A SUBMILLIMETER VIEW OF STAR FORMATION NEAR THE H II REGION KR 140

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ABSTRACT

We present the results of 450 and 850 μm continuum mapping of the H II region KR 140 using the Submillimeter Common-User Bolometer Array (SCUBA) instrument on the James Clerk Maxwell Telescope (JCMT). KR 140 is a small (5.7 pc diameter) H II region at a distance of 2.3 ± 0.3 kpc. Five of the six IRAS point sources near KR 140 were mapped in this study. Our analysis shows that two of these IRAS sources are embedded late B-type stars lying well outside the H II region, two are a part of the dust shell surrounding the H II region, and one is the combined emission from an ensemble of smaller sources unresolved by IRAS. We have discovered a number of relatively cold submillimeter sources not visible in the IRAS data, ranging in size from 0.2 to 0.7 pc and in mass from 0.5 to 130 $M_\odot$. The distribution of masses for all sources is well characterized by a power law $N(M) \propto M^{-\alpha}$ with $\alpha = 0.5 ± 0.04$, in agreement with the typical mass function for clumped structures of this scale in molecular clouds. Several of the submillimeter sources are found at the H II molecular gas interface and have probably been formed as the result of the expansion of the H II region. Many of the submillimeter sources we detect are gravitationally bound and most of these follow a mass-size relationship expected for objects in virial equilibrium with nonthermal pressure support. Upon the loss of nonthermal support, they could be sites of star formation. Along with the two B stars that we have identified as possible cluster members along with VES 735, we argue that five nearby highly reddened stars are in a pre-main-sequence stage of evolution. 

Subject headings: H II regions — ISM: clouds — stars: formation — submillimeter

1. INTRODUCTION

KR 140 (l = 133°425, b = 0°055; Kallas & Reich 1980) is a small (5.7 pc diameter) H II region located in the Perseus arm of the Galaxy at a distance of 2.3 ± 0.3 kpc (Kerton, Ballantyne, & Martin 1999). It is close to, but apparently isolated from, the W3/W4/W5 star formation complex. The region is ionized by VES 735, an O8.5 V(e) star (Kerton et al. 1999). It has been the subject of a recent multiwavelength study (Ballantyne, Kerton, & Martin 2000) utilizing the data set of the Canadian Galactic Plane Survey (CGPS; Taylor 1999).

Surrounding the H II region are six IRAS point sources (see Table 1 and Fig. 1; there is a faint source coincident with VES 735 as well). These are the brightest sources within several square degrees, suggestive of a region of enhanced star formation. In particular, infrared point sources located at the periphery of H II regions are of interest because they may be associated with star formation induced by the expansion of the H II region (e.g., Sugitani, Fukui, & Ogura 1991). Characterization of these sources is important in order to form a complete picture of the star formation history in that area.

Determining the true nature of these sources is hampered by the low resolution of the commonly available IRAS image products: 4' for the Infrared Sky Survey Atlas (ISSA, Wheelock et al. 1994), and 1' (after HIRES reprocessing) for the IRAS Galaxy Atlas (IGA, Cao et al. 1997) and Mid-Infrared Galaxy Atlas (MIGA, Kerton & Martin 2000). At these resolutions, a collection of objects can appear as a single point source. Moreover, areas of extended dust shells surrounding H II regions can be misidentified as point sources. While the IRAS colors can be used as a general guide to the nature of the source (e.g., Hughes & MacLeod 1989), they can sometimes be misleading (see §§ 4.1.1 and 4.1.4).

Moving from the infrared wavelengths observed by IRAS to the submillimeter yields two advantages. First, the current generation of submillimeter mapping bolometers have far better resolution than the IRAS data and sufficient sensitivity to allow star formation regions at the distance of KR 140 to be investigated. Second, the submillimeter observations are sensitive to colder dust not detected by IRAS and thus allow a more complete picture of the dust distribution. The observations we have obtained have both clarified the nature of the IRAS point sources surrounding KR 140 and have led to the discovery of new discrete sources not visible in the IRAS data.

In § 2, the observations are described. Data analysis techniques are outlined in § 3. In § 4 the results of the analysis are discussed. Finally, in § 5 the conclusions are presented.
2. OBSERVATIONS

The observations were obtained through the CANSERV service observing program at the James Clerk Maxwell Telescope (JCMT) using the Submillimeter Common-User Bolometer Array (SCUBA, Holland et al. 1999). Observations using SCUBA in its “jiggle-map” mode were obtained in 1997 December and observations in the larger scale “scan-mapping” mode were obtained in 1998 July.

SCUBA was used to acquire 450 and 850 µm data simultaneously. At these wavelengths, the beam can be approximated as a Gaussian with a FWHM of about 8" at 450 µm and 14.5" at 850 µm (Matthews 1999). The main-beam solid angle can then be calculated using the standard formula \( \Omega_{\text{MB}} = 1.133 \theta_{\text{FWHM}}^2 \) (Kraus 1966).

2.1. Jiggle Maps

Jiggle mapping, being closely related to pointed observations, allows users to make images of objects on the scale of the SCUBA field of view, ~2'. The northwest rim of KR 140 was selected as the target for the initial jiggle maps because the brightest infrared source (IRAS 02160 + 6057) is located there (see § 4.1.1 for the analysis of this source). Figure 2 shows the resulting jiggle maps (~2' x 2' in size). A chop throw of 2' with a position angle of 135° was used to obtain a reasonable sky estimate by avoiding bright infrared emission associated with the H II region. Beam sizes of 8.5' and 14.5' were achieved for this set of observations. The average normalized sky transparency during the observations was 0.81 at 850 µm and 0.34 at 450 µm. The expected noise equivalent flux density per pixel for the bolometer arrays is approximately 0.08 and 0.95 Jy Hz\(^{-0.5}\) at 850 and 450 µm, respectively (Holland et al. 1999). The measured noise levels in the maps are ~0.01 and ~0.08 Jy beam\(^{-1}\) at 850 and 450 µm, respectively, which is consistent with the expectations from sky transparency and bolometer characteristics. There are no strong point sources visible in either map. Instead, extended emission is quite evident in the 850 µm map (S/N ~ 4–8). The same region of emission is barely visible in the 450 µm map. However, convolving the image to the 850 µm resolution reduces the noise level to 0.05 Jy/(850 µm beam) and results in the extended emission being clearly visible (S/N ~ 3–7).

