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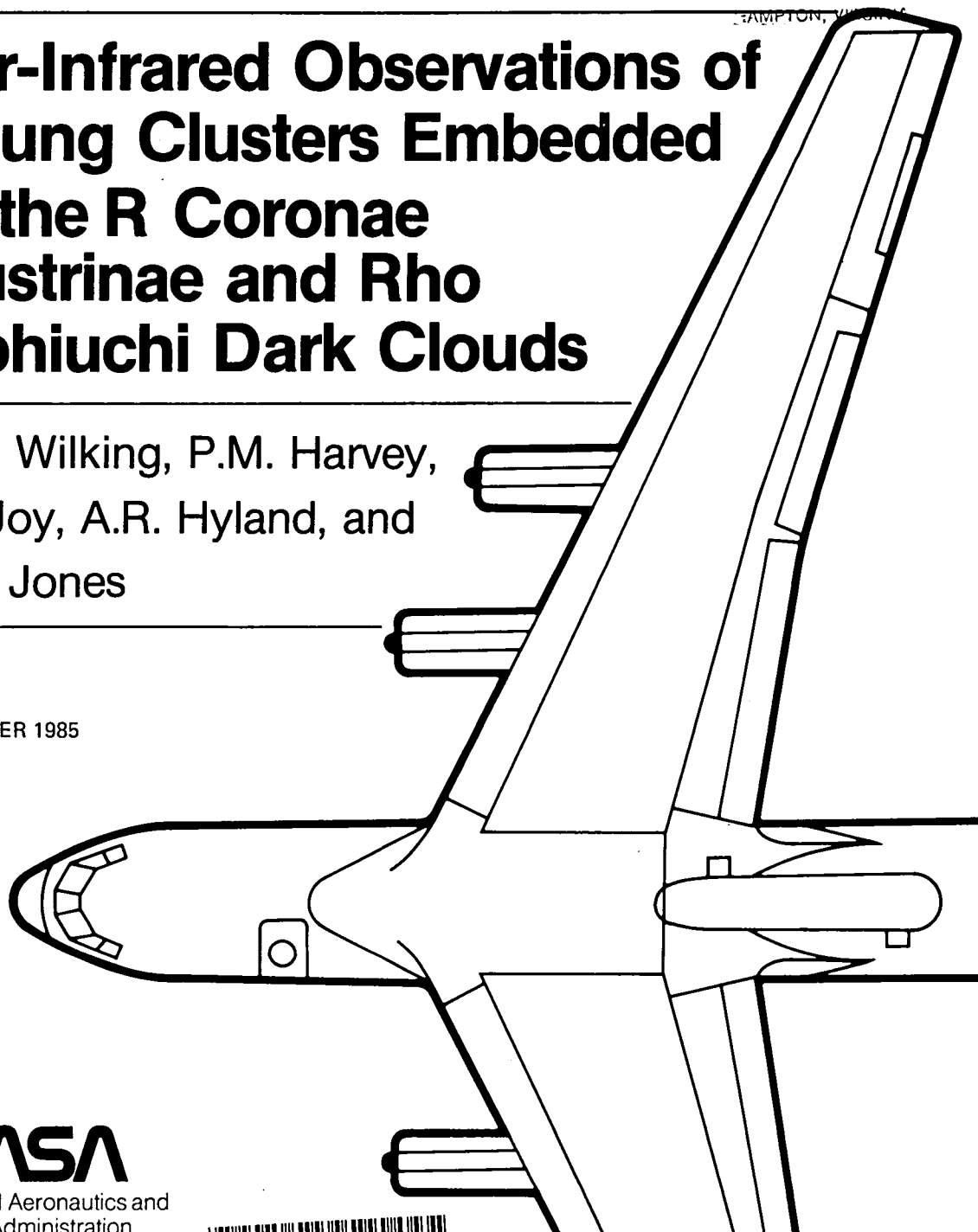B.A. Wilking, P.M. Harvey,
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ABSTRACT

We have made multicolor far-infrared maps in two nearby dark clouds, R Coronae Austrinae and ρ Ophiuchi, in order to investigate the individual contribution of low-mass stars to the energetics and dynamics of the surrounding gas and dust. We have detected emission from cool dust associated with five low-mass stars in Cr A and four in ρ Oph; their far-infrared luminosities range from 2 $L_{\odot}$ up to 40 $L_{\odot}$. When an estimate of the bolometric luminosity was possible, it was found that typically more than 50% of the star's energy was radiated longward of 20μm. Meaningful limits to the far-infrared luminosities of an additional eleven association members in Cr A and two in ρ Oph were also obtained. The dust optical depth surrounding the star R Cr A appears to be asymmetric and may control the dynamics of the surrounding molecular gas. The implications of our results for the cloud energetics and star formation efficiency in these two clouds are discussed.

I. INTRODUCTION

Nearby dark clouds (<200 pc) offer the best laboratory in which to study low mass star formation. It is here that one has the sensitivity and spatial resolution to sample low-luminosity objects embedded in the cloud. Through the selection of nearby clouds which are free of the dominating effects of massive star formation (M > $10M_\odot$), it is possible to investigate the various contributions of the individual stars to the energetics and dynamics of the surrounding gas and dust. In dark clouds where high densities of low mass stars have formed, the study of individual stars can ultimately be used to gain insight into the luminosity function of the young cluster and to explore the likelihood that enough molecular gas has been converted into stars to form a gravitationally bound gas-free cluster (see Wilking and Lada 1984 for review).

Two of the best examples of nearby clouds undergoing the prodigious formation of low mass stars are the dark clouds associated with R Coronae Austrinae (130 pc, Marraco and Rydgren 1981) and with ρ Ophiuchi (160 pc, Bertiaud 1958, Whittet 1974). The number of similarities between the two clouds is striking. Both clouds are located 17 degrees out of the plane of the galaxy, almost mirror images at $l \sim 355°$. The molecular gas in each complex is centrally condensed into a dense core ($n(H_2) > 10^4$ cm^{-3} (Loren, Sandqvist, and Wootten 1983) characterized by active star formation. Lower density streamers of gas and dust emanate away from these cores for tens of parsecs. Far-infrared observations have established the absence of massive star formation in these clouds; the most massive star in the Cr A cloud is ~B8 (Cruz-Gonzales, McBreen, and Fazio 1984) and ~B2 V in the ρ Oph cloud (Garrison 1967).

The high density of low mass stars in these dark clouds has been established primarily through Hα emission surveys, searches for variables and near-infrared surveys of the core regions. In the Cr A cloud, Hα emission surveys have been performed by Knacke et al. (1973) and Marraco and Rydgren (1981) and near-infrared studies by Glass and Penston (1975) and Vrba, Strom and Strom (1975,1976). The preliminary results of the most sensitive survey (K = 14 mag) of the Cr A cloud have been reported by Taylor and Storey (1984) and show that the density of young stars forming in the vicinity of the cloud core associated with the star R Cr A is much higher than previously thought. The total number of confirmed embedded sources is ~20 with an equal number of unclassified Hα emission objects and near-infrared sources. In the ρ Oph cloud, infrared surveys of the core region by Grasdalen, Strom, and Strom (1973), Vrba et al. (1975), Elias (1978), and Wilking and Lada (1983) have been combined with Hα studies by Struve and Rudkjobing (1949) and Cohen and Kuhi (1979) to compile a list of nearly 50 cluster members.

As alluded to earlier, both the Cr A and ρ Oph dark clouds have been surveyed in the far-infrared with an effective wavelength of ~91 μm (for a color temperature of 37K) and with ~1 arcmin resolution (Cruz-Gonzales, McBreen, and Fazio 1984, Fazio et al. 1976). These observations have had the sensitivity to detect emission from embedded stars of main sequence spectral type late B and earlier which deliver all of their luminosity to the surrounding dust. Unfortunately, these observations leave unanswered many of the questions related to the formation of lower luminosity objects. In particular, one would like to know the relative contributions of the lowest luminosity cluster members to the overall dust emission from the cloud and to be able to use this information to estimate the total luminosity of each star.

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Far-infrared observations are often critical to recover the total luminosity from low mass stars; far-infrared photometry of exciting stars for H-H objects by Cohen et al. (1984a) has shown that typically over 50% of the total luminosity of these stars is radiated longward of 20 μm. In addition, the dust temperature and optical depth structure of the dust surrounding the known sources of far-infrared emission cannot be derived from observations at a single wavelength.

