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ISO Observations of Starless Bok Globules: Usually No Embedded Stars

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Abstract. We have used ISOCAM to search the cores of a sample of small Bok globules previously classified to be mostly starless based on analysis of IRAS data. The ISO observations at $6.75\mu\text{m}$ (LW2 filter) and $14.5\mu\text{m}$ (LW3 filter) were sufficiently deep to enable detection of any low-mass hydrogen burning star or young stellar object (YSO) embedded in these globules. Of the 20 Bok globules observed by ISOCAM to date, we have reduced the data for 14. Of these, 13 show no evidence for faint red ($S_\nu(LW3) > S_\nu(LW2)$) stars missed by IRAS. One (CB68) does show the first mid-infrared detection of the very cool IRAS source toward this cloud, and may be a Class I or 0 YSO. We conclude, based on these new ISO observations, that Bok globules which have no IRAS sources are in general bona fide starless molecular clouds.

1. Introduction

“Starless” Bok globules are interesting because they hold the potential for serving as laboratories for investigations of the physical conditions present in molecular clouds preceding new star formation, and may reveal important clues concerning the relevant physics involved in initiating cloud core gravitational contraction or collapse. Unknown, however, is whether these small molecular clouds are truly free of embedded low-mass stars, which could inject energy and turbulence into the clouds.

IRAS data were incapable of being used to definitively state whether apparently starless globules were fully free of embedded stars. At the distance characterizing the mean of the CB globule sample (about 600 pc), the IRAS Point Source Catalog has a limiting flux sensitivity corresponding to a relatively high lower-mass limit for stars and YSOs of about $0.7 M_\odot$.

In order to detect all previously undiscovered members of any embedded low-mass/YSO stellar population in the starless Bok globules, we conducted an ISOCAM search. At mid-infrared wavelengths, pre-main sequence stars and pro-

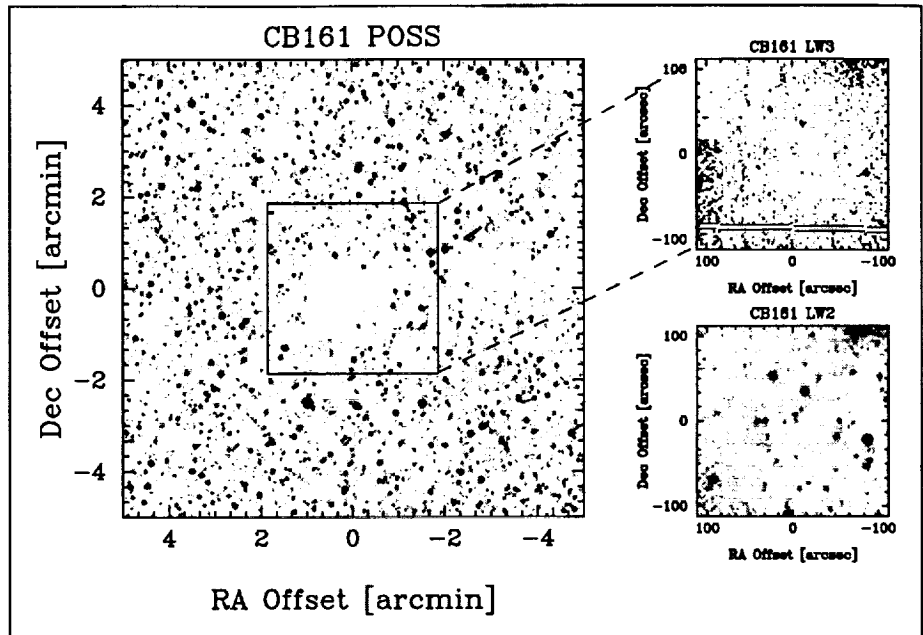


Figure 1. Comparison of optical and ISOCAM images of CB161. Although stars appear in the ISO images, no faint red embedded sources are seen toward this globule core.

protostars will be bright relative to optical and near-infrared wavelengths, and very low-mass main sequence stars will have detectable mid-infrared photospheric emission.

2. Source Selection and Observations

The science goal was to be able to detect low-mass main sequence stars more massive than $0.08 M_{\odot}$ and all protostars and YSOs within starless globules out to distances of 600 pc. This translates to the need to detect stars and YSOs with $15\mu\text{m}$ flux levels hundreds of times lower than the IRAS $12\mu\text{m}$ PSC limit. By imaging through the LW3 and LW2 filters, the colors of many detected stars could be established. These colors could be used to identify young stellar objects (YSOs) by their redder colors, compared to normal, main sequence stars. The (5σ) flux limit goal in the LW3 filter was 3.3 mJy. In the LW2 filter, the limit was lowered in order to be able to distinguish bluer, normal, mostly background stars from YSOs. This yielded a (5σ) flux limit of 0.6 mJy.