2.2. Scan Maps

Larger scale maps of KR 140 at 450/850 µm were obtained in 1998 July using the recently (at the time) developed “scan-mapping” observing mode, which allows larger areas to be mapped out by scanning the array across the sky. These maps included the jiggle-map region and enabled the study of the other IRAS point sources near KR 140.

The raw bolometer data were reduced using the standard SCUBA software (Holland et al. 1999) for flat-field and extinction corrections. The data were then further reduced and transformed into the final maps using a matrix inversion technique (Johnstone et al. 2000a) that effectively minimizes the difference between the individual chop measurements and the resulting map. One advantage of this technique compared to standard reductions is that the bolometer input may be weighted to account for variations in the quality of the measurement. Figure 3 shows maps created at this stage. Weiner filtering these maps (see, e.g., Press et al. 1992) removes the high (spatial) frequency noise associated with the individual chop measurements without affecting structure on scales equal to or larger than the JCMT beam. Further processing of the map proves useful. Because of the finite chop size, SCUBA maps have their low

Table 1: IRAS Point Sources Near KR 140

| IRAS            | \( \alpha_{2000} \) | \( \delta_{2000} \) | PSC Flux Density (Jy) |
|-----------------|---------------------|---------------------|-----------------------|
|                 |                     | 12 µm               | 25 µm | 60 µm | 100 µm | \( \log (L_{\text{IR}}/L_{\odot})^a\) |
| 02174+6052      | 02 21 08.5          | +61 06 00           | 0.88 ± 0.05          | 2.46 ± 0.1 | ≤32.0 | ≤127.9 | 2.8 |
| 02171+6058      | 02 20 51.4          | +61 12 01           | 0.36 ± 0.05          | 1.8 ± 0.1  | 11.6 ± 1 | 63.5 ± 11 | 2.5 |
| 02168+6052      | 02 20 33.0          | +61 05 56           | 2.2 ± 0.5            | 2.2 ± 0.5  | ≤32.0 | 127.9 ± 18 | 2.9 |
| 02160+6057      | 02 19 47.3          | +61 11 24           | 2.4 ± 0.4            | 3.0 ± 0.6  | 47.4 ± 9 | 215.1 ± 34 | 3.0 |
| 02157+6053      | 02 19 24.6          | +61 07 15           | 0.82 ± 0.13          | 1.31 ± 0.17 | 21.8 ± 3 | ≤215.1 | 2.9 |
| 02156+6048      | 02 19 21.2          | +60 59 45           | ≤0.27                | 0.36 ± 0.05 | 3.6 ± 0.6 | ≤44.14 | 2.2 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\(^a\) Calculated using Emerson (1988) technique and assuming a distance of 2300 pc.

\(^b\) Not in scanned region.
spatial frequency modes suppressed. Restoring these modes requires a large resampling which also amplifies any existing low-frequency noise. Furthermore, correlated errors introduced by variations in the sky opacity and the drift in the bolometer response produce excess residual low-frequency modes. Thus the large-scale structure in the map is less reliable, and in order to better visualize the small-scale features in the data, the low-frequency modes were entirely suppressed. This was achieved by convolving the filtered map with a $\sigma = 130''$ Gaussian beam (twice the largest chop throw) and then subtracting the convolved map from the original to remove any large-scale structure. Both images were then brought to a common $20''$ resolution to facilitate comparison. In Figure 4, the resultant maps are displayed. Noise levels are $\sim 0.01$ and $0.05$ Jy beam$^{-1}$ at 850 and 450 $\mu$m, respectively.

Figure 5 compares the derived 850 $\mu$m scan map for the region with other data obtained from the CGPS database (see Ballantyne et al. 2000 for details).

3. ANALYSIS

Our quantitative analysis focuses on the discrete sources detected in our maps. The next three subsections describe how the sources were detected and the subsequent measurements of flux, size, temperature, mass, and density for these objects. Interpretation of these results is presented in § 4.

3.1. Source Detection, Flux, and Size

Individual sources were identified through a combination of visual inspection of the maps and by using a two-dimensional version of the automated clump-finding algorithm CLUMPFIND (Williams, de Geus, & Blitz 1994) that separates objects along minimum flux surfaces within the map. In total, 22 sources were detected: 11 at both 850 and
450 μm, nine sources at only 850 μm, and two at only 450 μm. These last two sources may be visible at 850 μm, but it is hard to be certain because of the increased noise at that location caused by edge effects from processing. The flux-weighted centroid of each source was determined and used as a measure of the source position. We have assigned the acronym KMJB to these new submillimeter sources. Except for one of our sources (KMJB 1 = IRAS 02174 + 6052) detected near the edge of the map, there was no significant difference in the centroid positions between the two observed wavelengths (when applicable). For KMJB 1 we have reported the 850 μm centroid position because of the higher quality of the data. Table 2 lists the positions of the sources indicated by the white crosses in Figure 4.

To estimate the size of the sources, an azimuthally averaged Gaussian profile was fitted to each source using the image analysis program “kview” (Gooch 1995). To take into account the beam size, a simple convolution of a Gaussian source with a Gaussian beam was assumed, \( \theta_{\text{observed}}^2 = \theta_{\text{beam}}^2 + \theta_{\text{object}}^2 \) where \( \theta_{\text{beam}} = 20' \). Physical sizes \( (D_{\text{eff}} = \theta_{\text{object}} d) \) were calculated assuming a distance \( d = 2.3 \pm 0.3 \) kpc to KR 140 and tabulated in Table 2. The effective diameters range from 0.7 pc down to the resolution limit, 0.1–0.2 pc. This size scale of a few times 0.1 pc is typical for cores observed within molecular clouds (Evans 1999).

