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STAR FORMATION IN SMALL GLOBULES: BART BOK WAS CORRECT!

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ABSTRACT

We have probed a large sample of optically selected, small molecular clouds (Bok globules) using *IRAS* co-added images to search for associated young stellar objects. The *IRAS* images were examined for point sources located within the boundaries of the optical and infrared extents of 248 clouds. A total of 57 of the globules (23% of the sample) show evidence for associated point sources. From a comparison of the 12 and 25 μm fluxes of these objects, we find a distribution of spectral indices consistent with the presence of circumstellar dust. Similar analysis of other point sources within the *IRAS* images, but far from the globule boundaries, shows only normal stellar spectral indices. All young stars more massive than 0.7 $M_\odot$ were likely found. However, extrapolation of a Miller-Scalo initial mass function to the hydrogen-burning limit indicates that only about 20% of the total number of stars were found. It is therefore likely that almost every Bok globule harbors a young star. The inferred star formation efficiency is about 6% again based on the Miller-Scalo initial mass function. Interestingly, this is the best test in 43 years of the conjecture made by Bart Bok that dust globules could represent the earliest stage of star formation. We are pleased to report that his conjecture was correct.

Subject headings: infrared: sources — interstellar: matter — luminosity function — nebulae: general — stars: formation — stars: luminosities — stars: pre–main-sequence

I. INTRODUCTION

Bok globules are nearby dark clouds of gas and dust, usually isolated and displaying the simplest of shapes. They can be crudely separated into two broad classes: the large globules, with masses greater than $\approx 100\ M_\odot$ (e.g. B5; Young *et al.* 1982); and the small globules, with correspondingly smaller masses ($\approx 10\ M_\odot$; Clemens, Yun, and Heyer 1991, hereafter CYH). As early as 1947, Bok speculated that globules were undergoing gravitational collapse on their way to form stars (Bok and Reilly 1947). However, recent analyses of the molecular gas component of several globules have found virial stability (Leung 1985, and references therein) or hydrostatic stability (Dickman and Clemens 1983) to be prevalent.

Because of their small sizes, regularity, and isolation, globules are convenient objects in which to study the formation of an individual star. The small globules are especially well suited, as they are the simplest clouds, with single, central condensations and little supersonic gas motions (e.g., Dickman and Clemens 1983). However, only a few studies of such Bok globules have been performed (cf. Villere and Black 1980; Leung, Kutner, and Mead 1982), with only a few clouds sampled. Recently, we (CYH) analyzed *IRAS* co-added survey images and CO data for the entire collection of 248 small molecular clouds optically selected and cataloged by Clemens and Barvainis (1988, hereafter CB). For an assumed distance to these clouds of 600 pc, we found a mean globule mass of 11 $M_\odot$ and mean $L_{\rm FIR}$ of 6 $L_\odot$, making these clouds an ideal laboratory for probing single, low-mass star formation.

Since Bok's conjecture, only a handful of small globules have been found to contain embedded infrared point sources (e.g., B335; Keene *et al.* 1983). In order to perform a large-scale, systematic search for point sources in Bok globules, we have analyzed the infrared emission from the CB clouds as detected by the *Infrared Astronomical Satellite* (*IRAS*). Our findings are astonishing: one in every four globules harbors a detectable young star! But, because our search was flux-limited, stars less massive than about 0.7 $M_\odot$ could not be detected. We used a Miller-Scalo (1979) initial mass function to estimate the number of stars missed by our search, deriving a value of about 300 unseen stars. If these stars are uniformly distributed among the sample of the globules, then we conclude that almost every globule must contain a young star. Hence, Bok's assertion that the globules are a strongly star-forming population was entirely correct.

In the next few sections, we describe the details of our search and present evidence to establish the youth of the objects found. We conclude by estimating the star formation efficiency for these clouds and the luminosity function for their offspring.

II. DATA ANALYSIS

Our analysis was performed on the 248 optically selected small molecular clouds in the CB catalog. The data consisted of co-added *IRAS* survey images at 12, 25, 60, and 100 μm wavelength of 1° × 1° fields containing these globules. The selection and image processing of these data are fully described in Yun and Clemens (1990). For this study, the images were processed to remove unrelated background emission by median filtering with very large kernels ($\approx 17'$). These filtered images were then subtracted from the original images. Next, these background-cleaned 60 and 100 μm images were analyzed using a single-temperature modified blackbody model (λ^{-1} emissivity; Yun and Clemens 1990) to obtain dust temperature $T_{60/100}$ and dust optical depth images τ_{100}. These temperature and opacity images, together with the optically cataloged globule extents and orientations, were used as templates to guide the search for associated young stellar objects (YSO). The actual search consisted of inspecting the co-added 12 and 25 μm intensity images to look for pointlike sources within the optical or infrared boundaries of each cloud.

