NEW MEMBERS OF THE INFRARED CLUSTER IN THE ORION MOLECULAR CLOUD

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ABSTRACT

Near-infrared high-resolution scans (3″.5) of the core of the Orion Molecular Cloud (#1) have revealed 26 sources. Eleven of these are identified with faint visible stars. The remainder are thought to be highly reddened stars embedded in the molecular cloud and include at least two of the previously known infrared cluster members. Comparison of the distribution of infrared and visible stars on the plane of the sky and in an infrared color-magnitude diagram shows that the obscured infrared sources form a separate cluster of stars. The newly discovered sources appear to fall into two categories: (1) optically identified stars probably on the front surface of the cloud and associated with the Trapezium cluster; and (2) unidentified infrared stars probably associated with the molecular cloud and the embedded infrared cluster. It is plausible that the newly discovered infrared sources in the OMC-1 region are stars less massive than the previously known members and younger than visible stars of similar mass in the Orion Association.

I. INTRODUCTION

The Orion complex, at a distance of 500 pc, is one of the most well-studied regions of star formation. Prominent there at visual wavelengths is a large OB association, Orion OB1, which consists of four subgroups of different ages elongated parallel to the galactic plane (Blaauw 1964; Warren and Hesser 1978). Stars of spectral types O–M have been identified in the association, with a pre-main-sequence (PMS) turnup occurring at type ~A0 (Walker 1969; Cohen and Kuhi 1979). The youngest subgroup is the Orion Nebula Cluster, Orion OB1d, the age of which is on the order of 10^6 yr (Warren and Hesser 1978). The surface density of stars in the Orion Nebula Cluster peaks strongly at the Trapezium, a group of bright OB stars which power the optical nebula. Warren and Hesser (1978) conclude that these stars are somewhat younger than less massive cluster members.

About one arcminute north of the Trapezium is a group of bright infrared sources. This group may be the newest cluster of massive stars to be formed in Orion. It consists of several luminous discrete sources (Rieke, Low, and Kleinmann 1973; Wynn-Wiliams and Becklin 1974; Downes *et al.* 1981), including the well-known Becklin-Neugebauer source (hereafter referred to as BN; Becklin and Neugebauer 1967), and extended infrared emission, the Kleinmann-Low nebula (hereafter referred to as KL; Keinmann and Low 1967). The cluster lies at the density peak of the massive Orion Molecular Cloud #1, OMC-1 (Zuckerman and Palmer 1974, and references therein), and the total luminosity of the infrared complex is $\gtrsim 10^5\ L_\odot$ (Werner *et al.* 1976). There is little information on the size and population of the OMC-1 cluster; only objects of high luminosity ($L \geqslant 10^3\ L_\odot$) have so far been identified by their emission in the 5–20-μm region, and some of these may not be stellar (Downes *et al.* 1981). In this paper we present the results of a new infrared (1.6–3.5 μm) search for additional members of the cluster. Lying relatively close to us, the OMC-1 star-formation region represents the best opportunity to detect lower-mass star formation associated with O and B stars.

II. OBSERVATIONS

The data were obtained with the 3.8-m United Kingdom Infrared Telescope on Mauna Kea. In February 1980, a region 37″ × 40″ (R.A. × Dec.) centered on BN was scanned with a 3″.5 beam at 1.6, 2.2, and 3.5 μm, using a focal plane chopper at the $f/9$ focus. A small beam throw of 3″.5 in declination was used in order to suppress background extended emission and thus enhance the detection of point sources. The scans were made with a step size of one-half beamwidth in the north-south direction, and the position relative to BN was checked every four scans: the error in position was always less than 0″.5. Magnitudes of the sources were calibrated relative to BS 4550 (assumed magnitudes 4.44, 4.38, and 4.33 at 1.6, 2.2, and 3.5μm, respectively). The 2σ limiting magnitudes of the scans are 12.9, 11.8, and 9.2 at 1.6, 2.2, and 3.5μm, respectively. At 2.2 μm, these limits are principally due to confusion with background radiation rather than sensitivity. The positions of the sources were determined relative to BN and are accurate to 2″.

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TABLE I. Positions and magnitudes.