Flux measurements of the sources were obtained using the Imview software package. The uncertainty in each measurement is dominated by the uncertainty in choosing a correct background level. To quantify this uncertainty, we interactively selected three different bounding polygons for each source and used two different functional forms for the background (twisted plane and twisted quadratic) that were fit to the boundary points of the polygon. The six resulting flux measurements were then averaged together and the standard deviation of the measurements was calculated and used as a conservative uncertainty estimate. The results are summarized in Table 2.

3.2. Temperature

The spectral energy distribution (SED) of the dust emission was parameterized using what we call a “bluebody” spectrum after Dent, Matthews, & Ward-Thompson (1998)—a single-temperature Planck function with a \( v^2 \) dependence (\( \beta = 2 \)) for the dust emissivity. While this is clearly a gross oversimplification of the dust properties, Dent et al. (1998) and Gordon (1995) point out that the quantities derived from these simple fits are often consistent with results derived from a more complex, and often non-unique, analysis of the data.

For the isolated sources detected by IRAS, this SED was fit to the submillimeter and 100 and 60 μm IRAS data. However, for two sources, IRAS 02168 + 6052 and IRAS 02157 + 6053, this technique was not possible because of the significant beam size difference between IRAS and SCUBA: multiple submillimeter sources were detected within the larger IRAS beam. In these cases, and for sources without IRAS counterparts, the submillimeter photometry was used where possible to derive a 450/850 μm bluebody color temperature. This estimate can be rough for two reasons. For warmer dust, one is out on the Rayleigh-Jeans tail of the Planck function, which is relatively insensitive to temperature. The calculated temperature for colder dust is still very uncertain because of the relatively poor quality of the 450 μm data.

For sources detected at only a single wavelength, representative masses were calculated using a temperature of 20 K, as has been done in other single-wavelength analyses of millimeter and submillimeter data (e.g., Johnstone et al. 2000b; Motte, André, & Neri 1998). This temperature is a typical value observed for compact dust features found by submillimeter studies of the Orion molecular clouds (Chini et al. 1997; Lis et al. 1998).

3.3. Mass and Density

Table 2 summarizes the mass and density estimates. The mass calculation used the standard formulation of...
Hildebrand (1983) for an optically thin molecular cloud with a uniform temperature

\[ M = d^2 F_c C_v/B_c(T), \]  

where \( M \) is the total (dust and gas) cloud mass, \( d \) is the distance to the objects, \( F_c \) is the observed flux density, \( B_c(T) \) is the Planck function evaluated at dust temperature \( T \), and \( C_v \) is a factor combining the dust opacity \( (k_c) \) and the dust-to-gas mass ratio \( [C_v = M_d/(M_d + M_g)] \).

Table 3 summarizes various values of \( C_{850} \) derived from the literature. Most of the articles cited report the value of \( C_v \) at 1 mm, and the values shown have been calculated assuming that \( C_v \propto \nu^{-2} \) (\( \beta = 2 \) for the opacity). The canonical Hildebrand (1983) value is derived from the observations of the reflection nebula NGC 7023 (Hildebrand 1983). While this is empirically derived, ideally it should be applied to observed objects that have similar properties to the calibration object (Hildebrand 1983); this is probably not the case here, where we find lower temperatures and higher densities. The Draine & Lee (1984) value is appropriate for dust in the general ISM; however, it is known that properties of dust in dense clouds differ from those in the diffuse ISM (Kim, Martin, & Hendry 1994). The difference in optical properties arises from a combination of coagulation, leading to an increase in grain porosity, and the accretion of volatile grain mantles. The remaining values in the table are from various models that have attempted to deal directly with these processes. Various authors suggest different values ranging at 850 \( \mu \)m from 21 to 86 \( g \) cm\(^{-2}\), depending on the gas density and temperature. Since we do
not know the density in advance, we have adopted a value of $C_\nu = 50 \text{ g cm}^{-2}$ at 850 \text{ \textmu m} and, assuming a $\beta = 2$ dust emissivity, $C_\nu = 14 \text{ g cm}^{-2}$ at 450 \text{ \textmu m} for this investigation. This is in general agreement with the results of a recent detailed observational study of circumstellar material by van der Tak et al. (1999).

The masses derived in our study range from 0.7 to 130 $M_\odot$. They can be linearly scaled to another value of $C_\nu$ if desired. The uncertainty in the distance to KR 140 leads to a systematic 26% uncertainty in the derived masses. The average tabulated uncertainty in the flux density measurements is 17% at 850 \text{ \textmu m} and 28% at 450 \text{ \textmu m}. Uncertainties relating to the derived temperature are harder to quantify because of the simple bluebody model we have used and because the temperature enters into the mass derivation nonlinearly through the Planck function. Figure 6 shows the change in the mass derived from 850 \text{ \textmu m} flux measurements produced by varying the temperature. At lower temperatures, the derived mass is very sensitive to the temperature. For example, reducing the temperature by only 2 K will cause the derived mass to almost double. The same absolute change at 15 K causes an increase of only 28%, and at 25 K the change is only 12%. Based on these considerations, a total uncertainty (not including the uncertainties in $C_\nu$) for the derived masses of $\pm 50\%$ is an optimistic minimum value (see, e.g., Gordon 1995).

For each source, the cube of $D_{\text{eff}}$ was taken as a rough estimate of the volume and used to calculate a density. Considering both the lack of information about the true three-dimensional structure of the sources and the uncertainty...
tainty in the masses, these densities should be considered as only order of magnitude estimates.

4. DISCUSSION

In this section, we first consider what the new submillimeter observations can tell us about the nature of the IRAS point sources, drawing on the multifrequency data available. Discussion about the newly detected sources and the region as a whole follow in §§ 4.2, 4.3, and 4.4.