The globules to be observed were drawn from the CB catalog with the additional criterion that they not have IRAS PSC detections in all four IRAS bands. Table 1 indicates that 11 of the globules have no IRAS sources within the ISOCAM search area. Of the remaining three globules, CB161 has a blue $12/25\mu\text{m}$ source, CB160 has a $100\mu\text{m}$ -only detection, and CB68 has a three-band detection of a very red source.

We used the ISOCAM CAM01 AOT with a 3 arcsec pixel field of view in micro-stepping mode, to create a raster of 5 x 5 camera center placements,

spaced by 32 arcsec, spanning a total field size of 3.7×3.7 arcmin, toward each globule core. In the LW3 filter, six exposures of 2.1 sec each were obtained at each pointing. For the LW2 filter, four exposures of 5.04 sec each were similarly obtained. In each of the central pixels of the mosaic, the effective integration time is 2 min in the LW3 filter and 3 min in the LW2 filter. The data were processed using a combination of the ISOCAM Interactive Analysis (CIA) software and routines written at IPAC. Transient removal, flat-fielding, and mosaic reconstruction were performed during a week-long IPAC run. Post-processing image analysis and photometry was performed using IRAF. Figure 1 shows a POSS optical image and the LW3 and LW2 ISOCAM mosaic images for the starless Bok globule CB161/B118. The bright sources seen in the LW2 image have counterparts in the POSS image. The LW3 sources also have bright LW2 counterparts, confirming their blue (non-embedded) colors.

3. Results

The ISO data were examined for the presence of sources in the LW3 mosaics, and detections were compared to the LW2 mosaic sources to establish colors. Only one globule had a distinctly red LW3/LW2 source (CB68), while another had a flat spectrum source (CB152). Otherwise, all detected sources had blue colors. Globule fields toward the central galactic bulge generally contained many of these blue sources, as noted in Table 1. These are likely normal bright stars, as shown by the correspondence in Figure 1 between LW2 stars, LW3 stars, and optically bright stars. The search flux limits, measured from the mosaic images, are presented in Table 1, below. The limits represent 5σ values for apertures of size twice the FWHM of the PSFs in the LW2 (FWHM 3.6 arcsec) and LW3 (5.0 arcsec) filters. The mean LW2 5σ limit measured is 0.07 mJy, almost ten times lower than needed. Similarly, the mean LW3 limit is 0.21 mJy, about a hundred times better than the IRAS PSC $12\mu\text{m}$ limit.

Table 1. Starless Bok Globules Observed with ISOCAM.

| Globule Desig. | α [2000] | δ [2000] | IRAS Source | $5\sigma S_\nu$ [LW2] [mJy] | $5\sigma S_\nu$ [LW3] [mJy] | Comments |
|-------------------|---|----------------------|----------------|--------------------------------|--------------------------------|--------------|
| CB63 / LBN11 | $15^{\text{h}}50^{\text{m}}37^{\text{s}}$ | $-04^{\circ}03'02''$ | ... | 0.08 | 0.20 | Offset Field |
| CB66 / L121 | $16^{\text{h}}39^{\text{m}}30^{\text{s}}$ | $-14^{\circ}05'51''$ | ... | 0.07 | 0.20 | |
| CB67 / L31 | $16^{\text{h}}50^{\text{m}}31^{\text{s}}$ | $-19^{\circ}07'25''$ | ... | 0.03 | 0.21 | Big Cloud |
| CB68 / L146 | $16^{\text{h}}57^{\text{m}}16^{\text{s}}$ | $-16^{\circ}09'22''$ | x234 | 0.07 | 0.23 | 1 Red * |
| CB152 / B316 | $18^{\text{h}}41^{\text{m}}36^{\text{s}}$ | $-02^{\circ}09'17''$ | ... | 0.17 | 0.31 | 1 White * |
| CB154 | $18^{\text{h}}42^{\text{m}}20^{\text{s}}$ | $+16^{\circ}00'06''$ | ... | 0.06 | 0.20 | |
| CB160 / B117 | $18^{\text{h}}53^{\text{m}}40^{\text{s}}$ | $-07^{\circ}25'30''$ | xxx4 | 0.03 | 0.23 | Blue *s |
| CB161 / B118 | $18^{\text{h}}53^{\text{m}}55^{\text{s}}$ | $-07^{\circ}25'52''$ | 12xx | 0.05 | 0.21 | Blue *s |
| CB183 | $19^{\text{h}}13^{\text{m}}21^{\text{s}}$ | $+16^{\circ}34'41''$ | ... | 0.07 | 0.20 | Blue *s |
| CB195 / L701 | $19^{\text{h}}34^{\text{m}}47^{\text{s}}$ | $+12^{\circ}20'48''$ | ... | 0.07 | 0.18 | Blue *s |
| CB202 | $19^{\text{h}}42^{\text{m}}33^{\text{s}}$ | $+18^{\circ}52'09''$ | ... | 0.07 | 0.20 | Blue *s |
| CB228 | $20^{\text{h}}51^{\text{m}}19^{\text{s}}$ | $+56^{\circ}15'49''$ | ... | 0.06 | 0.15 | |
| CB235 / L1142 | $21^{\text{h}}56^{\text{m}}19^{\text{s}}$ | $+59^{\circ}00'08''$ | ... | 0.06 | ... | LW3 Bad |
| CB246 / L1253 | $23^{\text{h}}56^{\text{m}}44^{\text{s}}$ | $+58^{\circ}34'32''$ | ... | 0.06 | 0.16 | |