Source	Coordinates[a] R.A.	Dec.	Magnitudes[b] 1.6 μm	2.2 μm	3.5 μm	V[c]	Name[d]
a	$5^h32^m45^s.66$	$-5°24'09''.4$	11.1	11.2	> 9.2	18	
b	45.75	15.4	11.0	10.8	9.0 ± 0.4	18	
c	45.89	20.3	11.8	11.6	> 9.2	> 18	
d	46.07	31.7	> 12.5	11.4	8.3	> 18	
e	46.14	13.5	10.5	10.3	9.2 ± 0.4	16	
f	46.31	26.9	> 12.4	11.3 ± 0.4[e]	8.1[e]	> 18	
g	46.35	16.6	10.1	9.7	8.6	16	
h	46.36	01.2	9.3	9.0	7.8	13.6	π 1819
i	46.43	24.6	12.1	9.8	6.4	> 18	IRc3
j	46.55	32.9	> 12.3	11.6 ± 0.4[e]	7.8[e]	> 18	
k	46.63	30.2	10.0	9.6	7.1	16	
BN[f]	46.70	17.0	9.2	5.1	1.4	> 18	IRc1
l	46.85	13.7	11.6	9.8[e]	7.7 ± 0.4[e]	> 18	
m	46.91	23'58.1	12.9 ± 0.4	11.8	> 8.8	> 18	
n	46.91	24'26.9	> 12.5	10.1	6.5	> 18	IRc4(?)
p	46.91	30.5	12.4	11.2[e]	> 8.8	> 18	
q	47.03	10.1	12.0 ± 0.4	9.9 ± 0.4	7.6 ± 0.4	> 18	
r	47.03	24.6	> 12.5	> 11.8	7.1	> 18	IRc2(?)
s	47.15	00.5	12.6	> 11.8	> 8.8	> 18	
t	47.23	27.5	9.5	9.0	8.9[e]	13.8	π 1839
u	47.39	25.7	11.7	10.6	7.0	17	
v	47.45	33.0	9.3	8.9	7.8	13.1	π 1840
w	47.75	24.5	> 12.5[e]	11.3	8.4 ± 0.4[e]	> 18	
x	47.75	30.5	12.8 ± 0.4	11.0	> 8.8	> 18	
y	47.88	09.2	8.8	8.1	g	13	
z	47.87	19.1	10.2	9.8	g	14/17(?)	

[a] The coordinates are for epoch 1950.0.
[b] Infrared magnitude errors are ≲ 0.3 unless otherwise noted; upper limits are 2σ.
[c] The V data are from Strand (1958) and Strand and Teska (1958).
[d] The π numbers refer to stars from the list of Parenago (1954).
[e] Source is confused with brighter neighboring source or extended emission.
[f] The position for BN is from Becklin and Neugebauer (1968).
[g] Source is at edge of map.

In November 1980, a larger area (133″ × 112″; R.A. × Dec.) including the OMC-1 cluster was scanned at 2.2 μm with a 5″ beam and a 10″ throw in right ascension using the chopping secondary at the $f/35$ focus. The sensitivity of these scans is the same as that of the 3″.5-resolution 2.2-μm scans.

III. RESULTS AND ANALYSIS

a) The Scans

Within the 0.4 arcmin^2 covered by the 3″.5 scans, 26 discrete sources, including BN, are evident; these are listed in Table I. Also listed are V magnitudes for 11 of the sources for which positional coincidence indicates a probable identification with visible stars (Strand 1958). Figure 1 shows the sources superimposed on a map of 20-μm flux distribution in the BNKL region (Downes *et al.* 1981). At 2.2 and 3.5 μm the brightest of the new sources are 15 and 100 times fainter than BN, respectively.

The errors in the magnitudes depend on surrounding extended emission and the proximity of other sources as well as brightness. We assume errors of 0.3 mag or less, unless otherwise noted in Table I. The precision of the infrared positions was found to be 1″.2 rms by comparing them with the positions of several sources identified with optical stars. The optical positions are from Strand (1958).

Sources were considered unresolved if the profile was no wider than that of the standard in the scan direction, and the source did not appear in more than three adjacent scans. By these criteria, 23 of the sources in Table I are unresolved. Of the remaining three sources, f and j are confused with a brighter source at the wavelengths at which they were detected, and thus their sizes cannot be determined. Source q is definitely extended.

It is important to realize that the results of the present search are confusion limited; there are 26 sources within a search area of 120 resolution elements. This fact has several consequences which should be kept in mind when considering the results and their analysis: (1) Some of the sources may be multiple, (2) Identification with previously known cluster members cannot be established definitely from position alone, (3) Local enhancements in the extended emission may be mistaken for discrete objects.

Figure 2 shows the spatial distribution of 2.2-μm sources in the Trapezium-BNKL area as determined from the 5″ scans. Also shown are the point sources found in a 2.2-μm map of a region to the south of BNKL made by Becklin *et al.* (1976). The sensitivity of this second map is almost identical to ours; the resolution is slightly lower at 7″.5. A close agreement between the two maps in the overlap region shows that the two maps can be combined to investigate the distribution of visible and