4.1. The Nature of the IRAS Sources

4.1.1. IRAS 02160 + 6057 = KMJB 15

The source IRAS 02160 + 6057 identified with the northwest dust arc has been the subject of two molecular line investigations. Wouterloot & Brand (1989) identified it as a potential star-forming area via its IRAS colors (see their paper for the exact selection criteria) and examined it (along with about 1300 other IRAS point sources) for CO emission. They found a CO feature in that direction at a velocity of $-49.7 \, \text{km s}^{-1}$ (LSR), which corresponds to CO in the associated background molecular cloud (Ballantyne et al. 2000), and assigned it the catalog number [WB89]417. This point source was not detected in a subsequent $H_2O$ line survey by Wouterloot, Brand, & Fiegle (1993).

A comparison of the scan maps with the IRAS images of KR 140 for this region provides a striking example of how much the morphology of the dust emission associated with an $H\alpha$ region can change with wavelength. In the IRAS images, this region (Fig. 5; Ballantyne et al. 2000, Fig. 2) is the dominant feature at all bands. In contrast, while the feature is visible in the submillimeter maps, it is certainly not the dominant one. This contrast indicates that the dust emission one sees from this area is from relatively hot dust with no additional cool components along the line of sight. This is consistent with the lack of significant clumped CO emission in this area, which could have indicated a region containing colder dust grains (see Fig. 5). The submillimeter and infrared emission are also aligned spatially, which is what we would expect if the submillimeter emission is just coming from the hot dust we see in the IRAS bands (see Fig. 2).

Morphologically, IRAS 02160 + 6057 appears to be part of the partial dust shell surrounding KR 140. This line of sight has one of the highest column densities of warm dust in the KR 140 $H\alpha$ region, so it is possible that a protostar could be forming there as a result of the expansion of the $H\alpha$ region. However, examination of the HIRES images shows no pointlike features in the dust arc and none are found in the new submillimeter observations.

The average mean flux density at 850 $\mu$m is $0.7 \pm 0.1$ Jy in the jiggle map and $1.0 \pm 0.3$ Jy in the scan map. For our calculations we have used $0.8 \pm 0.2$ Jy as the flux density at 850 $\mu$m. At 450 $\mu$m, we used the flux density from the jiggle maps, $4 \pm 1$ Jy, since the feature is not seen in the 450 $\mu$m scan maps. To construct an SED for the source, we measured infrared flux densities in the same region at 60 and 100 $\mu$m using HIRES images of KR 140. We found $F_{60} = 42 \pm 5$ Jy and $F_{100} = 101 \pm 8$ Jy. Combining this infrared data with the submillimeter data, we obtain a best-fit bluebody curve to the SED with $T = 27.5$ K (see Fig. 7). Comparison with the azimuthally averaged dust temperatures for KR 140 (see Fig. 5 in Ballantyne et al. 2000) shows that our derived temperature is consistent with dust being heated by the central star VES 735.

We conclude that IRAS 02160 + 6057 is not a point source but simply part of the dust shell associated with KR 140. This naturally explains the nondetection of $H_2O$ in the Wouterloot et al. (1993) study. Using equation (1), we find a mass of $9 \, M_\odot$ in this segment of the shell; the density there is $10^{2.9} \, \text{cm}^{-3}$, the lowest for all of the sources, and it would be even lower if allowance were made for limb brightening (line-of-sight distance greater than $D_{\text{eff}}$). The structure of this dust shell (morphology, density, temperature) was examined in detail in § 6 of Ballantyne et al. (2000).

4.1.2. IRAS 02168 + 6052 = KMJB 6, 7, and 8

At submillimeter wavelengths, the region around the single IRAS point source IRAS 02168 + 6052 contains three sources (see Fig. 8). The brightest submillimeter source in the area (KMJB 8) is well off the 60 $\mu$m centroid and is associated with the CO emission. It is also detectable at 450 $\mu$m. The resulting color temperature is $8 \pm 2$ K. This leads to a mass of $80 \, M_\odot$ and a density of $10^{4.1} \, \text{cm}^{-3}$.

![Fig. 6.—Effect of changing temperature on the mass derived using equation (1). Deviations in the derived mass from starting temperatures of 10 K (solid line), 15 K (dashed line), and 25 K (dash-dotted line) are shown. Horizontal solid lines indicate changes by a factor of 2. At lower temperatures, the derived mass is much more sensitive to temperature.](image1)

![Fig. 7.—SED for the sources KMJB 15, 3, and 1, constructed using cospatial HIRES and SCUBA data. Various symbols indicate measured flux densities and the lines indicate the best-fitting bluebody curves (fit to submillimeter far-infrared points only).](image2)
The three submillimeter sources are located within the material located behind KR 140 (Ballantyne et al. 2000).

0.08 Jy beam$^{-1}$

The gray-scale image is the 850 \mu m scan map linearly stretched from $-0.028$ to $0.092$ Jy beam$^{-1}$. Contours of HIRES 60 \mu m emission are overlaid (solid contours, 130–180 MJy sr$^{-1}$ at 10 MJy sr$^{-1}$ intervals). Integrated CO emission ($V_{LSR}$ = $-48.46$ to $-50.93$ km s$^{-1}$) is indicated by the dashed contours ($6$–$7.5$ K at 0.5 K intervals).

Fig. 9.—Close-up of the region surrounding IRAS 02157 + 6053. White crosses indicate KMJB 17 to 19 (left to right). The gray-scale image is the 850 \mu m scan map linearly stretched from $-0.028$ to $0.092$ Jy beam$^{-1}$. Contours of HIRES 60 \mu m emission are overlaid (solid contours, 130–180 MJy sr$^{-1}$ at 10 MJy sr$^{-1}$ intervals). Integrated CO emission ($V_{LSR}$ = $-48.46$ to $-50.93$ km s$^{-1}$) is indicated by the dashed contours ($6$–$7.5$ K at 0.5 K intervals).

