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FAR-INFRARED DETECTION OF LOW-LUMINOSITY STAR FORMATION IN THE BOK GLOBULE B335

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ABSTRACT

We have detected a very cold, compact far-infrared source at the center of the Bok globule B335. The bolometric luminosity of the globule within a 90″ beam is $7.6 L_\odot$ $(D/400\ \mathrm{pc})^2$ of which $\gtrsim 70\%$ probably comes from an embedded source. The density of the globule is sharply peaked toward the center; the mass of the central core derived from the 400 μm optical depth is 6.5 $M_\odot$ $(D/400\ \mathrm{pc})^2$. For a uniform spherical concentration $\lesssim 30''$ diameter, this implies a volume H_2 density $\gtrsim 10^6$ cm^{-3} $(D/400\ \mathrm{pc})^{-1}$. If the embedded energy source is a pre–main-sequence star on the Hayashi track, it must have a mass of less than 2 $M_\odot$. The far-infrared source does not have a near-infrared or radio continuum counterpart.

Subject headings: infrared: sources — interstellar: matter — stars: formation — stars: pre–main-sequence

I. INTRODUCTION

B335 is an outstanding example of an isolated dust cloud of the type identified by Bok as a "large globule" (Bok and Cordwell 1973, and references therein). It was the first such object detected in the far-infrared (Keene *et al.* 1980, hereafter Paper I). The visually opaque region is approximately 2′ E-W × 3′ N-S, and the central 40″ region has a visual extinction greater than 30 mag (Keene, Capps, and Whitcomb 1983). The absence of foreground stars places an *upper limit* on its distance, *D*, of 400 pc (Bok and McCarthy 1974). Tomita, Saito, and Ohtani (1979), however, suggest that the distance may be approximately 250 pc.

The possibility that globules are sites of star formation (e.g., Bok and Reilly 1947; Bok 1948) has been explored recently both by observers and theorists. Martin and Barrett (1978) and Dickman (1978b), among others, have studied molecular line emission from globules and concluded that they are gravitationally bound objects possibly in the process of collapse. Models by Kenyon and Starrfield (1979) and by Villere and Black (1980) have supported this hypothesis. Schwartz (1977), Bok (1978), and Reipurth (1983) have concluded that star formation has already occurred in a few of the globules associated with the Gum nebula.

Most Bok globules appear to be small, quiescent dark clouds with no internal sources of heating. A survey of nine globules (Keene 1981, hereafter Paper II) showed that their far-infrared intensities are nearly uniform and are consistent with the premise that they are heated by the interstellar radiation field (ISRF). In that survey, however, we found that the surface brightness of B335 in a 1.′7 beam is about a factor of 2 larger than that of the other globules. The measurements presented here were made with higher spatial and spectral resolution and with higher signal-to-noise ratios than those in Papers I and II. They reveal that the far-infrared source in B335 is more compact than was previously assumed, ruling out the ISRF as the dominant heat source. The new far-infrared size, luminosity, and temperature which we derive suggest that we may be seeing for the first time low-mass star formation embedded deeply in a Bok globule.

II. OBSERVATIONS

We observed B335 with the NASA 3 m Infrared Telescope Facility (IRTF) in 1981 February and the Kuiper Airborne Observatory (KAO) 0.9 m telescope in 1981 October and 1982 August. Table 1 contains a summary of the observations.

The IRTF observations were made with the University of Chicago ^{4}He-cooled submillimeter photometer ("CH"; Whitcomb, Hildebrand, and Keene 1980) during a period of exceptionally clear and dry weather; we estimate that the zenith precipitable water vapor was $\lesssim 0.25$ mm. The chopper throw was 5′ in R.A.