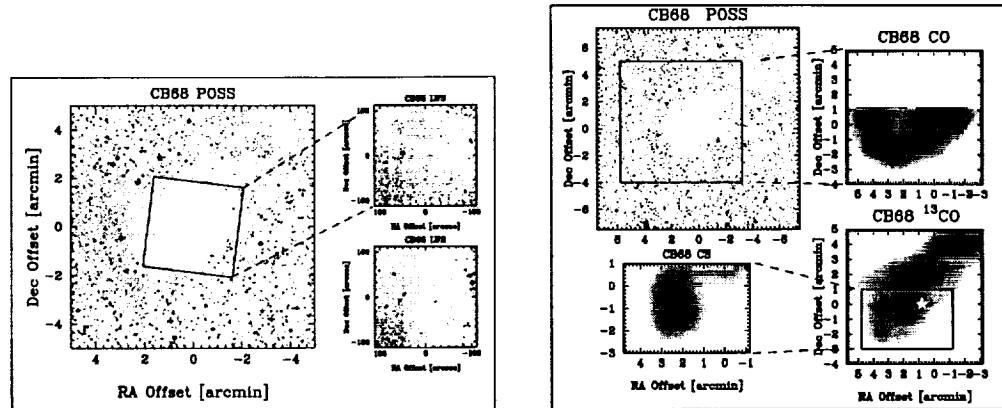


Figure 2. Comparison of CB68 images. (Left Panel) Optical POSS compared to ISOCAM LW2 and LW3 mosaics. (Right Panel) POSS compared to FCRAO maps of CO, ^{13}CO , and CS. ISOCAM source position is indicated in the radio maps of ^{13}CO and CS as a white star.

The faint red ISO source in the CB68 globule (see Figure 2) is within $30''$ of the IRAS PSC object 16544-1604 in an otherwise empty ISO and IRAS field. In order to test for association with the CB68 globule, we used mm CO and CS mapping at FCRAO in December 1996. Figure 2 shows the POSS images, ISOCAM images, a CO map, a ^{13}CO map, and a CS map. The globule has a strong ^{13}CO core and a weak CS core. The cloud also shows a bright rim in the POSS images, which seems also present in the partial CO map shown. Although, the red ISO source in CB68 does not appear within the half-power contours of the CS emission, an HCN map by Alfonso et al. (1997) peaks very close to the ISO source. Combining the IRAS and ISO fluxes into one spectral energy distribution reveals a source which is very red from LW2 through IRAS Band 4 ($100\mu\text{m}$), indicative of either a Class I or Class 0 YSO.

4. Conclusions

ISOCAM surveying is very efficient for certifying that small Bok globules are "star-free." Of 14 globules examined, 13 show no faint red sources to flux levels more than several hundred times fainter than IRAS could detect.

The one red source found, in CB68, is most likely associated with the bright, red IRAS source 16544-1604 detected in the three reddest IRAS bands. The combined SED indicates a Class I or Class 0 source likely located within this small Bok globule.

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