The infrared colors of the infrared point source IRAS 02168 + 6052 indicate KMJB 6 to 8 (top to bottom). The star indicates the position of BIRS 128. The gray-scale image is the 850 \mu m scan map ($-0.04$ to 0.08 Jy beam$^{-1}$; linear stretch). Solid contours are HIRES 60 \mu m emission (130–220 MJy sr$^{-1}$ at 30 MJy sr$^{-1}$ intervals). Dashed contours show integrated CO ($J = 1$–$0$) emission [contours at 7, 9, and 11 K; integrated from $-45.5$ to $-47.2$ km s$^{-1}$ ($V_{LSR}$)]

KMJB 6 breaks up into three discrete objects at 450 \mu m. We calculated a 450/850 color temperature using the combined flux of the sources at 450 \mu m and the measured flux density at 850 \mu m. The derived dust temperature is 7 ± 2 K. The corresponding mass is about 55 $M_\odot$, and the overall density in this region is around 10$^4$ cm$^{-3}$. KMJB 6 and 8 are most likely cold molecular cores; however, the very cold temperatures derived for these objects should be confirmed with future spectral line observations.

KMJB 7 is located near the position of IRAS 02168 + 6052 and is most likely a dense knot of dust and gas within the dust shell surrounding KR 140. As in KMJB 15, the shell is the source of the prominent ridge of emission seen in all of the IRAS emission bands. Faint submillimeter emission from the dust shell is visible as a diffuse ridge running between KMJB 6 and KMJB 8. The temperature of dust within this shell was measured to be around 30 K (Ballantyne et al. 2000), which is consistent with the ratio of 60 and 100 \mu m to 850 \mu m fluxes. Using this dust temperature, we derive a mass of 1 $M_\odot$ for the knot that is KMJB 7.

4.1.3. $IRAS\,02157+6053 = KMJB\,17,\,18,\,and\,19$

This region (see Fig. 9) is associated with molecular material located behind KR 140 (Ballantyne et al. 2000). The three submillimeter sources are located within the larger CO envelope running roughly southwest to northeast, following the orientation of the 60 \mu m contours. The IRAS scan pattern for this region places the major axis of the detectors along a southwest to northeast direction, so the point source catalogue (PSC) fluxes are the contribution of the ensemble of sources in the area. The crowded nature of the region makes it difficult to use the IRAS flux densities to determine temperatures.

Nevertheless, KMJB 19 is well off the 60 \mu m centroid and, hence, relatively cold. It is detectable at 450 \mu m, leading to a 450/850 \mu m color temperature of 8 ± 2 K. The resulting mass (50 $M_\odot$) and density (10$^4.6$ cm$^{-3}$) are consistent with the object being a cold molecular core, like KMJB 8.

Mass estimates were obtained for KMJB 17 and 18 using the 850 \mu m flux and assuming a temperature of 20 K (which is roughly consistent with explaining the 60 \mu m emission). The mass and lower limits on the density (the sources are point sources) are both consistent with the objects being molecular cores. KMJB 18 is probably warmer than KMJB 17 given the facts that they are of comparable brightness at 850 \mu m and 18 is located closer to the centroid of the 60 \mu m emission. Taking this into account would accentuate the mass and density differences.

4.1.4. $IRAS\,02171+6058 = KMJB\,3$

This source is located to the northeast and outside of the KR 140 radio continuum emission. It seems likely that this relatively bright source is associated with molecular material at the distance of KR 140. On the basis of the SED, this would be a class I object (Andre, Ward-Thompson, & Barsony 1993). We proceed with the analysis assuming a distance of 2.3 kpc and show that this consistently explains a number of observational characteristics of the source.

The infrared colors of the infrared point source IRAS 02171 + 6058 are characteristic of an ultracompact H II (UC...
H II region based on the criteria of Wood & Churchwell (1989): \( \log \left[ F_\nu / F_\nu (12) \right] > 1.3 \) and \( \log \left[ F_\nu / F_\nu (25) \right] > 0.57 \). They also match the criteria of Hughes & MacLeod (1989) for an H II region: \( \log \left[ F_\nu / F_\nu (25) \right] > 0.23 \) and \( \log \left[ F_\nu / F_\nu (12) \right] > 0.40 \). It should be noted that the PSC 60 \( \mu m \) flux is of moderate quality (as defined in the IRAS Explanatory Supplement 1988), but it is in agreement with a flux density measurement we made from the HIRES images of the region. The source does not meet the additional flux criteria set by Hughes & MacLeod (1989), \( F_{100} \geq 80 \) Jy, which was designed to help filter out reflection nebulae and extragalactic objects. The source was included in a CS (2–1) survey by Bronfman, Nyman, & May (1996) and a methanol maser survey by Lyder & Galt (1997), but in both cases no detections were made.

Since this IRAS point source is detected at 12, 25, 60, 100, and 850 \( \mu m \), it is surprising that it is not seen at 450 \( \mu m \). We fit a single-temperature bluebody to the 850, 100, and 60 \( \mu m \) data points to obtain a temperature estimate of 27 K (see Fig. 7). This best fit predicts a flux density of 2.8 Jy at 450 \( \mu m \), which normally should be detectable, especially in the smoothed scan map. However, there is a large gradient in the 450 \( \mu m \) scan map around this position because of enhanced noise at the edge of the map, which may be making it hard to detect the source. The fitted SED yields a total mass of 5 \( M_\odot \). Using 0.23 pc as a typical length scale, the density is found to be \( 10^{4.1} \) cm\(^{-3} \).

Note that this dust is not heated by the exciting star of KR 140; there must be a source internal to the cloud. The total flux derived from the best-fit SED gives a luminosity of \( L = 10^{2.5} L_\odot \) assuming a distance of 2.3 kpc. This can be compared to the bolometric luminosity for main-sequence B5 V to B8 V stars, which ranges from \( L \sim 10^{3.0} \) to \( 10^{3.3} L_\odot \) (Lang 1992).

This is consistent with the lack of a corresponding point source in the 1420 MHz continuum image. The sensitivity of the 1420 MHz CGPS images is 0.2 mJy per 1’ beam (Taylor 1999). Ionization equilibrium can be used to relate this brightness level to the rate at which a star is emitting ionizing photons \( Q \). At the distance of KR 140, this brightness level corresponds to \( \log (Q) = 44.0 \) for a point source, so any embedded O or early B main-sequence stars (which have \( \log (Q) \geq 47 \); Kerton 2000) would certainly be detected in the CGPS radio data.