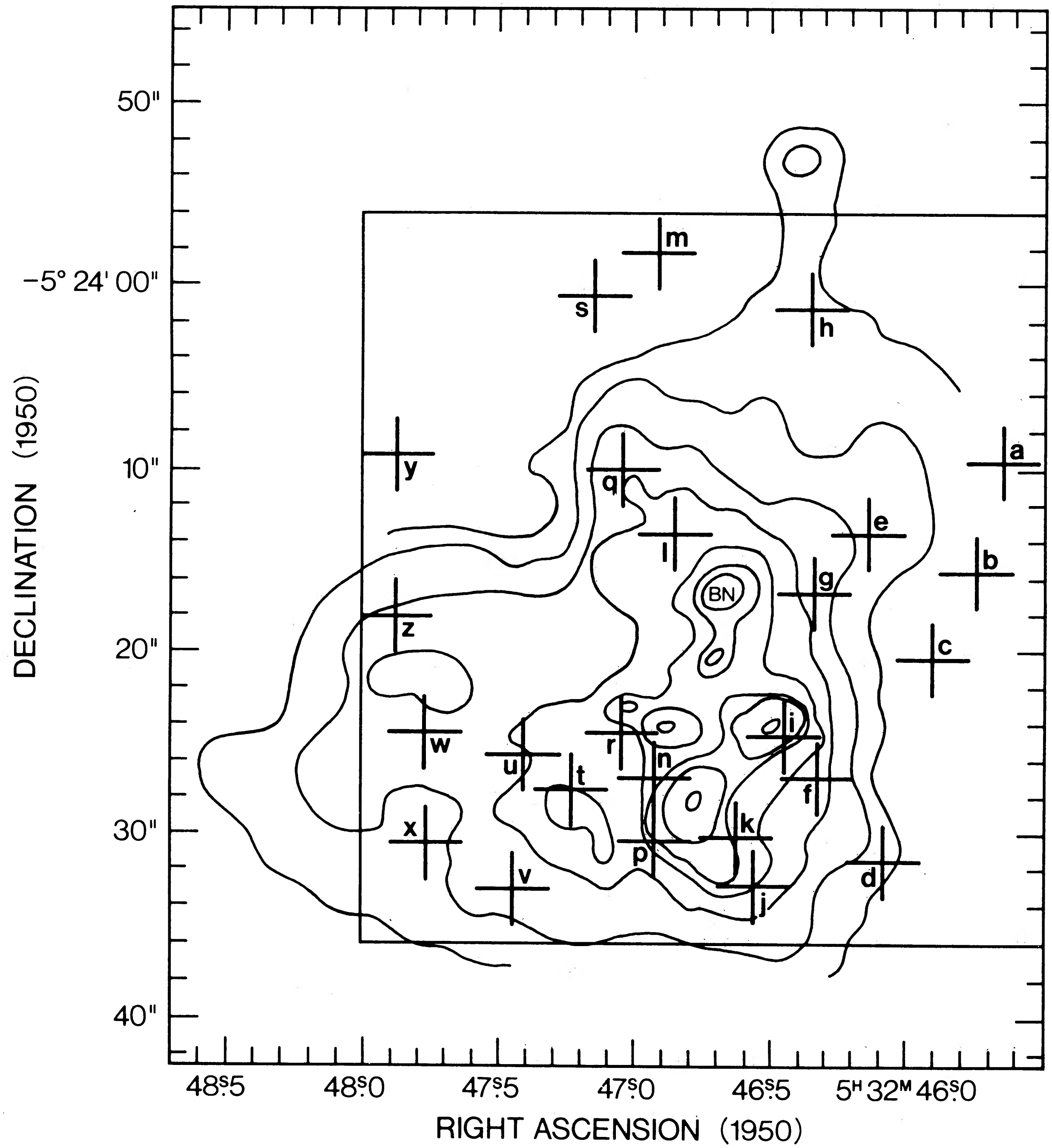

FIG. 1. A map of the infrared cluster region showing the location of the newly discovered 1.6–3.5-μm sources. The extent of the 3".5 scans is indicated by the inner boundary. The solid contours indicate the 20-μm flux [Downes *et al.* (1981), adapted from their Fig. 1]. The size of the crosses identifying the 1.6–3.5-μm sources reflects their positional uncertainty relative to the 20-μm map.