Most of the KAO observations were made in 1981 with the new Yerkes Observatory "H-1" far-infrared

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TABLE 1

SUMMARY OF OBSERVATIONS

Observatory[a]	Photometer[b]	Passband	Mean Wavelength	Beam Size (arcsec)	Flux Density (Jy)	Errors Stat.	Errors Total[c]	Calibration Object[d]
KAO	G-2	45–80	60	33	7	1	2	W3(OH)
	H-1	85–120	110	42	35	5	9	W3(OH)
	H-1	85–120	110	90	34	8	11	W3(OH)
	H-1	130–150	140	42	38	5	9	W3(OH)
	H-1	130–150	140	90	45	5	10	W3(OH)
	H-1	150–200	180	90	80	8	18	W3(OH)
	SMM	160–230	190	102	84	17	24	W51
	H-1	160–300	200	90	67	3	14	W3(OH)
	SMM	160–1000	235	102	61	7	14	W51
IRTF	CH	300–900	400	48	20	2	4	W51
UH	A-1	300–900	450	83	34	9	11	W51
IRTF	MP	520–2000	1000	102	1.8	0.6	0.7	W51

[a]KAO: Kuiper Airborne Observatory, 0.9 m telescope; IRTF: Infrared Telescope Facility, 3 m telescope; UH: University of Hawaii, 2.2 m telescope.

[b]G-2: Yerkes Observatory (YO) far-infrared array photometer; H-1: YO far-infrared photometer; SMM: University of Chicago (UC) f/14 submillimeter photometer; CH: UC f/35 submillimeter photometer; A-1: UC f/10 submillimeter photometer; MP: UC f/35 millimeter photometer.

[c]Includes a 20% contribution due to uncertainty in calibration.

[d]W3(OH): assumes spectrum of the form $\nu B(\nu, T)$ with $T = 40$ K for 60 μm < λ < 200 μm and $F(\nu) = 9000$ Jy at 100 μm into a 42″ beam and 12,000 Jy into a 90″ beam. W51: assumes spectrum of the form $\nu B(\nu, T)$ with $T = 40$ K and $F(\nu) = 48{,}000$ Jy at 100 μm for $\lambda < 500$ μm (Ward, Gull, and Harwit 1977; Thronson and Harper 1979; Whitcomb *et al.* 1983). The flux density at 1 mm was assumed to be 150 Jy (Harvey 1974).

photometer. The detector for this system is a 0.32 K ^{3}He-cooled germanium/diamond composite bolometer developed at the University of Arizona. The photometer contains eight-position, ^{4}He-cooled aperture and filter wheels. Spectral passbands are set by a combination of two thallium bromide reflection filters and interchangeable metal-mesh transmission filters (Whitcomb and Keene 1980). The optics and spectral passbands are described by Harper *et al.* (1983); the detector and ^{3}He cryostat are described by Low and Kurtz (1983). At 200 μm, the observed noise equivalent flux density of approximately 25 Jy Hz$^{-1/2}$ is approximately 3 times better than of the "SMM" photometer (see Table 1) used to make most of the observations presented in Papers I and II.

The 60 μm observations were made from the KAO in 1982 with the Yerkes Observatory "G-2" array photometer (Smith 1982). For these observations we used an aperture mask to restrict the detectors' fields of view to 33″. The chopper throw for all the KAO observations was also approximately 5′ in R.A.

III. RESULTS

a) *Source Size and Position*

The results of our mapping of B335 are displayed in Figure 1. The lines show the beam profiles determined by scanning across Mars (Mars diameter [~ 6″] ≪ beam diameter [≥ 42″]). Figures 1*a* and 1*b* compare the 110 μm beam profile with a five-point cross map of B335 made on the KAO. At 110 μm the source is not resolved by the 42″ beam. The multi-aperture measurements at 110 and 140 μm (Table 1) also indicate that a compact component dominates the short-wavelength emission from B335. Both the 200 and 400 μm observations (Figs. 1*c* and 1*d*) are consistent with a diameter

