mass. The infrared observations of the sources associated with R CrA and TY CrA are consistent with models of the evolution of protostellar envelopes of intermediate mass. However, the TY CrA source appears to have passed the evolutionary stage of expelling most of the hot dust near the central source, yielding an age of about 1×10^6 years.

Subject headings: infrared: spectra — nebulae: reflection — stars: formation — stars: individual — stars: pre–main-sequence

I. INTRODUCTION

The dark cloud region in Corona Australis (CrA) contains two bright and prominent reflection nebulae, NGC 6729 and NGC 6726/7, embedded in an extended and highly obscured cloud of interstellar gas and dust. At the apex of the cometry reflection nebula NGC 6729 is the emission-line variable star R CrA, while the F0e star T CrA lies at the southeastern edge of the nebulosity (Herbig 1960). The irregular variable TY CrA illuminates the reflection nebula NGC 6726. The area surrounding R CrA contains several irregular variable stars and a large number of Hα emission objects, which appear to be young objects associated with the dark cloud. Extensive near-infrared observations of the region by Knacke *et al.* (1973), Glass and Penston (1975) and Vrba, Strom, and Strom (1976) have detected numerous infrared sources which have been identified with the young stellar association around R CrA. Most of these sources are T Tauri–like objects with large infrared excesses, suggesting the presence of circumstellar envelopes. The infrared observations have shown that the age of the group is probably less than 10^6 years (Knacke *et al.* 1973), presumably in the radiative phase of their pre–main-sequence evolution. The region in the vicinity of R CrA is thus very similar in evolutionary stage to the dark cloud regions in Taurus and Ophiuchus, which also show evidence of recent star formation (Elias 1978; Grasdalen, Strom, and Strom 1973; Vrba, Strom, and Strom 1975). The region surrounding R CrA is also where the optical extinction reaches its maximum value ($A_v > 3.5$ mag), as revealed by the star counts of Rossano (1978). Among the results of the extensive molecular line survey of this cloud by Loren (1979) is the existence of a high-density core ($M \sim 250$–$520\ M_\odot$) located at the position of R CrA. The cloud appears to be undergoing a nonhomologous collapse, along magnetic field lines, with little associated rotation.

Because the CrA dark cloud is located well below the galactic plane ($l = 359°$, $b = -17°$) and relatively nearby, at a distance of 126 pc (Marraco and Rydgren 1981; Gaposchkin and Greenstein 1936), it is a good candidate for far-IR observations of a region of recent star formation. A similar situation exists for the dark cloud in Ophiuchus, where far-IR observations were important in detecting the embedded heating sources in the cloud and in determining the detailed temperature and density distribution of the dust (Fazio *et al.* 1976; Harvey, Campbell, and Hoffman 1976).

II. THE 40–250 MICRON OBSERVATIONS

The far-IR observations were made on 1975 June 16 with the Center for Astrophysics/University of Arizona 102 cm balloon-borne telescope. Fazio (1977) gives a detailed description of the telescope, detectors, and observing procedure. The observations were made by moving the telescope in an automatic raster pattern, scanning in cross-elevation and stepping in elevation. Each of the three identical far-IR bolometers subtended half-power angles of 0.′9 in cross-elevation and 1.′3 in elevation. The beam centers were separated by 1.′5 in elevation. The reference beam was 5.′3 in cross elevation from the primary beam. The bandpass of the filter and optics was from 40 to 250 μm. The source positions were determined with respect to SAO stars using a star field camera; these positions have an uncertainty of $\sim 30''$ in elevation and azimuth. The flux calibration was made using Mars as a reference and the emission model of Wright (1976).

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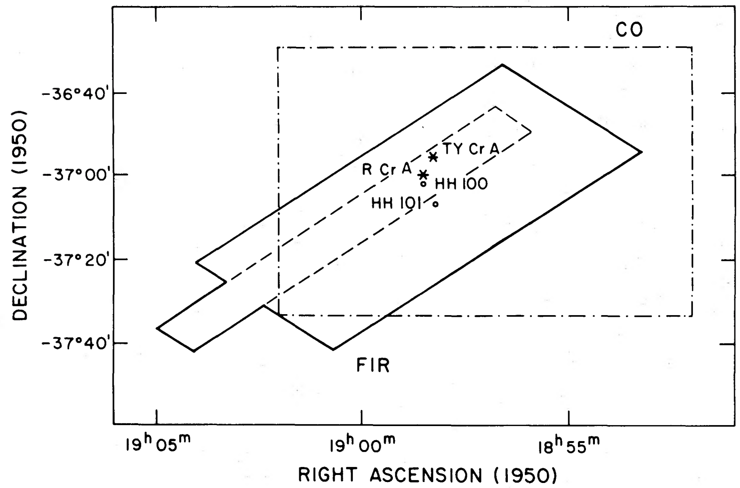