Chini, Krügel, & Wargau (1987) derived a relationship between the total luminosity (as seen reradiated by dust) of a compact H II region and the gas mass:

\[
L = (56 \pm 21) M_g^{0.93 \pm 0.06},
\]

where \( L \) and \( M_g \) are the luminosity and gas mass in solar units. The lowest luminosity and mass considered in their study was \( L = 10^{3.6} L_\odot \). Using an extrapolation of this relationship, the luminosity derived for this object above corresponds to a mass of \( 6^{+5}_{-2} M_\odot \). This is consistent with the independently determined measurement of the mass based on the submillimeter observations and indicates that the Chini et al. (1987) relationship may hold to lower \( L \) and \( M \) values than covered in their study of regions with ionizing stars.

4.1.5. IRAS 02174+6052 = KMJB 1

The IRAS PSC fluxes for this object are only of marginal use since they contain two upper limits at 60 and 100 \( \mu m \). To get more information, we examined HIRES images of the KR 140 region. At 100 \( \mu m \), the source is not visible against the very strong emission coming from the nearby dust shell of the H II region. We were able to measure flux densities at the other three IRAS bands. At 60 \( \mu m \), we obtained a flux density of \( 12 \pm 2 \) Jy. This is consistent with the upper limit reported in the PSC. Flux densities obtained at 12 and 25 \( \mu m \) agreed with the PSC values. Like KMJB 3, this has a class I SED. The object does have \( F_\nu (60)/F_\nu (25) \) and \( F_\nu (25)/F_\nu (12) \) colors in the range expected for an UC H II region as set by Hughes & MacLeod (1989), although the \( F_\nu (25)/F_\nu (12) \) color is at the lower limit. Wood & Churchwell (1989) used the \( F_\nu (60)/F_\nu (12) \) color and a higher limit to the \( F_\nu (25)/F_\nu (12) \) color to define UC H II regions, and this object does not match their criteria for an UC H II region. Therefore, from the IRAS colors alone it is unlikely that the object is an UC H II region.

We fit a single-temperature bluebody to the 850, 450, and 60 \( \mu m \) data points to obtain a temperature estimate of 22 K (see Fig. 7). The best-fit curve predicts a flux density of 68 Jy at 100 \( \mu m \), which is consistent with the upper limits reported in the PSC. This value is also below the 100 \( \mu m \) flux density limit set by Hughes & MacLeod (1989). Values from this best-fitting curve were then used to derive a total mass of 19 \( M_\odot \).

Using the SED, and assuming a distance of 2.3 kpc, we calculated a total luminosity of \( 10^{2.8} L_\odot \). As with KMJB 3, there is no corresponding 1420 MHz continuum source. This is what one would expect for a star with luminosity corresponding to B5 V. Using this luminosity and the mass-luminosity relation of Chini et al. (1987) (eq. [2]), we obtain a mass estimate of \( 14^{+1.4}_{-0.9} M_\odot \) in agreement with the value derived from the submillimeter observations.

4.2. Cumulative Clump Mass Function

The cumulative mass distribution for the sources detected in this study is shown in Figure 10. A least-squares fit to the data of a \( N(>M) = N_0 M^{-\alpha} \) power law resulted in \( \alpha = 0.49 \pm 0.04 \). Kramer et al. (1998) compiled results from a number of studies and showed that a power-law distribution with \( \alpha = 0.65 \pm 0.10 \) describes the clump mass dis-

![Fig. 10.—Mass function for the submillimeter sources in KR 140. The cumulative clump number is plotted against mass (jagged solid line). Overlaid are power-law distributions with different indices, 0.49 (best fit; lower solid line), 1.0 (dash-dotted line), and 1.5 (steeper like typical stellar IMF; dashed line). The 1.0 and 1.5 curves have been fixed to match the best-fit curve at the third most massive object.](image)
tribution in molecular clouds for clumps with masses ranging from $10^{-4}$ to several $10^4 M_\odot$. The two studies contained within Kramer et al. (1998) that are closest to our study with respect to the mass range covered agree within the stated uncertainties. Clumps in the mass range 0.6 to 160 $M_\odot$ surrounding the H II region S140 were found to follow an $\alpha = 0.65 \pm 0.18$ power law, while clumps in the mass range 0.8 to 50 $M_\odot$ surrounding the H II region NGC 1499 followed $\alpha = 0.59 \pm 0.18$. In Figure 11, we have plotted the cumulative mass distribution for the larger scale cores (0.05 to 0.3 pc in size) in $\rho$ Oph using the data from Motte et al. (1998). These objects also follow a power-law relationship similar to what we find in KR 140, $\alpha = 0.6 \pm 0.08$.

In contrast, millimeter and submillimeter studies of the nearby $\rho$ Oph region have shown that the mass distribution of the smaller scale fragments (2400 to 5000 AU in size) contained within the cores appears to mimic the stellar initial mass function (IMF; Motte et al. 1998; Johnstone et al. 2000b). Testi & Sargent (1998) used the Owens Valley Radio Observatory (OVRO) interferometer to study similarly sized objects in the more distant Serpens molecular core. They also found a steep power-law distribution consistent with the stellar IMF, $\alpha = 1.1$. The key similarities in these three studies are that they probed sufficiently small linear scales (0.01–0.02 pc) and that a sufficient range in masses was observed to detect a steepening of the mass function above 0.5 $M_\odot$. These both appear to be important requirements. Of the studies listed by Kramer et al. (1998), only the study of the nearby ($d = 65$ pc) quiescent cloud L1457 has sufficiently high angular resolution to be comparable to the $\rho$ Oph and Serpens studies. However, the highest mass clump detected is only 0.2 $M_\odot$, so all of the detected objects lie on a shallow part of the mass distribution function ($\alpha = 0.77 \pm 0.3$). One can interpret this as either being consistent with the low mass portion of the stellar IMF or being consistent with a global power law for molecular cloud structure. Our study of KR 140 has sufficient overlap in mass coverage to probe the connection between cloud structure and the stellar IMF, but the larger scale objects that we detect at our relatively low resolution follow the well-established $\alpha \sim 0.5$ power law seen for structures within giant molecular clouds and for the clouds themselves (Williams, Blitz, & McKee 2000).