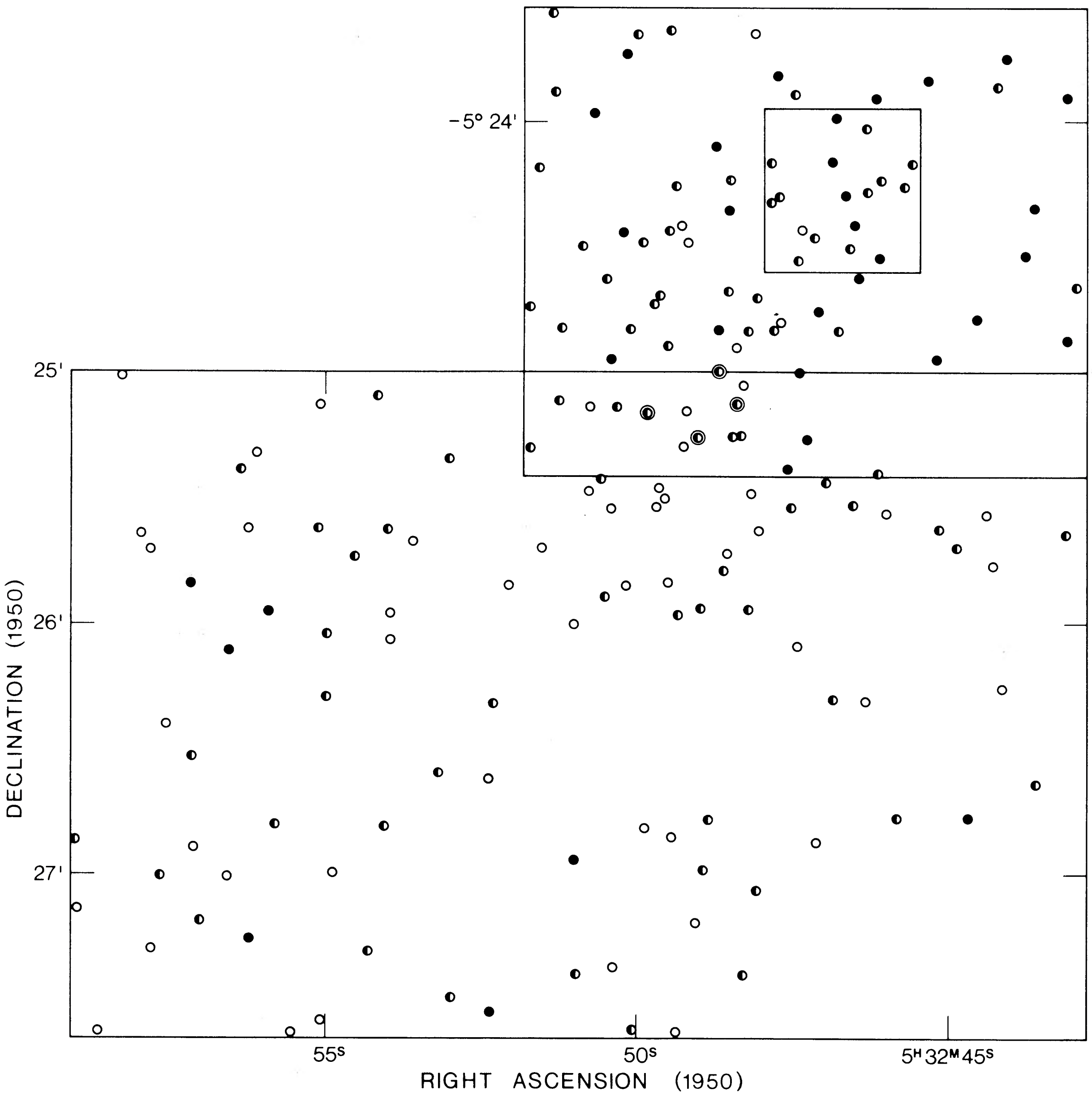

FIG. 2. Positions of the infrared sources found in the 5″ resolution 2.2-μm scans. The upper large box is the boundary of the 5″ scans while the small box shows the boundary of the 3″.5 scans. The lower large box is the area mapped by Becklin *et al.* (1976) with a 7″.5 beam. In the overlap region the data shown are those from our 5″ scans. Closed circles are 2.2-μm sources with no optical counterpart in the charts of Strand and Teska (1958). Open circles are optical stars with no infrared counterpart, and half-closed circles are stars seen both in the optical and at 2.2μm. The Trapezium stars are marked with larger open circles, around the half-closed symbols.

infrared sources in the region. There is good agreement between the 5″ and 3″.5 scans in the restricted region covered by the latter.

b) Distribution of the Sources

As noted above, the surface density of infrared sources is high in the area covered by 3″.5 scans (Fig. 1). In Fig. 2 it may be seen immediately that the surface density of 2.2-μm sources peaks broadly in an elongated area that runs NW-SE from the top of the small box to the Trapezium. Closer inspection shows that the optically identified sources are distributed throughout the area and peak at the Trapezium, while the sources seen only in the infrared are found preferentially to the northwest of the area. A Kolmogorov-Smirnov test was