Therefore, to assess properly the luminosities of low-mass stars embedded in the Cr A and ρ Oph dark clouds and to investigate the temperature and optical depth distribution of the emitting dust, we have performed new and sensitive multi-color far-infrared observations in these cloud cores. Critical to the study of these high density clusters, we have used a spatial resolution of 45 arcsec (FWHM) that allows us to separate contributions to the far-infrared flux from closely spaced stars. In the Cr A cloud, this spatial resolution permits us to explore the relationship between a Herbig-Haro object and its proposed exciting star. Our observations have resulted in the most sensitive and detailed information of the dust emission associated with low mass star formation in the Cr A cloud. At least five young stars contribute to the dust emission in the cloud and meaningful limits can be set to the far-infrared luminosities of an additional 11 association members. Our multi-color photometry has also revealed an apparent asymmetry in the distribution of dust surrounding the star R Cr A and presented us with the unusual situation of enhanced emission toward the H-H 100 nebula rather than its proposed exciting star. In the ρ Oph cloud, our observations of selected fields within the core region are used to determine the far-infrared luminosity of three luminous 20 μm sources and have revealed a previously unknown source of far-infrared emission.

The equipment and observations are described in Sec. II. Sec. III outlines the results of our multi-color observations for each cloud and discusses the luminosity, dust temperature, and dust optical depths for individual sources. The implications of these properties for low mass star formation in these clouds in discussed. Our results are summarized in Sec. IV.

II. OBSERVATIONS

All far-infrared observations were obtained using the 0.9 m telescope of the Kuiper Airborne Observatory. The three fields observed in the ρ Oph cloud were mapped during flights based in Hawaii in March 1983 (GS-30 and SR-3) and in Sydney, Australia in June 1983 (EL-29). All photometry of the Cr A cloud was obtained on two flights from Australia. A portion of our map of the R Cr A source has been presented by Cohen et al. (1984b).

All of the far-infrared photometry was performed simultaneously at 50 μm and 100 μm with the three spatial by dual spectral channel photometer described by Wilking, Lada and Young (pers. comm.). A spatial resolution of 45 arcsec (FWHM) was used with a chopper throw of 3 - 4 arcmin. The positional uncertainties of these observations are approximately 5 arcsec although an additional 10 arcsec uncertainty arises in the EL-29 field of the ρ Oph cloud due to the unusually large offsets necessary for guiding.

The simultaneous observations of two wavelengths at each spatial point permits a reliable determination of the color temperature of the dust and dust optical depth assuming optically thin dust emission with a 1/λ emissivity. In computing temperatures and optical depths, corrections were made to the 100 μm fluxes to account for the broader wings of the 100 μm beam; these fluxes were

divided by 1.2. The statistical one sigma uncertainty is ~ 2 K in the derived dust temperature and ± 20% in the dust optical depth.

The flux calibration was set through observation of Saturn. Properly accounting for geometry and emission from the rings, we adopted values of 8.5 x 10^4 Jy and 6.6 x 10^4 Jy for the 50 μm and 100 μm flux density of Saturn. We estimate the uncertainty of the calibration to be ±30%.

III. RESULTS

The Cr A Dark Cloud

Our far-infrared (FIR) photometry of the Cr A cloud consists of two extensive maps of the area surrounding the young emission-line stars R Cr A and TY Cr A and of seven single beam observations toward isolated association members not included in the maps. The 50 μm and 100 μm maps are presented in Fig. 1a and 1b, respectively, superposed on the POSS photograph (Whiteoak Extension) of the field. Far-infrared fluxes and integrated fluxes deduced for individual association members are presented in Table 1. The maps and individual sources are discussed below.

1. New Sources of Excitation for the Dust Emission Near R Cr A

As shown in our Fig. 1 and also by Cruz-Gonzales, McBreen and Fazio (1984 hereafter CMF) the most extensive and luminous dust emission in the dark cloud is excited by the emission-line star R Cr A. But eight of the cloud's numerous embedded infrared sources found by previous investigators also lie within the boundaries of our map. The higher sensitivity and spatial resolution of our observations indicate that of these eight, T Cr A (Knacke et al. 1973) TS 13.1, and TS 2.4 (Taylor and Storey 1984) appear to excite a

small fraction of the overall dust emission from this region. Enhanced emission is also observed toward the H-H 100 nebula. Useful limits to the dust emission toward TS 2.3 and TS 4.1 (Taylor and Storey 1984) can also be determined from our map (ref. Table 1). Two faint but very red near-infrared sources, IRS 7 and IRS 9 (Taylor and Storey 1984), lie within 20 arcsec of R Cr A and their relative contribution to the FIR source is impossible to determine given our spatial resolution. It should be pointed out that IRS 7 lies almost coincident with a radio continuum source found by Brown and Zuckerman (1975) and later observed by Rodriguez (1982) and could be a relatively important source of luminosity.

The appearance of these additional association members as heat sources for the dust emission in the R Cr A FIR source can be seen most clearly on our map of the dust color temperature presented in Fig. 2. Dust temperature enhancements toward T Cr A and associated with H-H 100 and TS 13.1 indicate there are several new exciting sources for the dust emission in addition to R Cr A. The subset of our data presented by Cohen et al. (1984b) showed a 125K dust temperature peak southeast H-H 100-IR which should be regarded as spurious. The temperature enhancement in this region was artificially produced due to the extended nature of the 100 μm relative to 50 μm flux surrounding R Cr A which our larger data set has revealed.

The relative contribution of the new excitation sources near R Cr A to the overall dust emission will be discussed in the following sections. To separate these contributions, we subtract the far-infrared emission which lies symmetrically distributed about R Cr A from the total. The residual emission is attributed to these newly identified sources.

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(a) The Pre-Main Sequence Star R Cr A

Classified as an emission-line irregular variable star of spectral type A5pe (Mendoza, Jaschek and Jaschek 1969) and Ae (Marraco and Rydgren 1981), R Cr A excites the surrounding reflection nebulosity (NGC 6729) and from the morphology of our far-infrared maps, the majority of the dust emission in the area. We estimate the total far-infrared luminosity of R Cr A to be ~40 L_O (20 μm -100 μm). By combining this with the luminosity emitted at shorter wavelengths (1.25 μm -20 μm) and extrapolating for the luminosity radiated beyond 100 μm assuming $F(\infty) = F(100 \ \mu m)$, we derive a bolometric luminosity for R Cr A of 120 $L_\odot$ with an estimated uncertainty of ±40%. Over half of this luminosity is emitted longward of 20 μm. This luminosity is consistent with an A star classification but suggests that the star may still be contracting toward the main sequence. Our value of 120 $L_\odot$ is in agreement with estimates of 150 $L_\odot$ by CMF and of 140 $L_\odot$ derived from the balloon observations of de Muizon et al. (1980) for a distance of 150 pc (105 $L_\odot$ at 130 pc).

The distribution of dust optical depth ($\tau_{100 \ \mu m}$) near the star R Cr A is shown in Fig. 3. The optical depth peak of the dust appears offset from the star by about 30 arcsec to the south. Consistent with this picture is the higher dust temperatures observed west and north of the star (Fig. 2). The asymmetric distribution of dust around R Cr A may help explain why the bipolar molecular gas outflow observed toward this region is centered on a position about 45 arcsec north of the star (Levreault, R.M., personal communication).

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(b) Dust Emission Toward the H-H 100 Nebula

Only 80 arcsec southwest of R Cr A is the arc-shaped nebulosity identified as a Herbig-Haro object by Strom, Strom, and Grasdalen (1974). They found a bright near-infrared source, H-H 100-IR, 20 arcsec east of the nebula which is the best candidate for the H-H exciting star. This near-infrared star has been observed to undergo variations in brightness which are believed to be intrinsic to a young pre-main sequence star (Axon et al. 1982, Reipurth and Wamsteker 1983). However, because of the molecular outflow centered near R Cr A and the fact that H-H 100 lies roughly colinear with R Cr A, H-H 99 and H-H 101 (for which no exciting star has been found, Cohen et al. 1984b), the star R Cr A is a viable candidate as the H-H 100 exciting star.

As shown in Fig. 1, our 50 μm data displays a secondary peak of emission toward the northern arc of the H-H 100 nebulosity with some enhancement of 100 μm emission from the same region. The increasing dust temperature gradient from the H-H 100-IR star to the secondary peak (Fig. 2) along with the relatively low optical depth toward this peak (Fig. 3) would be consistent with the idea that H-H 100-IR is the exciting star for the dust emission and the H-H nebula. The H-H 100 region may be yet another example where the dust emission is dominated by the H-H object rather than the actual exciting star (Cohen et al. 1984a,b). Assuming the far-infrared emission is excited by H-H 100-IR, a bolometric luminosity of ~14 $L_\odot$ is suggested for the star. Higher resolution far-infrared observation will be necessary to understand the precise relationship of H-H 100 and its proposed exciting star.

(c) The Low Luminosity Stars T Cr A, TS 13.1, and TS 2.4

The emission-line variable star T Cr A, which has been classified FOe by
Herbig and Rao (1972), lies 70 arcsec southeast of R Cr A and at the edge of
the R Cr A FIR source. Several positions measured toward this star display
enhanced 50 μm emission. As a result, enhanced dust temperatures and low
optical depths are inferred toward T Cr A (Fig. 2, 3), reminiscent of a star
which has swept out a small cavity in the surrounding cloud. No significant
FIR luminosity is provided by the star and an upper limit of 2 $L_\odot$ (20 μm - 100
μm) can be set from our observations. Consideration of the luminosity
radiated in the 1.2 μm - 20 μm region of 2 $L_\odot$ gives an upper limit of 4 $L_\odot$ for
the bolometric luminosity, which is consistent with the FOe classification.