The criteria used to select point sources likely to be associ-

1990ApJ...365L..73Y

ated with the globule were threefold. First, each associated point source at 12 and 25 μm had to be located within the infrared 100 μm optical depth–traced extent of the globule and no more than 2′ beyond the optical boundary as cataloged by CB. Second, detection of both 12 *and* 25 μm point sources with good spatial coincidence between the bands, usually better than 1′, was required. Finally, to ensure detection of embedded YSOs, we required the 12 and 25 μm point sources to coincide with local maxima in the longer wavelength $T_{60/100}$ temperature maps (i.e., to show evidence of local cloud heating).

An example is shown in Figure 1. This figure shows a contour plot of the $T_{60/100}$ dust temperature image of a globule (Fig. 1*a*) and the corresponding 12 μm emission image (Fig. 1*b*). The globule CB 60 (L1670) is indicated by a dashed ellipse near the center of the maps. Note the presence of a strong 12 μm source well within the cloud boundary and also the local peak in $T_{60/100}$ at the position of this source. There are also a few field sources, scattered across the image and unrelated to the globule. These have been used to obtain a reference sample of unrelated sources, as described below.

Examination of quadruples of images ($T_{60/100}$, τ_{100}, $S_{12\,\mu\mathrm{m}}$, and $S_{25\,\mu\mathrm{m}}$) for all 248 globules produced a sample containing 57 clouds showing 72 point sources within their boundaries. The point sources were then photometered using the IRAF[1] POLYPHOT aperture photometry routine. Because the *IRAS* observing and co-adding processes produced radically different point source response functions for each globule co-added field, the selection of the polygonal aperture appropriate for each particular co-added field was performed interactively while viewing contour plots of the 12 and 25 μm globule emission. The representative point source responses were generally taken from field sources, to avoid extended (non-pointlike) 12 and 25 μm globule emission. Overall, we estimate that in most cases more than 95% of the source flux has been detected.

To help establish the nature of the globule-associated point sources, we also selected a set of apparently unrelated point sources appearing in the same co-added fields but which were located well outside of the globules. These 47 sources were also measured using IRAF POLYPHOT at 12 and 25 μm using similarly chosen point source response functions.

The globule-associated point sources bear a striking resemblance to the *IRAS* Point Source Catalog (PSC) entries cataloged by CB as being within the optically opaque cores of these globules. Of the 72 point sources found here, 58 were PSC entries noted by CB. However, CB found a total of 145 such PSC entries positionally associated with their entire sample of globule cores. Since the co-added data used in the present study enabled fainter detections than present in the PSC, we conclude that this new effort has found all the true point sources among the PSC candidates. Interestingly, some 60% of the PSC entries for the globules must not be true point sources. Instead, these are likely due to the thermal dust emission from the small, but extended globule structures which were included in the PSC due to the rather large *IRAS* beam sizes. This conclusion is supported by the fact that most of the CB PSC globule detections occurred for the longer wavelength *IRAS* bands. We now believe we have identified all of the true point sources in the globules down to the flux limits of the 12 and 25 μm co-added images, as modified by our selection criteria.

III. RESULTS AND DISCUSSION

Although the point source selection criteria (especially the association with local 60/100 μm dust heating) ought to guarantee inclusion of only embedded young objects, a comparison of the globule-associated point sources with the field source sample yielded conclusive proof. The comparison we used involved the source characterization embodied in the spectral index (" color ") between 12 and 25 μm.