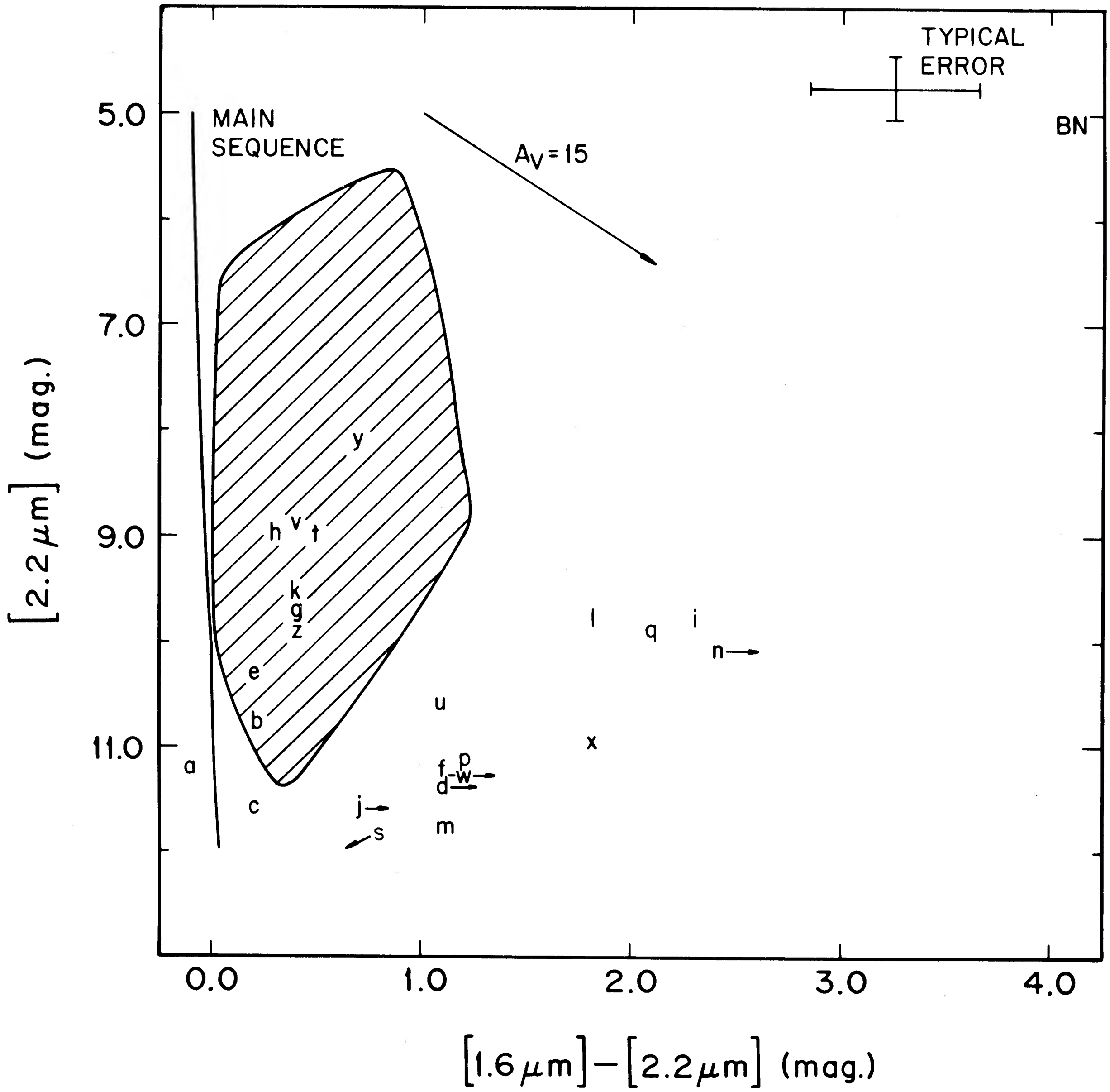

FIG. 3. [2.2 μm]-vs-[1.6 μm]–[2.2 μm] color-magnitude diagram. The hatched area is the region occupied by 0.2–3$M_\odot$ PMS stars in the Orion Association after dereddening (data from Cohen and Kuhi 1979). The location of main-sequence stars at the distance of the Orion Association (500 pc) is indicated. Also shown is the effect of 15 mag of visual extinction (reddening law from Becklin *et al.* 1978).

applied to the data to find the significance of the result that the sources not seen at V have a different distribution from those that are seen at V. Radial distance from the Trapezium was used as the parameter for the test. The results of this test show that there is a 96% probability that the invisible sources do not center on the Trapezium in the same way that the visible ones do.

c) Magnitudes and Colors

In Figs. 3 and 4, we have plotted a [2.2 μm]-vs-[1.6 μm]–[2.2 μm] color-magnitude diagram and a [1.6 μm]–[2.2 μm]-vs-[2.2 μm]–[3.5 μm] two-color diagram for the sources listed in Table I. The regions occupied by dereddened low- and intermediate-mass [(0.2–3)$M_\odot$] Orion Association stars (Cohen and Kuhi 1979) are indicated for comparison of the colors of the general optically visible association population to those of the infrared sample.

A number of results are apparent in Figs. 3 and 4. First, although many new sources were found in the BKNL region, none of them approaches BN in bright-