Lying in the southwest corner of the field of our R Cr A FIR map, TS 13.1
is an extremely red near-infrared source which excites dust emission just
barely resolved by our beam. A total of 3 $L_\odot$ are radiated in the FIR by this
source and, when combined with near-infrared data, a bolometric luminosity of
10 $L_\odot$ is obtained.

Although no clear-cut dust temperature enchancement is discernible toward
this red, extended near-infrared source (Taylor and Storey 1984), the
extension of the 50 Jy/beam contour around TS 2.4 in our 100 μm map suggests
that it may be a source of FIR luminosity. An upper limit 1.5 $L_\odot$ is measured
for the FIR luminosity of this star which lies only 80 arcsec west of R Cr A.
This implies a bolometric liminosity of < 3 $L_\odot$ for the source.

2) TY Cr A: A More Evolved Counterpart to R Cr A

The second most luminous source of FIR emission in the Cr A cloud is centered on and excited by the irregular variable star TY Cr A. As shown in Fig. 1, the dust emission delineates the reflection nebulosity (NGC 6726) powered by this young star which is classified as B8 (Marraco and Rydgren 1981). As pointed out by CMF, the energy distribution of this star peaks at 1 μm and again at 100 μm suggesting that it is a more evolved young star than R Cr A and has cleared away much of the hot dust which used to lie close to the star. The star now excites thermal emission from cooler dust which is associated with, but further removed from, the star. This ability of a young B star to dissipate its inner dust cloud as it emerges from its embedded state is characteristic of many young stars found associated with reflection nebulae in NGC 1333, S68, and NGC 7129 (Harvey, Wilking, and Joy 1984).

By summing the integrated flux from this extended FIR source we can estimate the luminosity provided to the dust by TY Cr A to be about 25 $L_\odot$ (20 μm -100 μm). Only a small amount of luminosity is radiated in the near-infrared ($\sim$3 $L_\odot$). Estimating the flux emitted longward of 100 μm results in a bolometric luminosity of $\sim$40 $L_\odot$. It would be expected that larger beam FIR observations which are more sensitive to extended emission may derive larger values for the dust luminosity. Our value for the bolometric luminosity is consistent with that found by CMF (58 $L_\odot$) and with a B8 star classification, considering the extended nature of the FIR source.

The dust temperature and optical depth structure are not presented for the TY Cr A FIR source but are relatively constant across the source: T_D $\sim$50 $\pm$ 3 K and τ100 μm $\sim$2.5 $\times$ 10^{-3}. The star HD 176386, which lies at the southern

end of the FIR source and only one arcmin south of TY Cr A, is found to be a slightly reddened ($A_v \sim 1$ mag) A0 star which probably lies at the front surface of the cloud (Marraco and Rydgren 1981). An enhancement in the 50 μm flux relative to the 100 μm flux, toward the star (Fig. 1) suggests it may contribute some heating to the dust. Our far-infrared data can be used to set an upper limit of 5 $L_\odot$ to the luminosity contributed to the heating of the dust from this star.

3) FIR Emission Outside of the Cr A Cloud Core

In addition to the FIR maps presented for the R Cr A and TY Cr A regions, observations of seven individual association members of the Cr A cloud which lie outside of these mapped regions were made. The results of these observations are presented in Table 1. Of the seven, only the emission line variable VV Cr A was detected and found to have a far-infrared luminosity of 3 $L_\odot$. This star displays a T Tauri spectrum (Marraco and Rydgren 1981) and our estimate of its bolometric luminosity of 12 $L_\odot$ suggests it is a relatively low mass star.

b) The Rho Ophiuchi Cloud Core

Using a calorimetric technique, Lada and Wilking (1984) have produced a luminosity function for the young cluster embedded in the ρ Oph cloud core. Correcting for known selection effects, their data suggest there is a deficiency of intermediate luminosity stars (L > 5$L_\odot$) in ρ Oph relative to the field star initial mass function. One uncertainty in their method is the amount of luminosity not accounted for longward of ground-based observations at 20 μm. Of the 32 cluster members in the ρ Oph core studied by Lada and Wilking (1984), only five sources display νF_ν energy distributions which are

still rising at 20 μm (**Table** 2). Our far-infrared observations of two areas in the core were directed toward assessing the luminosity longward of 20 μm for the two objects with steeply rising spectra which were most luminous at 20 μm: EL-29 and GS-30. (Two of the five sources which were not observed are visible objects believed to be T Tauri stars and are not expected to generate substantial far-infrared luminosity [SR-4 and VSSG-23, Lada and Wilking 1984].) We observed a third field toward the late B star SR-3 to determine the possible contribution of a nearby radio continuum source FG-11 (=OPH 11, Falgarone and Gilmore 1981) to the far-infrared emission from this region (Fazio et al. 1976). If it is embedded in the cloud, this radio continuum source could be a compact H II region excited by a B3 ZAMS star, making it one of the most massive stars in the cloud (Fig. 4).

1. GS-30: A Low-Luminosity Protostar

GS-30 (=EL-21) is the most luminous 20 μm source in the ρ Oph core region and has a steeply rising energy distribution from 1 - 20 μm characteristic of a young embedded protostar (Elias 1978). Lada and Wilking (1984) estimate a 1 - 20 μm luminosity of 6 $L_\odot$. The results of our 100 μm map of a 2' x 2' area centered on this source are not presented here but shows that GS-30 lies in the wings of strong dust emission excited by the B3 star Source 1 which lies 3' to the east (Harvey, Campbell and Hoffmann 1979, HCH). The 100 μm flux density falls off from 300 Jy to 50 Jy as one moves roughly east to west ±1 arcmin from GS-30. Comparing these data to those of HCH, it is difficult to regard GS-30 as a distinct source of FIR luminosity. If a deviation of the 100 Jy/beam contour in our map from the symmetry of the Source 1 80 μm map of HCH is attributed to an enhancement from GS-30, then an estimate of ~6 $L_\odot$ is obtained for the far-infrared luminosity of (20 μm - 100 μm) of GS-30. This

implies a total luminosity of ~12 $L_\odot$ which is consistent with the picture of this source as a star of relatively low mass. Higher resolution FIR observations would be necessary to determine more precisely the total luminosity of GS-30, but our observations suggest it is not a major luminosity source and that previous luminosity estimates have not greatly underestimated its mass.

2. Far-Infrared Emission Adjacent to EL-29

An area of about 10 arcmin^2 was mapped in the vicinity of the bright 20 μm sources EL-29 and WL-16. In the course of these observations, a new source of FIR emission was revealed but appears unrelated to EL-29. Instead, this warm dust emission appears coincident with several faint 2 μm sources.

(a) No Cold Dust Detected Toward EL-29

EL-29 displays a rising νF_ν energy distribution in the infrared similar to that of GS-30 and is also belived to be an embedded protostar (Elias 1978). Therefore it is surprising that we find no evidence for cool dust (T_D ~20-100K) toward this source. Since EL-29 is well isolated from the luminous dust emission from the early B stars in the ρ Oph core, we can set an upper limit to its FIR luminosity of 2$L_\odot$ and < 17$L_\odot$ for the bolometric luminosity.

The relatively narrow energy distribution which results for EL-29 is reminiscent of the energy distribution of evolved stars undergoing mass loss (Harvey, Thronson, and Gatley 1979, Harvey and Wilking 1982). If the cool dust toward EL-29 is indeed absent then its spectrum which includes strong absorptions at 3.1 μm and 10 μm (Elias 1978, 1984) would be consistent with a

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background star, either an M giant or a heavily reddened T Tauri star which has detached itself from the cloud (e.g., a reddened version of RY Tau, [Harvey, Thronson, and Gatley 1979]). However, because scattered near-infrared light is observed toward EL-29 by Elias (1978), it is most probable that the star is embedded in the cloud and that the cool dust which it excites is more extended than our 45 arcsec beam. The larger beam IRAS observations should be able to resolve such emission.

(b) A New Source of FIR Emission

A moderately strong source of FIR emission, FIRS 1, was unexpectedly discovered north and west of EL-29 (Fig. 5). Both the dust temperature and optical depth reach a maximum at the position of highest flux density suggesting an internal heat source: $T_D = 49 \pm 2$ K and $\tau_{100 \mu m} = 2.4 \pm 0.3 \times 10^{-3}$. FIRS 1 may be the 130 μm source discovered by the balloon observations of Sargent et al. (1983) but displaced to the south and west of their reported position. We failed to detect emission at the 60 Jy level at 100 μm toward the 130 μm source position with our linear array.