FIG. 1.—The region of sky covered by the far-IR raster scans. The area inside the dashed line, containing TY CrA and R CrA, was scanned at least four times. The area between the dashed and solid lines was scanned only once or twice. The dashed-dotted line shows the boundaries of the region scanned in the CO molecular line survey (Loren 1979). The locations of both HH objects are also shown in this figure.

III. THE RESULTS AND INTERPRETATION

a) *The Data*

The solid line in Figure 1 delineates the boundaries of the region scanned in the far-IR. The area inside the dashed line in Figure 1 was scanned at least four times with the remaining area scanned only once or twice. The total area scanned was 0.9 deg^2. The dash-dotted line shows the boundaries of the region observed in the CO molecular line survey of Loren (1979). The overlap between the far-IR observations, the radio molecular line survey (Loren 1979), and the near-infrared surveys (Glass and Penston 1975; Vrba, Strom, and Strom 1976) is quite good. The distribution of far-IR radiation observed is shown in Figure 2. Figure 3 shows the far-IR map superposed on an optical photograph of the region.

Table 1 lists the coordinates of the two far-IR sources detected, their peak and integrated flux densities, and their Gaussian deconvolved half-power sizes along the scan direction as shown in Figure 2. Assuming a 37 K blackbody spectrum for the sources, the effective wavelength for the observations was 91 μm. The color temperature of 37 ± 2 K was adopted from the far-IR observations of de Muizon *et al.*

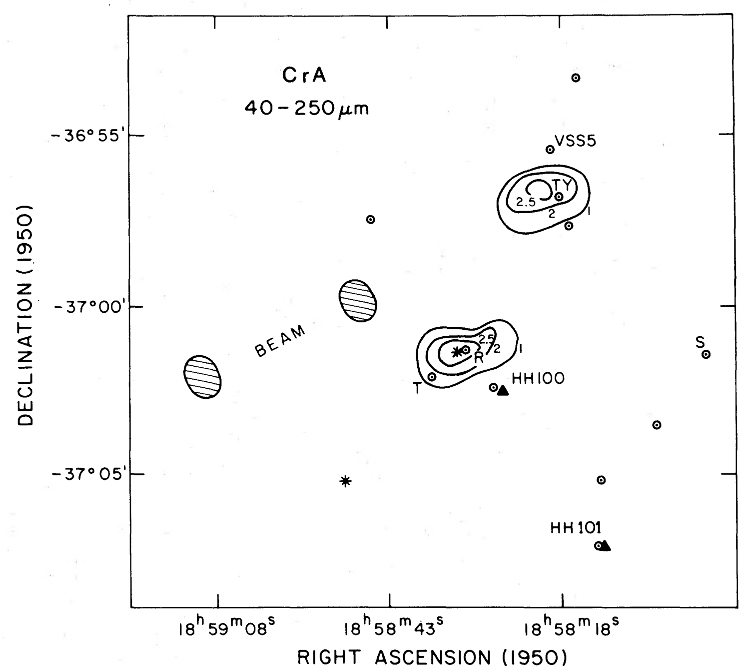

FIG. 2.—The 40–250 μm map of the core region of CrA. The contour unit is 400 Jy per beam. The location of other sources shown include: *circles*, the near-infrared sources (Knacke *et al.* 1973; Glass and Penston 1975; Vrba, Strom, and Strom 1976); *triangles*, HH objects (Strom, Strom, and Grasdalen 1974; Strom, Grasdalen, and Strom 1974); and *stars*, the compact H II regions (Brown and Zuckerman 1975).