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[1] IRAF is distributed by National Optical Astronomy Observatories which are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

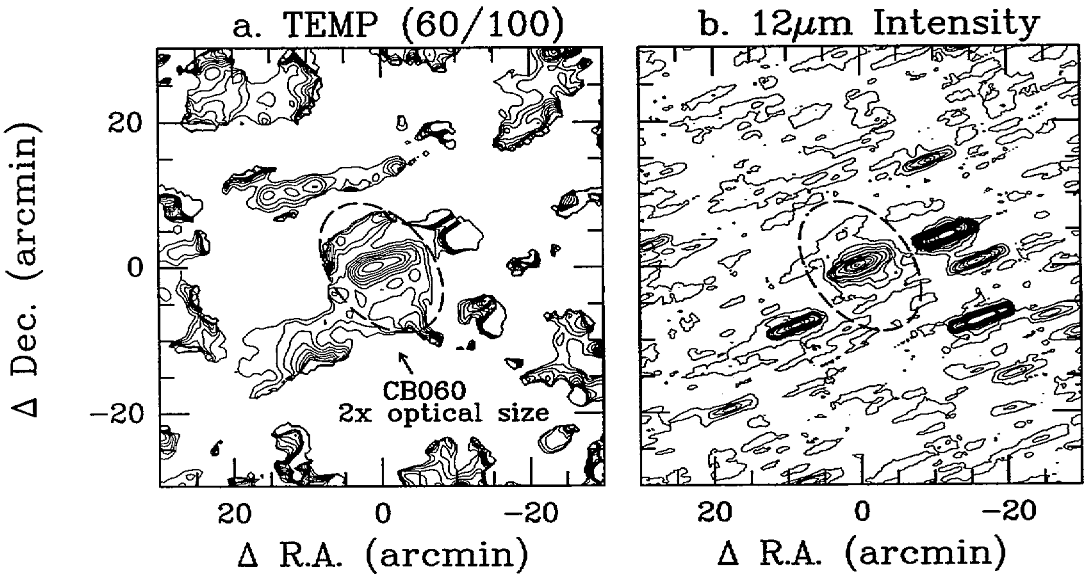

FIG. 1.—(*a*) Contour plot of the 60/100 μm dust temperature image of CB 60 (L1670) and (*b*) the corresponding plot of median-filtered background-subtracted 12 μm emission. A strong 12 μm source is located at a peak in the temperature map. A few other 12 μm field sources appear in the image and are likely not associated with the globule. The dashed ellipse was drawn with the same axis ratio and orientation as the optically opaque region cataloged by CB, but the axes have been multiplied by 2 for legibility. The corresponding plot of 25 μm emission shows a similar image with a strong source whose position coincides with the central 12 μm source.

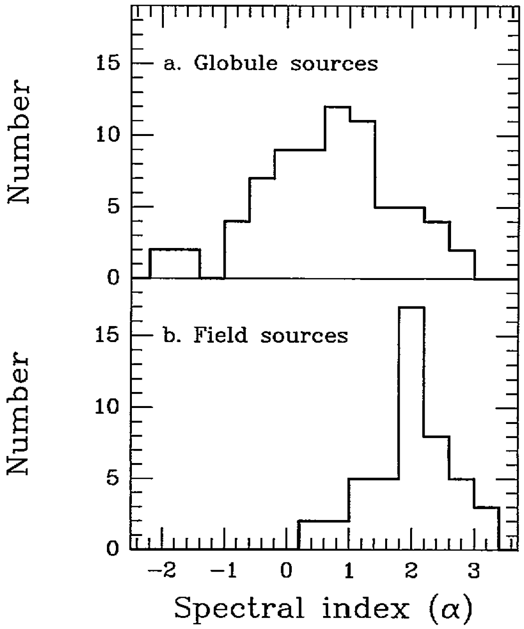

FIG. 2.—Histogram of the spectral indices between 12 and 25 μm found for (*a*) the 72 sources associated with the globules, and for (*b*) the 47 field sources. The two distributions are clearly different, with the globule population being characterized by less positive indices (colder dust temperatures).

We follow Adams, Lada, and Shu (1987) in defining a spectral index α as

$$\alpha = \frac{d \log (\nu S_\nu)}{d \log \nu} . \qquad (1)$$

Using this definition, the histograms of spectral indices for the globule-associated point sources and the field point sources are shown in Figure 2. The two distributions are clearly different, with the globule population characterized by less positive indices (colder temperatures).