While the temperature and optical depth structure of the dust toward FIRS 1 suggest an internal source, the exciting star for this emission has not been identified. A 1 x 1.5 arcmin map of the FIR emission peak was made at 2 μm to a detectable limit of K=14.7 mag with the IRTF and revealed only three faint infrared sources: WL-14, WL-21 and WL-22 (ref. Fig. 5). Their infrared spectral energy distributions are not shown here but only in the colors of WL-22 is there evidence for a steeply rising spectrum characteristic of protostars with circumstellar dust and gas (Wilking, Lada, and Young 1984). WL-14 or WL-21 could excite the FIR emission only if they are more evolved

stars surrounded only by cooler dust further removed from the star (e.g., TY Cr A), but the apparent compact nature of the FIR emission would argue against this.

(c) WL-16

A second bright near-infrared source, WL-16, which lies only 1.5 arcmin to the west of EL-29, was also included on the southern edge of our FIR map. This source emits about 2.5 $L_\odot$ in the near-infrared (1.25 μm -20 μm) and displays a strong (1.5 mag) silicate absorption (Wilking and Lada 1983, Lada and Wilking 1984). Extended 100 μm emission south of FIRS 1 and higher dust temperatures in the vicinity of WL-16 suggest it may be a significant luminosity source in this region. In fact, the FIR data of Cudlip et al. (1984),[1] which is better sampled in this region, shows stronger 90 μm emission in the vicinity of WL-16 than from FIRS 1. However, without more extensive mapping, a heretofore unknown heating source in the cloud near WL-16 is not ruled out. Attributing our observed southern dust emission to WL-16 would yield a total luminosity of 5 $L_\odot$ for this source.

3. Extended FIR Emission Excited by the Young Star SR-3

An extended, low surface brightness FIR source toward the young star SR-3 was first observed by Fazio et al. (1976). Radio continuum observations by Falgarone and Gilmore (1981) revealed a new 1.4 GHz source only 80 arcsec east of SR-3 (FG-11 = OPH-11) which could require excitation by a B3 ZAMS star if embedded in the cloud. Our FIR observations included both sources in the field to determine their relative importance to the dust excitation.

[1]Cudlip, W., Emerson, J.P., Furniss, I., Glencross, W.M., Jennings, R.E.,et al.,1984, preprint.

As shown in Fig. 6, SR-3 appears to be the exciting star for the dust emission. FG-11 does not appear to be a massive star or an important source of luminosity, and is not a B3 ZAMS star embedded in the cloud. It is quite possible that FG-11 is a background radio source. Lada and Wilking (1984) have pointed out that the near-infrared energy distribution of SR-3 shortward of 10 μm is consistent with that of a photosphere of a B9-A0 main sequence star reddened by ~5 mag of foreground extinction. The absence of hot dust near the star is consistent with the idea that SR-3 is exciting extended emission from cooler dust which is further removed from the star. Struve and Rudkjøbing (1949) also obtain an A0 classification for SR-3 from its visible spectrum.

The final test for the identification of SR-3 as the exciting star for this extended FIR emission would be to recover most of the luminosity of an A0 star ($\sim$100 $L_\odot$) from the FIR emission. Our estimate for the luminosity of SR-3 longward of 10 μm (including an extrapolation to wavelengths beyond 100 μm) is about 30 $L_\odot$. This estimate is probably a lower limit because of the extended nature of the source which is evident from our map. Indeed, a 2 arcmin resolution 90 μm map of the area by Cudlip et al. (1984) shows the source to be extended over a 4' x 6' area (four times greater than the covered by our map) with a luminosity of 65 $L_\odot$. Hence, SR-3 is most likely the sole source of excitation for the extended FIR emission.

IV. Summary and Implications

High resolution far-infrared observations (45 arcsec) have been made in two nearby southern hemisphere dark clouds which host a high density of young embedded stars. The spatial resolution and sensitivity of our observations allowed us to assess the contribution of the low luminosity stars in these clusters to the overall dust emission and to determine their bolometric luminosities. The majority of the young stars in both clouds for which bolometric luminosities could be determined emit 50% or more of their luminosity in the far-infrared. However, the 10 μm - 20 μm brightnesses or νF_ν energy distributions are not always correlated with the presence of emission longward of 20 μm.

In the Cr A cloud, the dust emission is dominated by the B8 -A0 stars TY Cr A and R Cr A which appear to be in different stages of their early evolution. In contrast to TY Cr A, R Cr A is still associated with large amounts of hot dust close to the star and a dense core of gas and dust. The asymmetric distribution of dust surrounding R Cr A may be important in the dynamics of molecular gas near the star. In addition to the two dominant B8-A0 stars, at least three other low luminosity stars contribute to the observed dust emission. Far-infrared luminosities (or meaningful limits) have been obtained for these and 11 other association members. When their bolometric luminosities can be determined, we find them to range between 3-14 $L_\odot$ which are consistent with stars of 2 $M_\odot$ or less (e.g., Cohen and Kuhi 1979).

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In the ρ Oph dark cloud, far-infrared emission was detected from a previously unidentified 2 μm source in the dense core while only upper limits could be obtained for the cloud's two brightest known 20 μm sources which have rising νF_ν energy distribution. These results underline the need for far-infrared observations in determining major luminosity sources and bolometric luminosities. Extended far-infrared emission toward the star SR-3 appears to be excited by B9-A0 star and not by a nearby radio continuum source for which a B3 ZAMS classification had been suggested.

Our far-infrared observations of the ρ Oph and Cr A clusters present us with a clearer picture of the dominant luminosity sources embedded in each cloud. This is essential information when considering the cloud energetics and efficiency of star formation, both of which are sensitive to the more massive stars. Therefore, we can begin to compare the star-forming properties of these two clouds. These comparisons can be very insightful because of the basic similarities between the ρ Oph and Cr A clouds. Not only are the two cloud complexes alike in their core-streamer morphology but also in their mass. The main cloud in Cr A is estimated to have a total mass of 6900 $M_\odot$ (Loren 1983 as compared to 7600 $M_\odot$ for the main cloud in ρ Oph (Aquilo 1980). Hence, any differences between the present populations of young stars in these clouds may ultimately lead us to discover the subtleties of the low mass star formation which are independent of cloud mass.

The energy balance in the ρ Oph and Cr A clouds can be easily understood by considering the known luminosity sources with existing CO and far-infrared observations. The major luminosity sources in the ρ Oph cloud are the B2 V star HD 147889 and the ~B3 star Source 1. Less luminous stars dominate the

energetics of the Cr A cloud; TY Cr A and R Cr A are B8-A0 stars. Many investigators have proposed the existence of additional embedded early-type stars in ρ Oph and Cr A in an effort to explain the presence of numerous radio continuum sources observed toward the clouds and the excitation of CO emission lines. However, the existence of these additional heating sources has simply not been borne out by far-infrared observations presented here and elsewhere (CMF, Fazio et al. 1976, Cudlip et al. 1984). Radio continuum emission can be excited collisionally by lower-luminosity embedded stars (e.g., Cohen, Bieging and Schwartz 1982) or by background objects. The warm CO temperatures in these clouds can be excited by the existing stars if they heat the dust and gas within a surface layer of the cloud. The heating of the surface of the western edge of the ρ Oph cloud core by two B stars can to a large degree explain the warm gas temperatures observed in the core (Cudlip et al. 1984). Likewise, the distribution of CO temperatures surrounding TY Cr A is understood in terms of a B8 star heating the cloud surface which is consistent with our far-infrared observations which show extended dust emission associated with the optical reflection nebulosity.

The star formation efficiency (SFE $= M_{stars}/(M_{stars} + M_{gas})$) is a difficult parameter to compute due to uncertainties is estimating the masses of stars and gas. In addition, the SFE can presently only be estimated for a fraction of the cloud. Our far-infrared observations suggest no major modifications to previous estimates for the SFE in the central 290 $M_{\odot}$ core of the ρ Oph cloud; a SFE of $>$ 25% has already been determined through extensive near-infrared and molecular-line observations (Wilking and Lada 1983, Lada and Wilking 1984).

In the Cr A cloud core much less is known regarding the nature of the embedded cluster. We define the cloud core as the 0.4 x 0.7 pc region centered on the star R Cr A where H_2CO observations indicate $n(H_2) > 10^4$ cm^{-3}. The inferred cloud mass is ~130 $M_\odot$ (Loren, Sandqvist, and Wootten 1983). Two-micron surveys of the core by Taylor and Storey (1984) have revealed 70 sources. By analogy with the well-studied cluster near R Cr A, we estimate about 20 (30%) of these infrared sources are field stars (Wilking, Taylor, and Storey 1984). Our far-infrared observations suggest that apart from three B8-A0 stars, the remainder of the Cr A association members are stars of relatively low mass (~2 $M_\odot$). Consequently, a population of 50 stars with an average mass of 1 $M_\odot$ would result in a SFE of ~28% for the Cr A core. This estimate has at least a factor of two uncertainty.