4.3. Nature of the Sources

How might the submillimeter sources relate to future star formation? The Bonnor-Ebert (BE) critical mass (Ebert 1955; Bonnor 1956) is given by

$$M_{BE} = \frac{2.4 R a^2}{G}.$$ \hspace{1cm} (3)

Using $R = D_{eff}/2$ and the standard formula for the isothermal sound speed ($a_s$), we can write

$$M_{BE} = 0.99 \left( \frac{D_{eff}}{pc} \right) \left( \frac{T_{gas}}{K} \right).$$ \hspace{1cm} (4)

To derive $M_{BE}$ from our data, we have assumed that $T_{gas} = T_{dust}$ since our CO data are of too low a resolution to give information about the gas dynamics or temperatures within specific clumps directly.

Figure 12 plots the derived submillimeter mass $M$ versus the corresponding $M_{BE}$ for each clump. Clumps with $M < M_{BE}$ are not gravitationally bound or unstable. Prominent among these are the sources we have identified as parts of the dust shell, 7 and 15; their existence depends on the pressure of the H II region and its dynamical expansion. All of the other “stable” sources (2, 10, 13, 16, 20, 21, 22) would also be pressure supported or transient. There are clumps that are detected at only one submillimeter wavelength and have no clear IRAS counterparts. For these, we have assumed $T = 20$ K. Adopting a lower $T$ would have led to a lower $M_{BE}$ and higher $M$ (Fig. 6), moving the clumps toward the region of instability. However, unless we adopted a substantially lower temperature ($\sim 7$ K), the clumps would remain in the stable region.

Clumps with $M > M_{BE}$ are massive enough to collapse under the effect of self-gravity. Excluding the clumps that have already formed stars (KMJB 1 and 3), we find eleven, including the aligned sources 11, 12, and 14, and 4, 5, 6, 8, 9, and 19. This result derives from the low temperature ($T < 13$ K) we have measured for these sources. KMJB 17

![Diagram](image-url)

**Figure 11.**—Same as Fig. 10 but for the large cores in $\rho$ Oph (Motte et al. 1998). Distributions with power-law indices 0.60 (best fit; solid lower line), 1.0 (dash-dotted line), and 1.5 (dashed line) are shown.
and 18 are also barely over the instability line. For these, we have assumed $T = 20$ K. Adopting a lower $T$ would move the clumps farther into the region of instability.

By combining the available observational data on molecular clouds, Larson (1981) showed that over a wide range in sizes gravitationally bound molecular clumps follow the relationships $\sigma \propto D_{II}^{0.4}$ and $\sigma \propto M_{II}^{0.2}$ where $\sigma$ is the velocity dispersion, $D$ is the largest linear dimension (in pc), and $M$ is the mass of the object; thus $M \propto D^2$. This is equivalent to saying that the objects have a constant column density. Figure 13 shows $M/D^2$ (or equivalently $A_V$) versus $D$. The bimodal distribution of the sources is apparent. All of the unbound sources, with $M < M_{BE}$, have a very low column density below $A_V \sim 2$. The average column density, $nD = 2.1 \times 10^{22}$ cm$^{-2}$, for all of the sources with $M > M_{BE}$ (except the outlying sources 5 and 12) is twice what would be deduced from Larson (1981). This may be because of our using a different tracer and, thus, a different length and mass scale. Myers (1983) showed that this result can be interpreted as virial equilibrium with nonthermal pressure support from turbulent gas motions.

As discussed by Evans (1999), star formation appears to occur only in cores with $N_H > 8 \times 10^{21}$ cm$^{-2}$ ($A_V \sim 4$). Theoretically, this is expected because of the sharp decrease in the ionization fraction within such cores, which, in turn, allows ambipolar diffusion to proceed at a faster rate (McKee 1989, 1999). In clouds where both magnetic and turbulent support are important, one still needs a low ionization fraction to allow collapse to proceed after the loss of turbulent support (Shu et al. 1999). The sharp decrease in the ionization fraction at $A_V \sim 4$ may also be related directly to the loss of turbulent magnetohydrodynamic support because of the reduction in ion-neutral coupling (Ruffé et al. 1998). Onishi et al. (1998) studied 40 molecular cloud cores in Taurus in C$^{18}$O and found that all of the cores with $N_H > 8 \times 10^{21}$ cm$^{-2}$ were associated with H$^{13}$CO$^-$ emission (which they interpret as being protostellar condensations) and/or cold IRAS sources. In our sample of sources around KR 140, only KMJB 1 and KMJB 3 have unambiguous evidence for star formation having occurred and both are high column-density sources. It would be interesting to investigate the other observed sources for evidence of star formation via higher resolution observations of dense gas tracers. KMJB 12, lying well above the line, is an interesting object for further study because of its large mass and location on the ridge boundary discussed below. Among the clumps with $M > M_{BE}$, KMJB 5 has an unusually low column density.

### 4.4. Clump and Star Formation in the KR 140 Region

Are the clumps just structure in the cloud that preexisted the formation of VES 735 and KR 140, or is there ongoing evolution? The three high-density sources 11, 12, and 14 are of particular interest. Their cold temperature, small size, and high density suggest that they are cold molecular cores. They are aligned along the edge of a CO cloud with $V_{LSR} = -46.0$ km s$^{-1}$ (Fig. 5) and also parallel to, but outside of, a ridge which appears in a high-resolution H$\alpha$ map (Kerton et al. 1999). These sources are probably not foreground to the H II region even with their large column densities they do not produce distinctive silhouettes on the H$\alpha$ map. This and the striking alignment suggest that a causal relationship exists between the formation of these clumps at this location and the expansion of the KR 140 H II region. We have estimated that the age of the KR 140 H II region is about $2 \times 10^6$ yr (Ballantyne et al. 2000), which is certainly sufficient time for a layer of gas to be swept up and become gravitationally unstable even for the low-density molecular cloud associated with KR 140. Other cold submillimeter sources (e.g., 6, 8, and 19) lie at the edge of the H II region (see Fig. 5) and their location is also suggestive of a link between the expansion of the H II region and their formation.