Weintraub (1990), using his catalog of pre–main-sequence emission-line stars, found that most of his 155 T Tauri stars exhibit values of *IRAS*-based spectral indices α between −1.0 and +1.1. In the classification scheme devised by Lada (cf. Lada 1987; Wilking, Lada, and Young 1989), negative spectral indices (his "Class I" objects) represent the earliest evolutionary state of pre–main-sequence objects still deeply enshrouded in dust envelopes. Objects with indices between 0 and 2 ("Class II") are typified by young, T Tauri stars, still showing emission from circumstellar dust. Indices greater than 2 are found for normal stars with little or no associated dust. Figure 2 therefore indicates that the field population is mostly composed of "normal" stars (shell stars or Mira variables). The globule-associated population, however, has indices appropriate for young stellar objects. Hence, we conclude that young stellar objects are commonly found in association with, or embedded in, small Bok globules. Among the globules with evidence for associated point sources, 45 globules contain a single source, nine globules contain two sources each, and three globules contain three sources each, yielding a total of 72 point sources in 57 globules. The histogram of globule–YSO spectral indices (Fig. 2*a*) is almost identical to the distribution of spectral indices observed for the population of embedded young stellar objects in the core of the ρ Ophiuchi dark cloud (Wilking, Lada, and Young 1989). Myers *et al.* (1987) found a similar spectral index distribution for the 34 sources they discovered in embedded dark cloud cores.

Having established the globule-associated point sources as a bona fide collection of YSOs, we sought to estimate a luminosity function for the sample. However, there are some limitations imposed by our incomplete knowledge of these sources.

First, there are no reliable determinations of the distances to the globules. Second, we currently have only two spectral points with which to construct the bolometric luminosity. Young stellar objects are typically rather poor blackbodies (cf. Myers *et al.* 1987), with very wide, flat spectra. Hence, although we used blackbody models with temperatures determined from the 12/25 μm spectral indices, these will underestimate the true bolometric luminosities. However, given our poor knowledge of the globule distances, this second concern is less catastrophic.

CB advanced two arguments to support a mean distance of 600 pc to their sample of clouds. For the purposes of estimating the luminosity function and star formation efficiency, we adopt this distance for *each* cloud found to contain a YSO. Calculation of the bolometric luminosity for each YSO involves an integration over all wavelengths. Given the known properties of dust emission, we divided the wavelength range into two intervals: (1) for $\lambda < \lambda_c = 10$ μm, we assumed blackbody spectra, characterized by the 12/25 μm spectral index for each source; and (2) for $\lambda > \lambda_c$, we adopted a modified blackbody (λ^{-1} emissivity law). The resulting histogram of bolometric luminosities is shown in Figure 3. The logarithmic-based mean is 3 $L_\odot$. Changing λ_c by a factor of 2 in either direction only increases the mean log *L* by 10%. In Figure 3, values range from about 0.4 $L_\odot$ to 40 $L_\odot$, with 78% of the sources residing between 1 and 15 $L_\odot$. This distribution is not very different from the one found by Myers *et al.* (1987) for *IRAS* sources in nearby dense cloud cores. Their distribution is more peaked with a mean of about 2 $L_\odot$ and with 76% of the sources having luminosities between 0.4 $L_\odot$ and 6.3 $L_\odot$. However, both distributions have maxima at $\log (L/L_\odot) = 0.2$ and the ranges in the luminosities and the dispersions are similar. Distance errors will likely lead to a broadened observed luminosity distribution. Hence, the true parent luminosity distribution of our globule YSOs is most likely narrower.

The lower luminosity limit of Figure 3 can be used to estimate the fraction of the true number of stars found using our

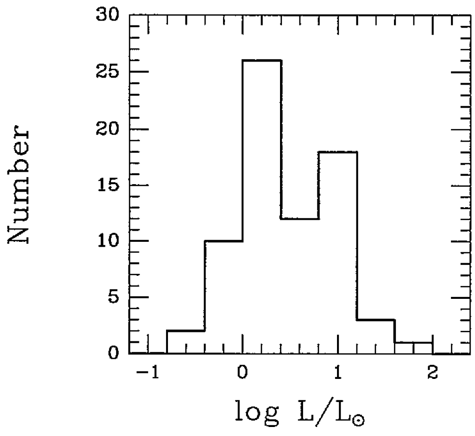

FIG. 3.—Observed luminosity function for the sample of globule associated point sources. The mean is at $\log (L/L_\odot) \approx 0.46$ corresponding to $L \approx 3\ L_\odot$.