The close agreement between the SFE in the Cr A and ρ Oph cloud cores must be considered fortuitous, however, it does emphasize several important points. First, as stated by Taylor and Storey (1984), star formation has been more active in Cr A than previously thought; the SFE computed above, albeit crudely, is 50 times greater than prior estimates. Second, in the absence of massive stars, the Cr A core may be the second example of a cloud forming a large aggregate of stars which will emerge as a gravitationally bound open cluster (e.g., Wilking and Lada 1984). Finally, because the SFE is a time-dependent quantity, we would expect clouds which have formed low-mass stars over a longer duration to display higher values for the SFE. Thus if the Cr A and ρ Oph clouds have formed stars at a similar rate, no relative age difference between their star-forming lifetimes is reflected in our current best estimates for the SFE. Clearly, tighter comparisons of star formation between the Cr A and ρ Oph clouds will await a better understanding of their

embedded stars and a more precise determination of the SFE.

One clear distinction between star formation in ρ Oph and Cr A is the presence of two early B stars which control the energetics in the ρ Oph cloud. Multi-wavelength observations of the luminosity function of the Cr A cluster are needed to explore whether the absence of early B stars in Cr A is merely a fluctuation in the statistics of small numbers or if it indicates a different star-forming age or mechanism between the two clouds. For example, Cudlip et al. (1984) have suggested the formation of the early B stars which lie at the western edge of the ρ Oph cloud core may have been initiated by an external disturbance. The location of the ρ Oph cloud within the youngest subgroup of the Sco-Cen OB association could expose the cloud to a variety of external forces. Therefore, the comparison of the ρ Oph and Cr A clouds may lead us to a better understanding of the effects of the cloud environment on star formation.

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TABLE 1

FAR-INFRARED FLUXES AND LUMINOSITIES FOR Cr A CLUSTER MEMBERS

Source Name	F(50μm)(Jy)	F(100μm)(Jy)	L_{FIR} ($L_\odot$)	References
R Cr A	290	570		(1), (2)
	665[a]	2060[a]	42 (20μm – 100μm)	
TY Cr A	145	190		SAO 210829, (1)
	475[a]	990[a]	23 (20μm – 100μm)	
TS 13.1	50	50	3 (20μm – 100μm)	(1), (2)
VV Cr A	45	55	3 (20μm – 100μm)	(3), (4)
H–H 100	140[b]	80[b]	2 (50μm – 100μm)	(5)
TS 2.4	25[b]	60[b]	<1.5 (20μm – 100μm)	(1), (2)
S Cr A	<21 (3σ)	<8 (3σ)	<1.5 (20μm – 100μm)	(3), (4)
HR 7169-70	<11 (3σ)	<9 (3σ)	<1 (10μm – 100μm)	SAO 210815-6, (4)
DG Cr A	<14 (3σ)	<9 (3σ)	--	18^h 58^m $32^s.4$, -37° 27' 54" (1950)
VSS-18	<14 (3σ)	<6 (3σ)	--	(3)
Anon-1	<21 (3σ)	<11 (3σ)	--	(3)
KS 15-E	<11 (3σ)	<14 (3σ)	--	Hα3, (6)
HD 176386	<60[c]	<60[c]	<5 (10μm – 100μm)	GP(p), (1), (2)
T Cr A	<40[d]	<40[d]	<2 (20μm – 100μm)	(1), (2)
TS 2.3	<30[d]	<35[d]	--	(2)
TS 4.1	<25[d]	<25[d]	--	(2)

TABLE 1 (CON'T)

[a] Integrated flux

[b] Integrated flux estimated from subtraction of a symmetric FIR source centered on R Cr A

[c] Limits set from emission observed toward the TY Cr A FIR source (Fig. 1)

[d] Limits set from emission observed toward the R Cr A FIR source (Fig. 1)

References:

(1) Wilking, Taylor, and Storey (1984), (2) Taylor and Storey (1984), (3) Vrba, Strom, and Strom (1976), (4) Knacke et al. (1973), (5) Strom, Strom, and Grasdalen (1974), (6) Marraco and Rydgren (1981).

TABLE 2

FAR-INFRARED FLUXES AND LUMINOSITIES FOR

ρ OPH CLUSTER MEMBERS

Source Name	F(50μm)(Jy)	F(100μm)(Jy)	L_{FIR} ($L_\odot$)	References
FIRS 1	110	155	3 (50μm – 100μm)	
EL-29	<11 (3σ)	<14 (3σ)	<2 (20μm – 100μm)	(1), (2)
SR-3	60[a]	80	--	--
	120[b]	425[b]	18 (10μm – 100μm)	(1), (2)
WL-16	30[c]	50[c]	2.5 (20μm – 100μm)	(1), (3)
GS-30	--	70[d]	6 (20μm – 100μm)	(1), (2)
WL-10	--	<26 (3σ)	<3 (10μm – 100μm)	(1), (3)
FIR 130μm	--	<60 (3σ)	--	(4)

[a] Flux measurement is offset from 100μm peak by 40 arcsecs

[b] Integrated Flux

[c] Flux measurement made 20 arcsec West of WL-16

[d] Flux estimated from enhanced dust emission in wings of the Source 1 FIR emission

References:

(1) Lada and Wilking (1984), (2) Elias (1978), (3) Wilking and Lada (1983), (4) Sargent et al. (1983)

Figure 1. - Contours of the far-infrared flux density in the Cr A dark

cloud. Superposed on the POSS photograph of the area, maps are

presented for emission associated with R Cr A and TY Cr A for both

50μm (Fig. 1a) and 100μm (Fig. 1b). The areas covered by these

observations are enclosed by the straight-line borders. Crosses mark

the position of several of the known association members.

Figure 2. - The dust color temperature in the vicinity of R Cr A. Contours

are given in steps of 5 K with crosses marking the positions of the

association members labeled in Fig. 1. The dashed contours merely

indicate the lowest level of detectable dust temperature of 40 K.

Figure 3. - The 100μm optical depth in the vicinity of R Cr A. Contours

are given in units of 10^{-3}. Crosses mark the positions of association
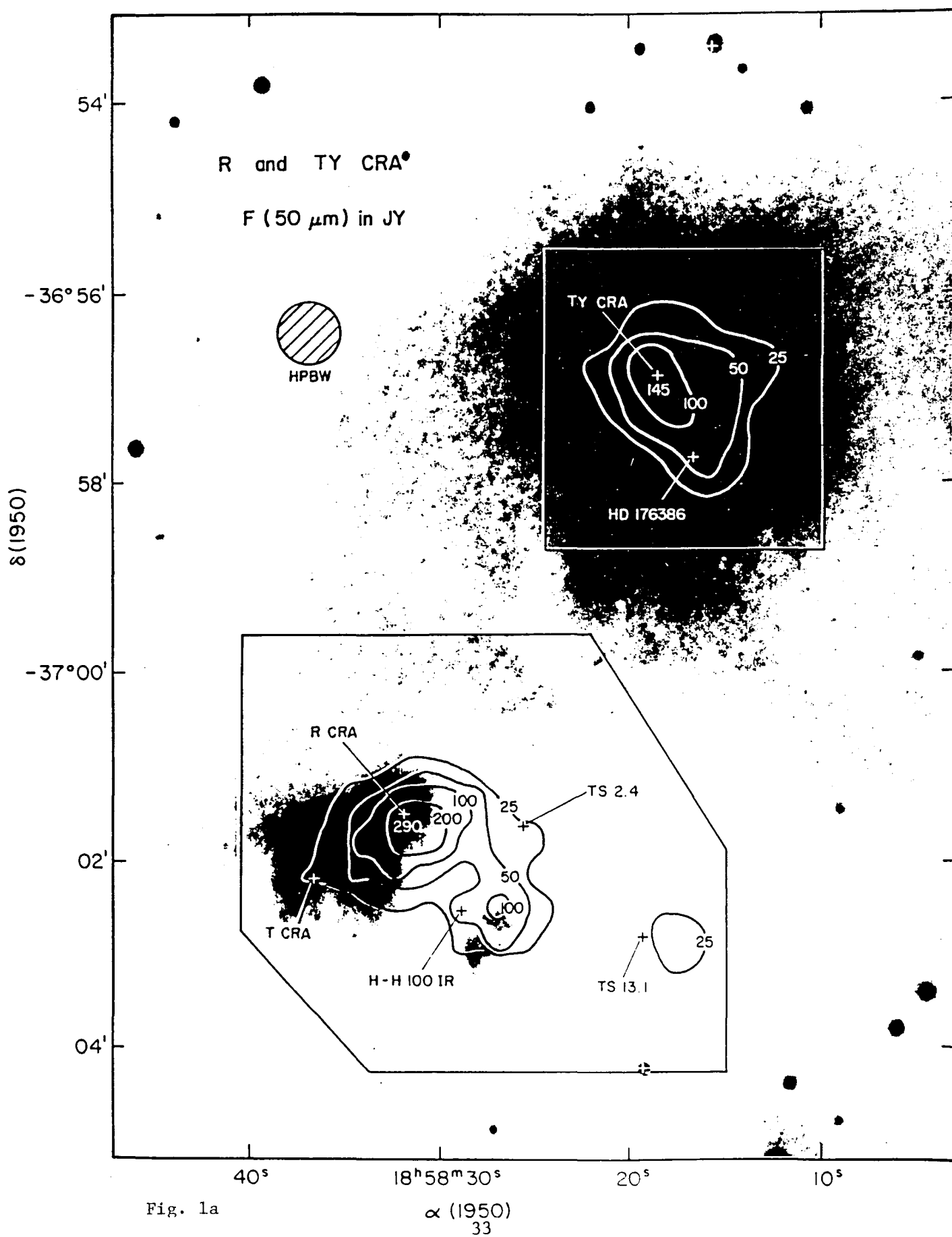
members labeled in Fig. 1.