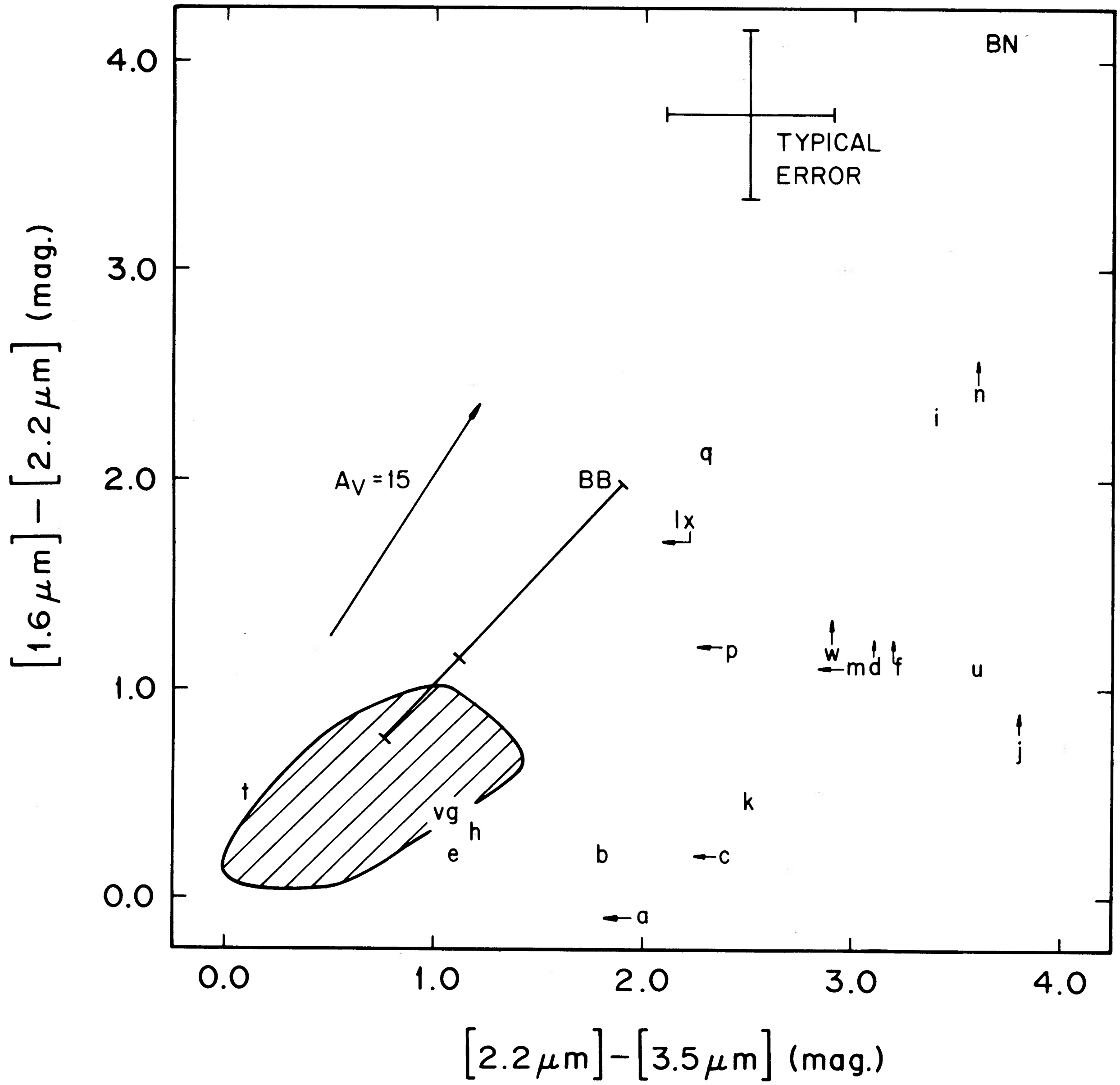

FIG. 4. [1.6 μm]–[2.2 μm]-vs-[2.2 μm]–[3.5 μm] two-color diagram. The hatched area is as in Fig. 3. Also shown is a segment of the locus of blackbodies (line marked BB), calculated for the filters used in this work and marked at temperatures of 1000, 1500, and 2000 K.

ness or color; there is a pronounced gap between BN and the new sources in Fig. 3. Second, a number of the new sources are very much redder than the Orion Association stars, which themselves show an intrinsic excess of 2.2- and 3.5-μm emission compared to field stars, a characteristic which is shared with stars in other dark cloud associations (Hyland 1981, and references therein). Such stars are generally accepted as PMS objects (Hyland 1981), and the excess flux is attributed to circumstellar dust emission (Cohen and Kuhi 1979; Hyland 1981). The colors of the new sources indicate that they may be heavily reddened PMS stars, some of them (b, i, k, u) having excess 3.5-μm flux compared to the optical PMS stars. It is also possible that some of the sources are clumps of material within the BKNL region shining by reflection, or unreddened stars with excess thermal 2.2- and 3.5-μm flux.

Estimates of the luminosity of the sources, assuming they are stellar, can be made as follows. If all of the 2-μm radiation results from photospheric emission and intrinsically the stars lie near the main sequence, then correcting for interstellar reddening gives absolute 2-μm mag in the range -1.5 to $+2.5$ mag. These values correspond to spectral types from B5 to F5. If there is excess