detection technique. If we take the cutoff luminosity to be 0.4 $L_\odot$ and assume that corresponds to a main-sequence star, our survey could detect all main-sequence masses greater than 0.8 $M_\odot$, which barely qualifies as a survey for low-mass stars! Alternatively, if we recognize that typical YSOs will exhibit enhanced luminosities, a somewhat different mass limit is reached. Using the modeling results of Adams and Shu (1985), or the deuterium-modified birthline of Stahler (1988), we find that young stellar objects of low mass spend much of their early lives with bolometric luminosities roughly 5 times their main-sequence luminosities. Hence, if we correct our blackbody-based bolometric luminosity limit for the wider and flatter spectra typical of these objects (≈ 2–$3 \times L_{\mathrm{BB}}$) and scale the result down by ≈ 5 to account for their youth, our detection limit is 0.7 $M_\odot$. The implication of these limits is that we may not have found all of the embedded low-mass stars. If the initial mass function (IMF) for stars formed in globules is at all similar to that of Miller and Scalo (1979), then we expect to see about 300 more low-mass stars ($0.1 < M < 0.7$ $M_\odot$). However, recent studies in regions of stellar cluster formation point to possible truncation of cluster IMFs below masses near our cutoff (cf. Rieke, Ashok, and Boyle 1989; DePoy *et al.* 1990). This renders uncertain our ability to predict the number of undetected stars. The ratio of stars detected to the total number of stars present in the clouds is therefore somewhere between about 20% and unity, dependent on the as yet unknown globule IMF. Note that if the Miller and Scalo IMF *is* the correct one to use, and the stars are distributed uniformly in the globule sample, *almost every globule must harbor at least one star*.

We made two estimates of the star formation efficiency (SFE) for these globules. The first estimate assumed that we had detected all of the embedded stars, and that they are roughly of mean mass 1 $M_\odot$. For cloud masses, we used the CYH average estimate of 11 $M_\odot$ per cloud. The resulting star formation efficiency is about 3% (72 stars in 248 globules $\times$ 11 $M_\odot$ per globule). However, this is a lower limit, given that we are insensitive to stars below 0.7 $M_\odot$. Using a Miller and Scalo IMF, the mass correction for unseen stars increases the SFE by about a factor of 2 for limits of 0.1 and 2.0 $M_\odot$ [$\log(L/L_\odot) \approx 1.5$ in Fig. 3]. Hence, extrapolating down to near the hydrogen-burning limit yields a star formation efficiency of $\approx 6\%$.

Finally, we investigated the effects of changing the assumed distance to the globules by a factor of 2. For a distance of 300 pc, our detection limit is 0.5 $M_\odot$, our detection fraction increases to 27% (corresponding to 85% of the globules harboring at least one seen or unseen star), and the SFE is $\approx 4\%$. Assuming a distance of 1200 pc, the detection limit is 1.0 $M_\odot$, the detection fraction is 13%, and the SFE is $\approx 6\%$. In short, our basic conclusion regarding the high frequency of YSOs in globules is unaffected by our poor knowledge of globule distances.

IV. SUMMARY

We have used *IRAS* co-added survey image analysis to identify the physical boundaries of the 248 small molecular clouds in the Clemens and Barvainis (1988) catalog and to search for embedded young stellar objects within those boundaries. A total of 72 bona fide point sources at both 12 *and* 25 μm were found near 60/100 μm temperature maxima in 57 clouds (23% of the entire sample). The spectral indices between 12 and 25 μm were determined for all of these sources and for 47 unrelated reference field sources.

Comparison of the spectral indices of the sources within globule boundaries with the indices for the field sources showed that the globule population is dominated by YSOs while that of the field is dominated by normal stars. Further, the histogram of globule source spectral indices is very similar to the same distribution for embedded young stars in the ρ Oph cloud core.

By using the 12 and 25 μm flux ratios, modified blackbody spectra were produced and integrated to yield a preliminary luminosity function for these globule YSOs. The luminosities range from 0.4 to about 40 $L_\odot$ for assumed distances of 600 pc to the globules. The mean luminosity is around 3 $L_\odot$. We advance arguments to show that the lower luminosity limit implies that we are seeing all stars more massive than about 0.7 $M_\odot$ but miss those below that level.

Using the average cloud mass derived by Clemens, Yun, and Heyer (1991), we estimate a star formation efficiency of about 3%. Correction for low-mass stars below our limit increases this to about 6%.

Finally, we point out that some 43 years after Bok argued that such globules could represent the earliest stage of star formation, we have conclusively tested his conjecture and found it to be sound. We *detected* stars in about one-quarter of the globules, and if the IMF is similar to that of Miller and Scalo, and the stars are uniformly distributed, we infer the presence of young stars in virtually every globule.

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