Figure 4. - The location of the three fields mapped in the far-infrared in

the ρ Oph cloud. The core region of the cloud is traced out by the

solid contours representing the integrated intensity of $C^{18}O$ emission

as observed by Wilking and Lada (1983); the lowest contour level is 2

K kms^{-1} and increases to 6 K km s^{-1} in steps of 2 K km s^{-1}. Dashed

lines outline the regions which we have mapped in the far-infrared and

crosses mark the positions of the prominent near-infrared stars found

in these fields. The position of the most luminous star in the core region, the B3 star Source 1, is also shown by a cross.

Figure 5. - Far-infrared emission from the EL-29 region of the ρ Oph cloud. Contours of 50μm and 100μm emission are shown as well as the boundaries of the area mapped. Values for the dust color temperature in degrees and the optical depth in units of 10^{-3} are shown inside boxes on the 50μm and 100μm maps, respectively. The positions of near-infrared sources in the area are marked by crosses in addition to the position of the 130μm source found by Sargent et al. (1983).

Figure 6. - Far-infrared emission from the SR-3 region of the ρ Oph cloud. Contours of 100μm emission in units of janskys are shown in addition to the position of the young star SR-3 and the radio continuum source FG-11 (=Oph 11).
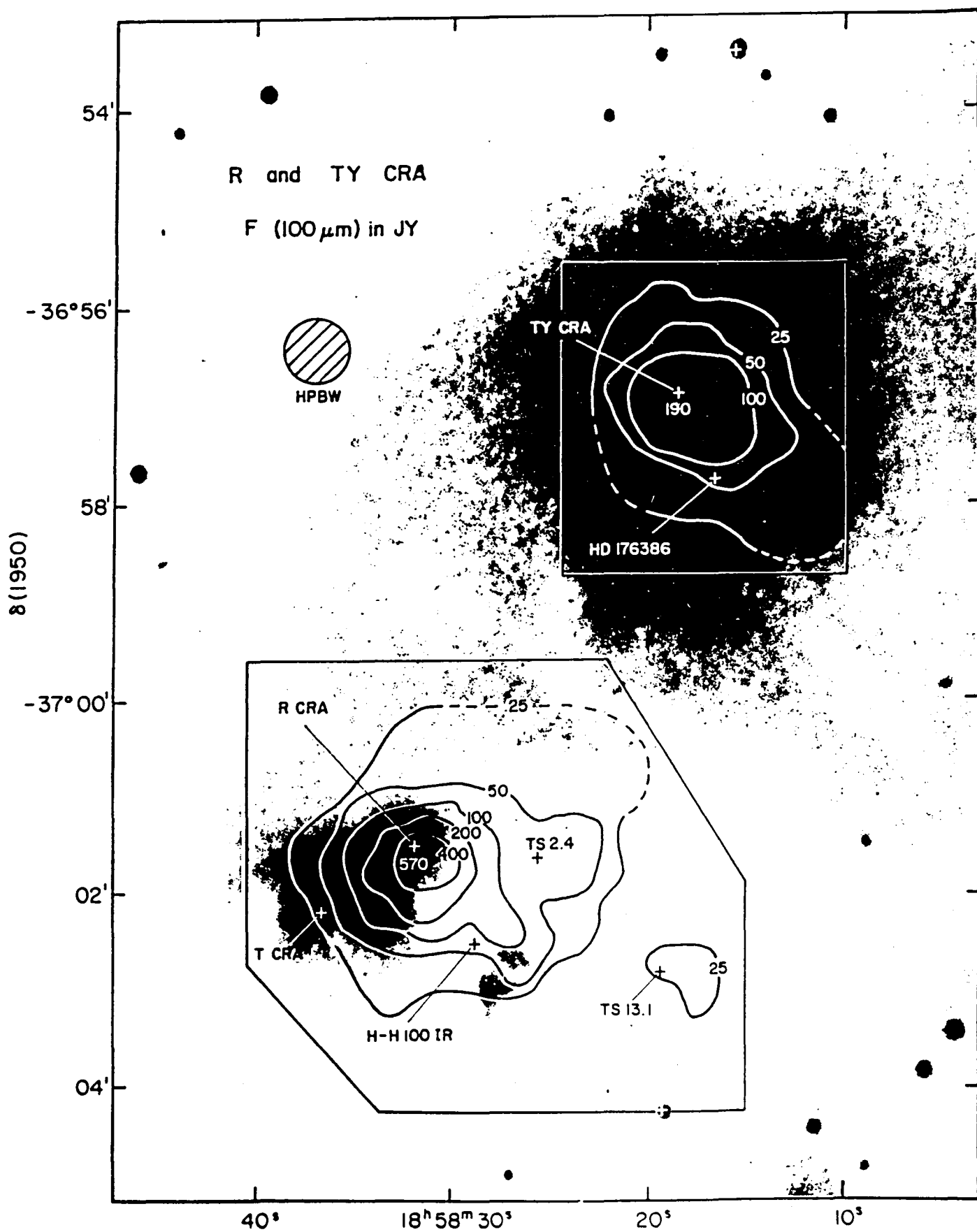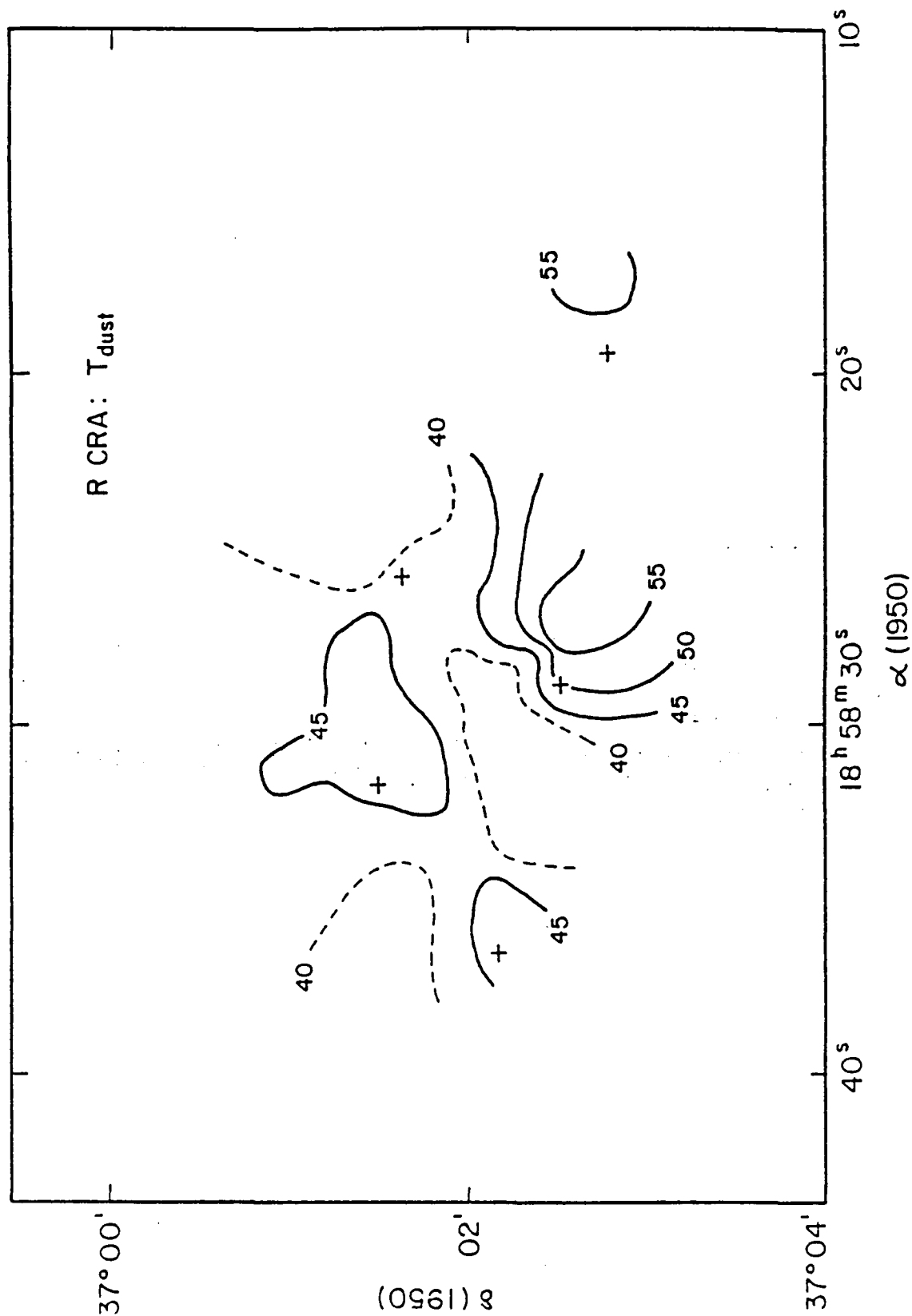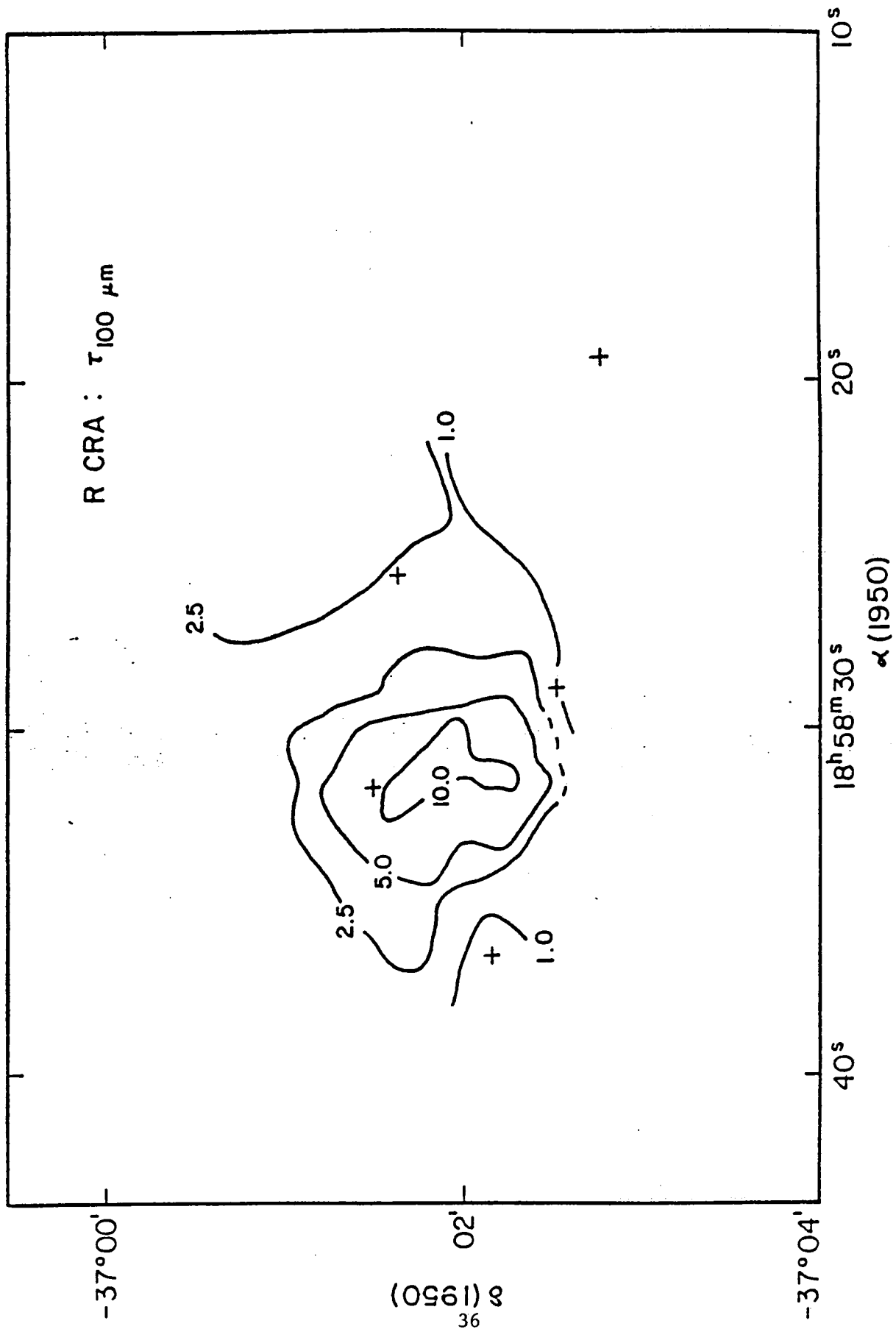
R and TY CRA