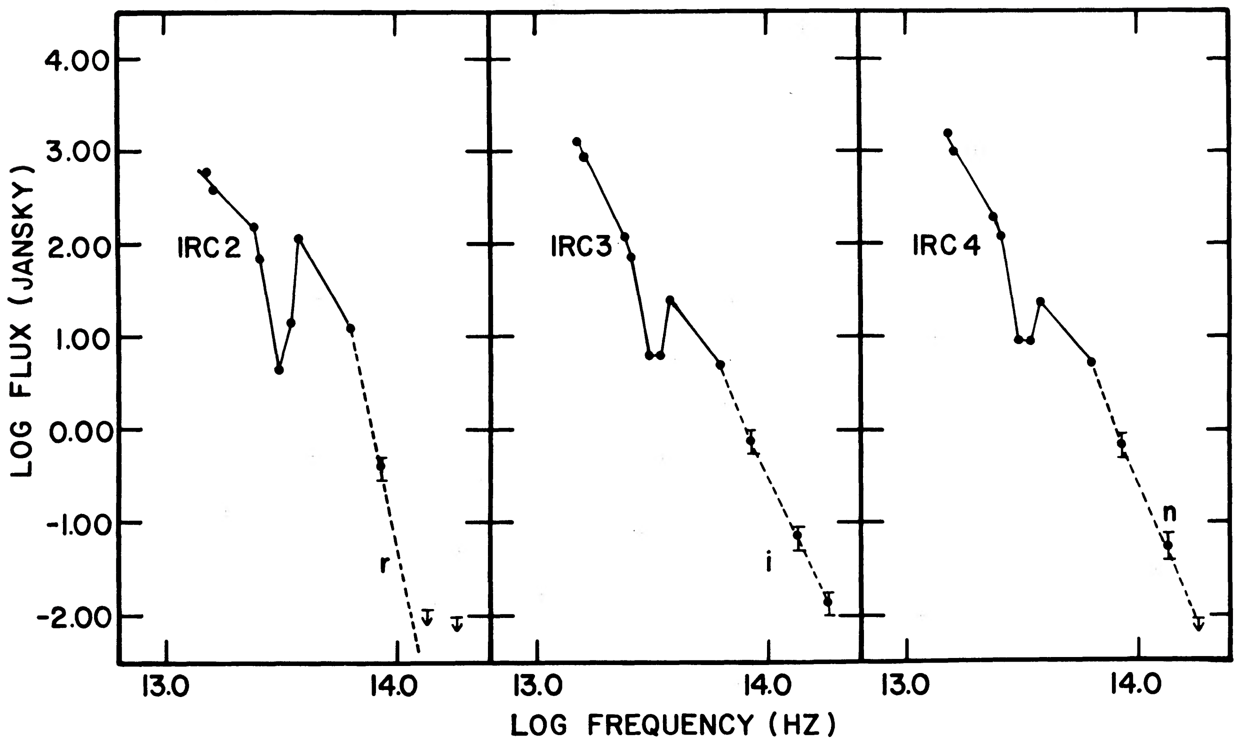

FIG. 5. Spectral energy distributions from Downes *et al.* (1981) for IRc2, 3, and 4 (solid lines). Plotted for comparison are the 1.6-μm, 2.2-μm, and 3.5-μm measurements of sources i, r, and n from Table I (points with error bars, or upper limits). The dashed lines are extrapolations of the energy distributions of the IRc sources through these points.

2-μm emission from circumstellar shells, then the spectral classes are even later; for example, if the excess is about 1 mag at 2.2 μm the spectral types range from A0 to G0. Therefore, if stellar, the newly discovered sources are likely to be less massive than the known OMC-1 members such as BN and IRc2.

A final result is that in Fig. 3 there is apparently a bimodal distribution of the stars. Since almost all of the visibly identified infrared stars are contained in the bluer group, which resembles the PMS stars in magnitude and color, the most natural explanation for this effect is reddening. Under this interpretation the blue group suffers almost no extinction, while the brighter members of the red group all show an extinction of $A_v \geqslant$ 10 mag. The groups of objects thus lie at different depths in the cloud; the visible group is on the front edge and the invisible group is well within the cloud behind a sheet of extinction. Exceptions to this may be sources c and s, which lie at the faint end of the distribution and whose infrared colors indicate they may belong to the foreground group, although they are not identified visually. In addition, source u lies closer to the red than the blue group, perhaps due to the chance superposition of a foreground star.

To test the significance of the apparent bifurcation, a Kolmogorov-Smirnov test was applied to the visually identified versus the nonidentified sources (excluding BN) using distance from the main sequence along the reddening line as the measured parameter. It was found that the bimodal distribution is significant at the 99.9% level, even though sources c, s, and u, identified above as likely exceptions to the groupings, were not excluded from the test. The errors in the data points were not explicitly considered; however, they would tend to smear out any bimodality observed in the figure. The dispersions around regression lines fitted to the two groups of sources are consistent with the error bars.

d) Identification with the IRc Sources

It may be seen from Fig. 1 that there are a number of possible positional identifications between 20-μm sources and 1.6–3.5-μm sources. By comparison of the energy distributions measured by Downes *et al.* (1981) with those presented here, we have tested the plausibility of these identifications and propose that three of them are likely to be real: IRc2 with r, IRc3 with i, and IRc4 with n. These comparisons are illustrated in Fig. 5. Sources i, n, and r are three of the brightest sources at 3.5 μm found in this work, a factor which strongly supports their identification with the IRc sources. It is possible that IRc7 is the correct identification for either n or r, thus leaving IRc4 or IRc2 unidentified, respectively. We feel, however, that the closer spatial and spectral correspondence of these two sources with IRc4 and

IRc2 make these identifications more plausible. The steep spectrum of IRc2 is consistent with the deep silicate band and the high extinction inferred for this source by Downes *et al.* (1981). The data of Aitken *et al.* (1981) imply a somewhat larger 3-μm continuum flux than observed by us; the explanation for this apparent discrepancy may be that Aitken *et al.* were sensitive to more background flux around IRc2 because they used a considerably larger beam throw.