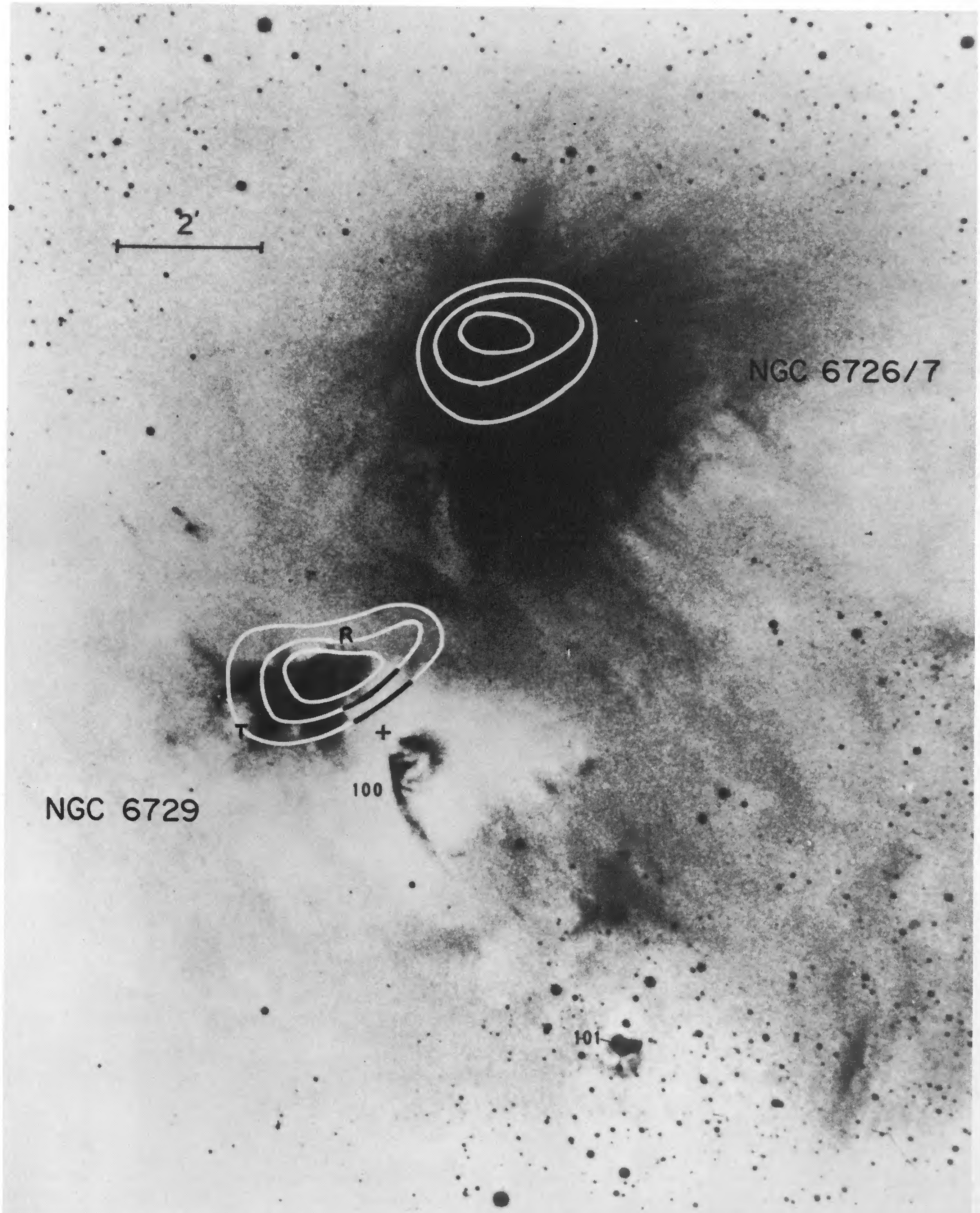

FIG. 3.—Overlay of the far-IR map on an optical photograph of the core region of the cloud

TABLE 1

FAR-INFRARED SOURCES IN THE CORONA AUSTRALIS DARK CLOUD

Source	Position α(1950)	Position δ(1950)	Peak Flux Density (Jy)	Integrated Flux Density (Jy)	Source Size (FWHM)	Luminosity ($L_\odot$)
I	$18^h58^m22^s$	−36°56′27″	1.2×10^3	2.4×10^3	0.′8	58
II	$18^h58^m34^s$	−37°01′22″	1.4×10^3	3.6×10^3	1.′4	148

(1980), who used a 4.′5 beam that did not resolve the two sources. The bolometric luminosities listed in Table 1 were obtained by integrating the spectral distributions given in Figure 4, and using a source distance of 126 pc. The combined luminosity of both far-IR sources is in good agreement with the luminosity of the single source given by de Muizon *et al.* (1980).