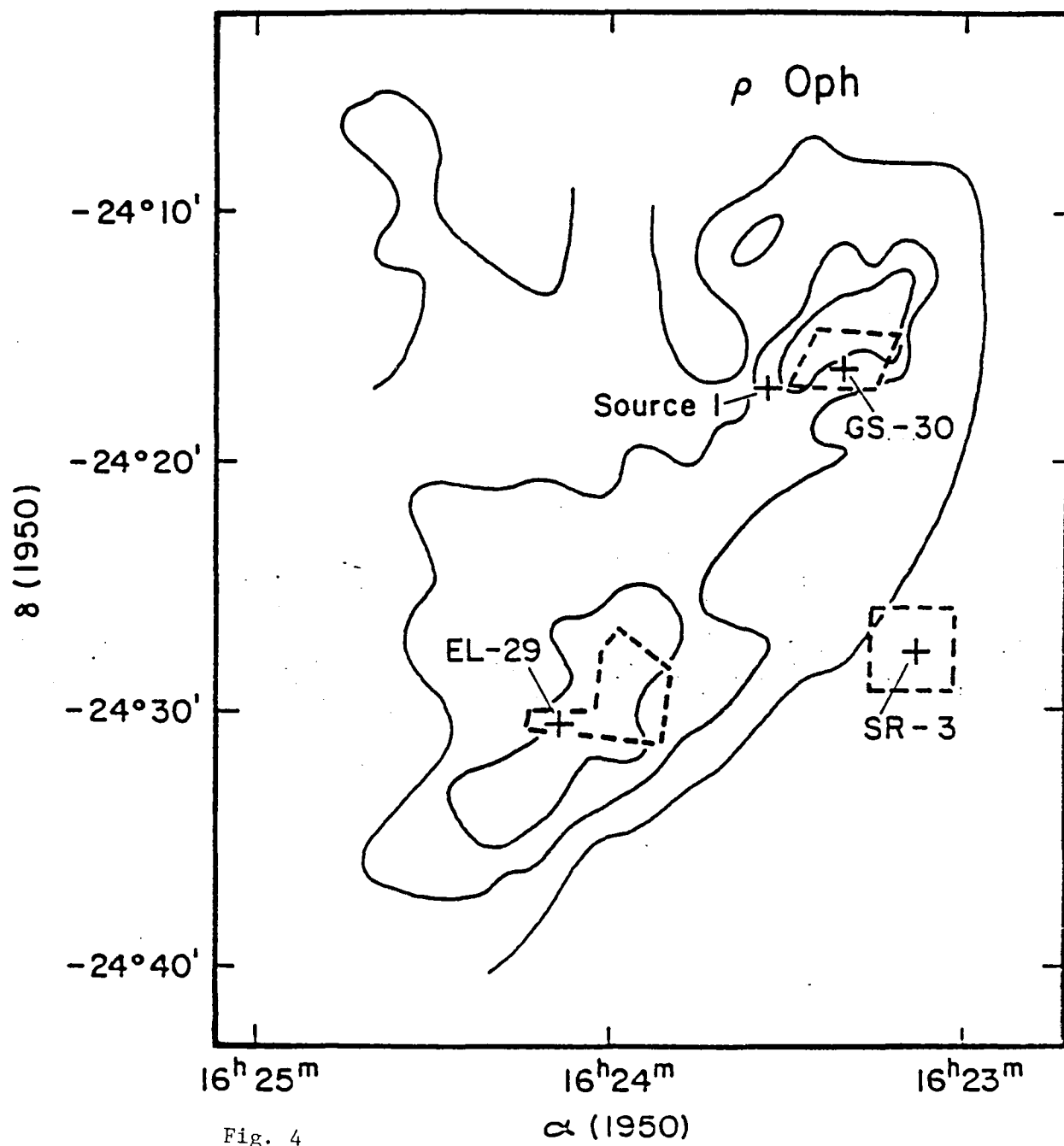F (50 μm) in JY

HPBW

TY CRA

50   25

+
145   100

+

HD 176386

R CRA

100   25

+
290   200

TS 2.4
+

+

50

T CRA

+

100

H-H 100 IR

+

TS 13.1

25

Fig. 1a

α (1950)

δ(1950)

54'

−36°56'

58'

−37°00'

02'

04'

40ˢ   18ʰ58ᵐ30ˢ   20ˢ   10ˢ

33

R and TY CRA

F (100 μm) in JY

HPBW

TY CRA

25

50

100

190

HD 176386

R CRA

25

50

100

200

400

570

TS 2.4

T CRA

25

H-H 100 IR

TS 13.1

-36°56'