This mix of clumps, some that appear to have formed in particular locations because of the action of other stars, some that appear to have formed spontaneously in various regions throughout a larger cloud, and some that are forming stars (this would include the clump that formed VES 735), is not unlike what is seen in other star-forming regions (e.g., for ρ Oph, see the discussion in § 6.3 of Motte et al. 1998).

It would be expected that a cluster would be forming near VES 735, so it is interesting to examine the stellar (or protostellar) content. Our analysis has shown that there are no UC H II regions in the vicinity of KR 140, so VES 735 appears to be the only O star to have formed in the region. From Ballantyne et al. (2000), the total mass of the molecular cloud associated with KR 140 is estimated to be about $5 \times 10^3$ $M_\odot$ O star formation in clouds with a cloud mass of below $10^4$ $M_\odot$ is considered rare (Elmegreen 1985; Williams & McKee 1997), so it would actually have been very unusual to find yet another O star in the vicinity of VES 735.

KMJB 1 and KMJB 3 contain embedded objects with the luminosity of main-sequence B stars. Their position in the molecular cloud suggests no causal relationship with the H II region; instead, they could have formed in the original molecular cloud along with VES 735. The evolution time for a 4–6 $M_\odot$ star ($\sim$ B5 V to B8 V) to the main sequence ranges from 0.4 to $8.4 \times 10^5$ yr (Palla & Stahler 1993). Ballantyne et al. (2000) estimate that VES 735 and KR 140 are 1–2 $\times 10^6$ yr old, ample time for these stars to have formed and evolved to their present state; in fact, their evolution is probably relatively delayed rather than coeval.

Close to KR 140, there are five bright infrared stars (BIRS 128 to 132; Elmegreen 1980; see Fig. 14 in Ballantyne et al. 2000) with very red $m_K - m_I$ colors (4.3 to 6.7; $m$ and $M$ in this paragraph refer to apparent and absolute magnitudes, respectively). BIRS 128 is just outside of KMJB...
7 (see Fig. 8), BIRS 131 and 132 are near KMJB 16, and BIRS 129 and 130 are seen projected against the H II region, north of VES 735. However, while Elmegreen (1980) considers the stars as possibly "embedded," there is no significant submillimeter (or infrared) emission coincident with their positions, which puts a limit $A_V \sim 1$ or $E_{R-\gamma} \sim 0.27$ on associated clumped dust. The general foreground extinction seen to affect VES 735 and KR 140 amounts to $A_V \sim 6$ (Kerton et al. 1999) or $E_{R-\gamma} \sim 1.6$. They are possibly more highly extinguished by the molecular material that lies behind KR 140 ($V = -46$ to $-54$ km s$^{-1}$). Using the CO and H I data cubes and gas-to-dust conversion factors from Digel et al. (1996) or Strong & Mattok (1996) $E_{R-\gamma} \sim 3$ seems possible. Nevertheless, the stars probably have intrinsically redder colors than early main-sequence stars ($M_R - M_J \sim 0$). They are not ionizing stars. They could be pre-main-sequence stars or evolved giants, though the latter seems less likely since these stars would have had lower mass than VES 735 yet have evolved sooner. Additional photometry at $J$, $H$, and $K$, when available from 2MASS, should help to clarify both this and the overall stellar content of the recently formed cluster.

5. CONCLUSIONS

Based on the analysis of the SCUBA 450 and 850 $\mu$m maps of the KR 140 region we conclude that:

1. The putative UC H II region IRAS 02160+6057 is actually part of the partial dust shell surrounding KR 140, to the northwest. IRAS 02168+6052 is also part of the partial dust shell, to the east.

2. The infrared point source IRAS 02157+6053 appears in the submillimeter as a number of discrete sources or clumps, some colder than the IRAS source.

3. The cumulative mass distribution of clumps follows a $N(>M) = N_o M^{-\xi}$ curve with $\xi = 0.49 \pm 0.04$. This is consistent with studies of clumps of this scale in other molecular clouds. At the distance of KR 140, we lack sufficient resolution to study the mass distribution of even smaller cores, such as has been done for the more nearby star-forming regions of $\rho$ Oph (Motte et al. 1998; Johnstone et al. 2000b) and Serpens (Testi & Sargent 1998). The use of current (OVRO) and future (Submillimeter Array [SMA], Atacama Large Millimeter Array [ALMA]) millimeter arrays is needed to build up a significant sample of star-forming regions and to probe different star-forming environments at sufficient resolution to probe the possible relationship between observed structures in molecular clouds and the observed stellar IMF.

4. The evolution of some of the clumps appears to have been affected by the KR 140 H II region. Three molecular cloud cores are aligned along the edge of a larger CO structure at the interface between the molecular and ionized gas. The alignment strongly suggests a causal relationship to the expansion of the H II region.

5. Many of the submillimeter sources we detect are gravitationally bound. Most of the sources with $M > M_{BE}$ follow a mass-size relationship expected for objects in virial equilibrium with nonthermal support. Upon the loss of nonthermal support, they could be sites of star formation.

6. A cluster of stars is probably forming along with VES 735. IRAS 02171+6058, previously thought to be an UC H II region on the basis of its PSC colors, has the luminosity of a lower mass embedded B star (later than B5 V). IRAS 02174+6052 is also an embedded star with similar luminosity (~B5 V). Both objects appear to have formed spontaneously in the molecular material outside KR 140. Their evolution is somewhat delayed relative to the evolution of the O star VES 735 and its H II region. We show that five BIRS stars are possibly pre-main-sequence stars. More infrared photometry, such as will be available from 2MASS, is required to delineate the cluster properties.

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