The far-IR contour map (Fig. 2) shows that the only near-infrared (1–20 μm) sources within the contours of source II are T CrA and R CrA, while TY CrA is the only near-infrared source associated with source I. The spectral types of these stars have been determined optically but not always with consistent results. R CrA has been classified as A5pe (Mendoza, Jaschek, and Jaschek 1969) and Ae (Marraco and Rydgren 1981) and TY CrA as a B9e (Herbig and Rao 1972) and B8 by Marraco and Rydgren (1981). The radiation from source II could be due to both R CrA and T CrA, but the peak of the far-IR emission coincides with R CrA, and since T CrA is an F0e star, it should not contribute significantly to the far-IR flux. The luminosities derived from the infrared observations lie in the region of Ae and Be stars on the H-R diagram (Cassinelli 1979) in agreement with the optical classification of R CrA and TY CrA.

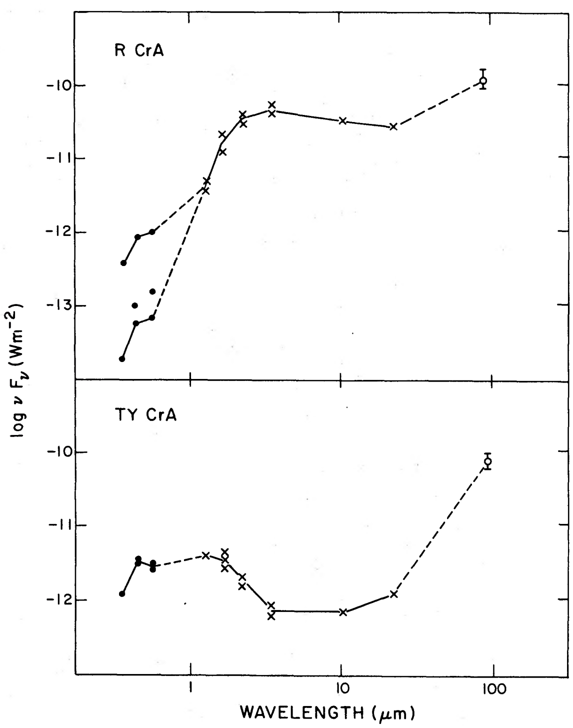

FIG. 4.—The energy distributions are shown for R CrA and TY CrA. The ordinate is νF_ν, and a horizontal line implies equal energy per octave of frequency or wavelength. The data points shown include *squares* (Herbig and Rao 1972; Marraco and Rydgren 1981), X's (Knacke *et al.* 1973, Glass and Penston 1975, Vrba, Strom, and Strom 1976) and *circles* (this paper). For the near-IR data no beam sizes are quoted except for the data of Vrba *et al.*, who used a 36″ aperture.

It is interesting to note in Figure 3 that the contours of the far-IR emission follow reasonably the overall shape and size of the reflection nebulae NGC 6729 and NGC 6726/7, indicating that the dust emission in the far-IR is probably the same dust observed in the optical region. A similar result was found for the reflection nebula NGC 7023 by Whitcomb *et al.* (1981). It should be noted that not only R CrA but also the nebula NGC 6729 is variable at optical wavelengths (Knox-Shaw 1920; Joy 1945).

b) The Herbig-Haro Objects

Two HH objects, each with a nearby near-infrared source, lie in the region scanned in Figure 1. The near-infrared spectrum of the star exciting HH 100 is similar to R CrA (Strom, Strom, and Grasdalen 1974) and is highly variable (Axon *et al.* 1982; Reipurth and Wamsteker 1983). Although this star is bright in the near-infrared, we did not detect it at far-IR wavelengths. Since HH 100 and its associated near-infrared source were scanned four times, our 3 σ upper limit of 400 Jy to the far-IR emission from a point source corresponds to a bolometric luminosity of 9 $L_\odot$, assuming a dust temperature (T_d) of 37 K. The upper limit to the far-IR emission from HH 101 and its associated near-infrared source is 600 Jy or 14 $L_\odot$ (assuming $T_d = 37$ K), since these sources lay in a less well mapped region (Fig. 1). These upper limits are comparable to those obtained by Fridlund *et al.* (1980) for HH objects in the L1551 molecular cloud. The detection of far-IR emission from HH objects in Orion by Harvey, Wilking, and Cohen (1982), at luminosity levels comparable to our upper limits, suggest that only small improvements in sensitivity will be required to detect HH 100 and HH 101.