-37°00'

54'

58'

02'

04'

δ(1950)

40ˢ   18ʰ58ᵐ30ˢ   20ˢ   10ˢ

α (1950)

Fig. 1b

34

R CRA: T_{dust}

α (1950)

δ (1950)

Fig. 2

35

Fig. 3

Fig. 4

37

Fig. 5

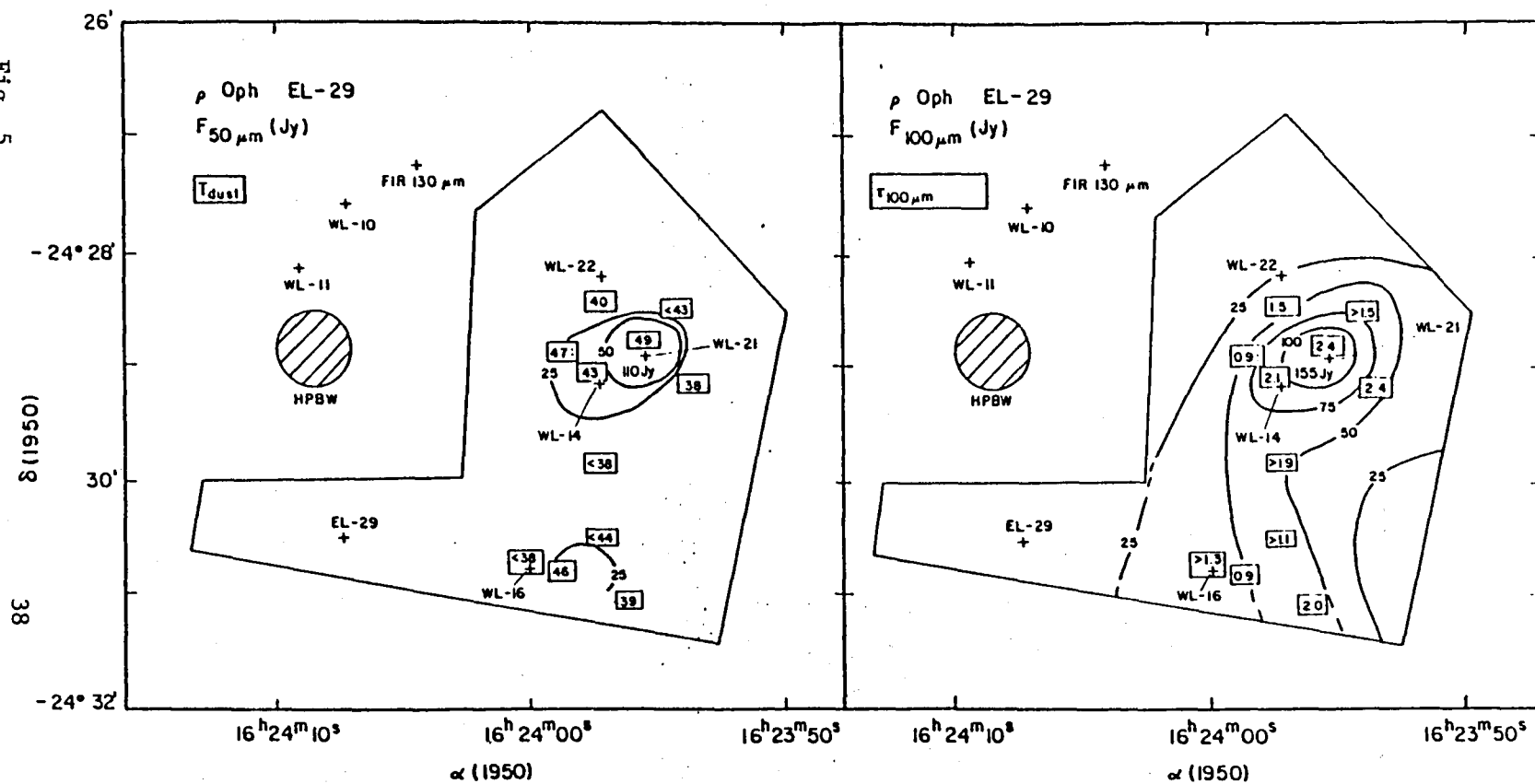β (1950)

38

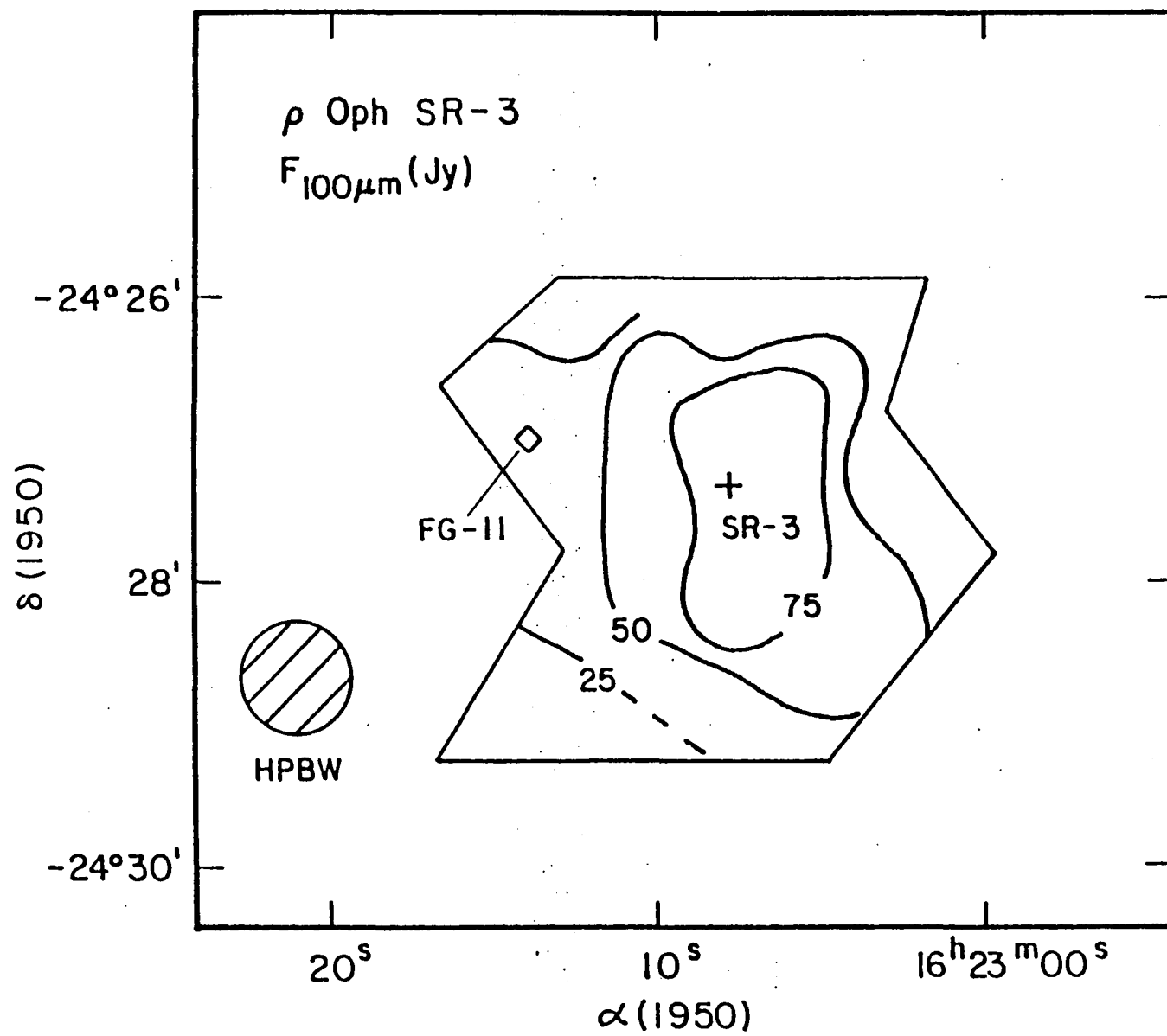ρ Oph SR-3
$F_{100\mu m}$ (Jy)

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16. Abstract

We have made multicolor far-infrared maps in two nearby dark clouds, R Coronae Austrinae and ρ Ophiuchi, in order to investigate the individual contribution of low-mass stars to the energetics and dynamics of the surrounding gas and dust. We have detected emission from cool dust associated with five low-mass stars in Cr A and four in ρ Oph; their far-infrared luminosities range from 2 $L_\odot$ up to 40 $L_\odot$. When an estimate of the bolometric luminosity was possible, it was found that typically more than 50% of the star's energy was radiated longward of 20 μm. Meaningful limits to the far-infrared luminosities of an additional eleven association members in Cr A and two in ρ Oph were also obtained. The dust optical depth surrounding the star R Cr A appears to be asymmetric and may control the dynamics of the surrounding molecular gas. The implications of our results for the cloud energetics and star formation efficiency in these two clouds are discussed.

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