IV. DISCUSSION

Werner, Capps, and Dinerstein have recently made 3.8-μm polarization observations of the BNKL region (Werner 1981). Exceedingly high polarization values have been found throughout the complex, and the pattern of position angles clearly demonstrates that much of the 3.8-μm flux from the region is scattered from central sources, probably IRc2 and BN. It is therefore possible that some of the new discrete red sources reported here are in fact clumps of dust within BNKL, shining by reflection, rather than stellar objects. Because the present observations were made with a small 3".5 beam and a 3".5 chopper throw, extended radiation will be suppressed and we feel that most of the new sources are stellar. The following discussion is therefore restricted to the interpretation that the sources are stellar.

The fact that the sources detected only in the infrared have a different spatial distribution from the visible stars (Fig. 2) implies either that there are two disjoint groups of stars, one more heavily reddened than the other, or that the visible distribution does not reveal the true distribution of a single cluster because of the effects of extinction. The bifurcation observed in Fig. 3 implies that there is a discontinuous distribution of stars in the line of sight to the core of OMC-1; in other words, at least in the direction of OMC-1 there is a grouping of observed stars which is physically separated from the foreground optical cluster Orion OB1d.

Whether the redder sources in Fig. 1 are physically associated with the OMC-1 cluster of bright infrared sources such as BN and IRc2 cannot be established definitely from the present data. However, the colors of the new sources are consistent with their being PMS stars reddened by an extinction of $A_v \geqslant 10$ mag. The best current value of the extinction to the OMC-1 cluster comes from the CO column density determined from near-infrared overtone bands in the spectrum of BN (Scoville 1981) and H_2 line profiles (Nadeau, Geballe, and Neugebauer 1981; Scoville *et al.* 1981) and has a value $A_v \simeq 30 \pm 10$ mag. Thus, the present observations are consistent with the hypothesis that the newly discovered infrared sources are part of the OMC-1 cluster.

Most of the stars are probably less massive than the previously known OMC-1 cluster members (Sec. III c). Therefore, it appears that the OMC-1 cluster has formed with a luminosity function not restricted to the highest-luminosity stars. The ages of the infrared sources are unknown; by analogy to the Orion Nebula cluster (see Sec. I) they may be considerably older than the massive OMC-1 cluster members. Since they seem to be in the cloud they may well be *younger* than the visible Orion OB1d cluster members of intermediate mass. In this case, the sources would present a new, younger phase of intermediate-mass stellar evolution for study.

Downes *et al.* (1981) have suggested that only BN and IRc2 are sources of luminosity for the OMC-1 complex on the basis that the other discrete sources are of a low color temperature; that is, that the other IRc sources are too cool to be more than just clumps of heated dust without a central luminosity source. One interpretation of our results is that IRc3, and IRc4, and/or IRc7 may also be sources of luminosity. However, Werner, Capps, and Dinerstein (in Werner 1981) have found these sources to be highly polarized at 3.8 μm. Thus a more likely possibility is that the IRc3, IRc4, and IRc7 shine by reflected radiation at the wavelengths of our observations.

V. SUMMARY

The principal observational results of this paper are as follows:

(a) To a limiting 2.2-μm mag of 11.8, the spatial distribution of sources seen only in the infrared in the region surrounding the Trapezium and the OMC-1 infrared cluster in Orion differs from that of the visible stars ($V \leqslant 18$ mag). The visible stars peak on the Trapezium, while the ones seen only in the infrared peak in the OMC-1 direction.

(b) Within a 0.4-arcmin^2 area centered on BN, 26 1.6–3.5-μm sources have been found, most of them unresolved with a 3".5 beam. The majority of the sources are previously undetected in the infrared. They are all significantly fainter than BN at 2.2 and 3.5 μm. The sources separate in the [2.2 μm]-vs-[1.6 μm]–[2.2 μm] color-magnitude diagram into two groups.

From these results we have made the following conclusions:

(a) The nonoptically identified infrared sources in the direction of the core of OMC-1 are separated in the line of sight from the visible sources by a screen of extinction, which reddens them. The reddened sources are likely to belong to the OMC-1 cluster; there are at least ten newly discovered sources in this category.

(b) If stellar, most of the new sources are probably less massive than BN and IRc2, though their luminosities are not known. The new sources may be younger than most of the visible PMS stars in the association. Thus, they may present a new phase of intermediate-mass stellar evolution for study.

Note added in proof.

Higher-resolution maps (2") of the central 15" of the KL nebulae at 2.2 and 3.8 μm by Genzel, Becklin, Downes, and Wynn-Williams indicate that most of the sources reported here appear stellar at that resolution.

Thus the interpretation that they are stellar is probably correct. While the analysis of the 2″ data will undoubtedly result in more detailed information about the region, the conclusions of the current investigation are unlikely to be significantly altered.

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