c) The Compact H II *Regions*

The two ultra-compact H II regions detected in the region of the CrA cloud (Fig. 2) have no optical or near-infrared counterparts. One of the compact H II regions is located near R CrA and has a flux density of 15 ± 3 mJy at 2.7 GHz (Brown and Zuckerman 1975). Rodriguez (1982), using the VLA at 5 GHz, obtained an accurate position $\alpha(1950) = 18^h58^m32.^s8 \pm 0.^s1$ and $\delta(1950) = -37°01'41''$, with a flux density of 11 ± 1 mJy and a source size of 0.″7. These two measurements show that the radio spectrum is approximately flat, but further measurements at other frequencies are desirable to confirm this. The second compact H II region found by Brown and Zuckerman (1975) lies 5′ southeast of R CrA

(Fig. 2) with a flux density of 8 ± 3 mJy. No far-IR source lies in the direction of this compact H II region. Our 3 σ upper limit to the far-IR emission is the same as for HH 100, namely 400 Jy and 9 $L_{\odot}$.

Using the formulae of Mezger, Smith, and Churchwell (1974) for the number of ionizing photons, N_c', needed to produce the observed radio flux density, assuming an electron temperature $T_e = 10^4$ K, a distance of 126 pc, and a spherical geometry, we obtained $N_c' \sim 2.5 \times 10^{43}$ s^{-1}. If this value is compared with the calculations of Panagia (1973), then a B3 V star ($L \sim 2 \times 10^3$ $L_{\odot}$) can provide the ionization. The upper limit to the total luminosity inferred from the far-IR observations for both the above H II regions is much less. The apparent dilemma would not exist if the sources were nonthermal and extragalactic. Statistical arguments, however, do not favor an extragalactic origin. Similar radio sources have been found in other dark cloud regions: compact H II regions without near infrared counterparts in the Ophiuchus cloud (Brown and Zuckerman 1975), and compact and luminous H II regions requiring much higher luminosities than seen in the far-IR in the Serpens cloud (Nordh *et al.* 1983). Strong radio continuum emissions have been detected recently for some low luminosity stars (Bertout and Thum 1982; Felli *et al.* 1982; Cohen, Bieging, and Schwartz 1982) with flux densities comparable to the radio sources in CrA. The radio emission from these stars is interpreted as resulting from an expanding ionized circumstellar envelope caused by mass loss from the central star. The lack of 2 μm emission could be explained by large extinction toward the source with $A_V > 100$ (Brown and Zuckerman 1975). However, at far-infrared wavelengths the source could still be detected. The radio of total flux to radio flux defined as $R = (L_B/d^2)F_R$, where L_B is the bolometric luminosity in units of $L_{\odot}$, d is the distance in kpc, and F_R is the 5 GHz flux density in mJy, varies from about 5 to 1000 for these sources (Cohen, Bieging, and Schwartz 1982). If we assume the two compact H II regions in CrA are similar to the H II regions associated with LkHα 101, DG Tau, and T Tau, we can then calculate the expected far-infrared flux. Using the average value of $R = 300$ seen for these sources, and taking $0.2L_B$ as the fraction of the luminosity observed in the 40–250 μm band (Harvey, Thronson, and Gatley 1979), the predicted far-infrared flux is about 600 Jy. For the H II region near R CrA this flux is only 20% of that observed. For the other compact H II region southeast of R CrA, this flux is just above our upper limit for detection. Our far-infrared observations cannot rule out the interpretation that these compact H II regions are being produced by winds from low-luminosity stars.

d) The Molecular Line Emission

Several molecular line studies have been made of this cloud (Loren 1979; Nachman 1979; Loren, Peters, and Vanden Bout 1974; Sandqvist and Lindroos 1976; Millman *et al.* 1975). The maximum in the ^{12}CO emission occurs at TY CrA with a weaker peak at R CrA (Loren 1979). The maxima in the intensity distribution of the molecules H_2CO, CS, HCN, and HCO^+ are at the position of R CrA (Loren 1979), indicating the existence of a high density core (M $\sim$ 250–520 $M_{\odot}$). The distribution of these molecules also exhibits an elongation parallel to the main southeast-northwest axis of dust cloud. Two additional secondary peaks are present to the south and southwest of R CrA with unidentified heating sources. Our far-IR results do not show the presence of sources at the positions of the secondary maxima.

IV. DISCUSSION

One of the principal results of this survey is the identification of the Herbig emission line stars R CrA and TY CrA as the heating sources for the far-IR emitting dust in the CrA dark cloud. Other potential sources, like the HH objects and one of the compact H II regions, were not detected to the sensitivity limit of our survey. These results are consistent with far-IR surveys of other dark clouds, such as Serpens (Nordh *et al.* 1982), Ophiuchus (Fazio *et al.* 1976), and L1551 (Fridlund *et al.* 1980), which also revealed low-luminosity objects as the source of heating.

The energy distributions of both R CrA and TY CrA are shown in Figure 4. The remarkable feature of this data is the extremely broad energy distributions and strong far-IR emission. The broad energy distributions imply emission from dust over a wide range of temperatures and radii from the stars. The extensive nature of the dust shells, size 10^{17} cm, is emphasized by the resolution of both sources in our far-IR beam (Table 1). The far-IR study of eight emission-line variable stars by Harvey, Thronson, and Gatley (1979, hereafter HTG) also found extremely broad energy distributions with strong far-IR emission. HTG modeled the flat energy distributions using a slow radial dependence of dust density ($\sim r^{-1}$), high maximum temperatures for the inner regions of the shell ($T \geq 1000$ K), and cool minimum temperatures for the outermost edge of the cloud ($T \approx 20$ K). The most important result of HTG is that for sources where the energy distribution is flat the dust density follows a r^{-1} dependence, suggesting strongly that the far-IR emission is due to thermal emission from circumstellar dust that is the remnant material left from the clouds from which the central stars condensed. The model in which circumstellar gas and dust are formed by mass loss from stars, assuming a constant mass loss rate and flow velocity, results in a dust density that varies as r^{-2}. Therefore, the extremely broad energy distributions observed for both R CrA and TY CrA suggests that they are young objects, possibly still embedded in the cloud from which they were formed.

Yorke (1979, 1980) has made model calculations describing the structure, evolution, and spectral and spatial appearance of collapsing protostellar clouds of intermediate mass (3 $M_{\odot}$, 10 $M_{\odot}$). The results of his model computations show that at a certain evolutionary stage the gas and dust dynamically decouple with the dust blown outward by radiative acceleration, whereas the gas continues to fall inward still dominated by the gravity of the central star. The hot dust near the central source is decreased with consequent decrease in the near-infrared luminosity. The spectral distribution of R CrA and TY CrA show at least qualitative similarities with Yorke's 3 $M_{\odot}$ model. Although both sources have similar far-IR flux densities and sizes (Table 1), the 1–20 μm luminosity of 48 $L_{\odot}$ for R CrA and 2.5 $L_{\odot}$ for TY CrA are very different. This large difference can be accounted for if TY CrA, but not R CrA, has passed the evolutionary stage of expelling most of the hot dust near the central source. Further evidence that the hot dust has been blown out from TY CrA comes from the double-peaked spectral distribution with a minimum in the emission between 3 μm and 10 μm (Fig. 4). Yorke's model (1980) predicts this spectral shape at an evolutionary time of 1.4×10^6 years after the formation of the central core. This estimated age ($\sim 10^6$ years) is in good agreement with that of Knacke *et al.* (1973) based on near-infrared photometry and comparisons with the Taurus, Orion I, and Scorpio-Ophiuchus clouds.

V. CONCLUSIONS

The results of this study can be summarized as follows:

1. The far-IR observations of the CrA dark cloud detected two extended sources, one associated with the Herbig emission-line star R CrA and the other with the irregular emission-line variable star TY CrA, with luminosities of 148 $L_{\odot}$ and 58 $L_{\odot}$, respectively, where we have assumed a dust temperature of 37 K. Using the luminosities derived from the infrared observations and the optical classifications of R CrA and TY CrA, these stars lie in the region of Ae and Be stars on the H-R diagram.

2. The broad energy distributions of these sources can be explained by a circumstellar dust shell model (HTG), with the near-infrared radiation arising from hot dust ($T > 1000$ K) close to the star, the far-IR radiation from cool dust ($T \sim 40$ K) at the outer part of the shell, and a $1/r$ radial dependence of the dust density. The circumstellar shell is extended and probably the remnant material of the protostellar cloud that formed the star. These results strengthen the earlier conclusions of Herbig (1960) and Strom *et al.* (1972) that these stars are in the pre–main-sequence stage of evolution. The infrared spectral features associated with TY CrA indicate that this star has blown out most of the hot dust near the central source and yield an age of about 1×10^6 years.

3. R CrA and TY CrA were the only heating sources identified for the CrA dark cloud. No far-IR emission was found associated with the HH objects, compact H II region, or any of the T Tauri stars in the cloud. The 3 σ upper limit to the luminosity of these sources is 10–15 $L_{\odot}$ (assuming $T_d = 37$ K).

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