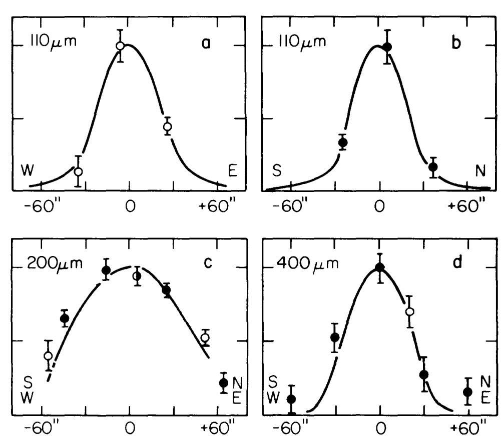

FIG. 1.—Scans of B335 compared to scans of Mars (diameter ≈ 6″; *lines*) at three wavelengths. Open circles indicate east-west scans; closed circles are north-south scans. At 400 μm, in Fig. 1*d*, we have averaged the signals in the north direction with those in the east direction, and likewise the south with the west; the open circle is a single measurement taken at 20″ E.

for the compact source $\lesssim 30''$. Thus the far-infrared size of the globule is much smaller than the optical size or the size observed in ^{13}CO (see, e.g., Martin and Barrett 1978 for a photograph and CO maps).

The position of the compact source as determined from the 110 and 400 μm observations is $\alpha(1950) = 19^h34^m34^s.7 \pm 0^s.7$, $\delta(1950) = 7°27'20'' \pm 10''$.

b) *Source Spectrum*

The observed flux densities are listed in Table 1, and the spectrum is displayed in Figure 2. The measurements made with 102″ beams and the measurement at 450 μm were previously reported in Papers I and II. We have omitted previously reported measurements for which the statistical signal-to-noise ratio was less than 3 and measurements for which there was uncertainty in the observed position. A spectrum of the form $\nu^2 B(\nu, 15\text{ K})$ (*solid line*) is a satisfactory fit to the observed *large beam* fluxes (83″–102″). Another satisfactory fit, except at the longest wavelengths, is given by a spectrum of the form $\nu B(\nu, 18\text{ K})$ (*dashed line*). However, these simple model spectra fail to reproduce the 60 μm flux density which lies significantly above both curves.

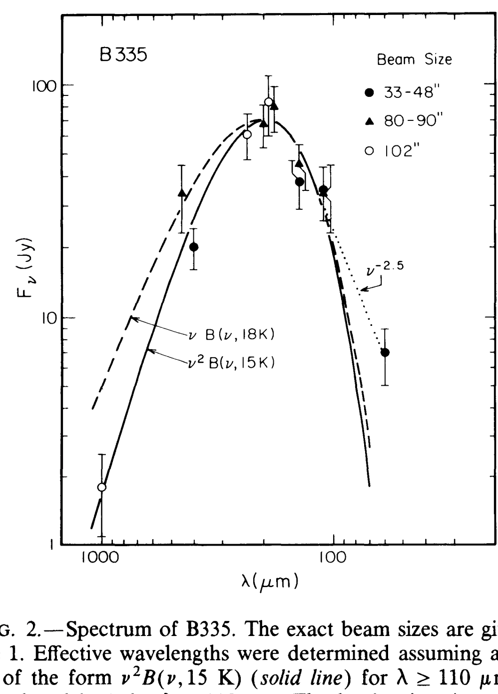

FIG. 2.—Spectrum of B335. The exact beam sizes are given in Table 1. Effective wavelengths were determined assuming a spectrum of the form $\nu^2 B(\nu, 15\text{ K})$ (*solid line*) for $\lambda \geq 110$ μm and $\nu^{-2.5}$ (*dotted line*) for $\lambda < 110$ μm. The luminosity given in the text was determined by integrating under the same two curves. The form $\nu^{-\alpha}$ is arbitrary. The value $\alpha = 2.5$ was chosen to give agreement between the derived 60 μm flux density and the spectrum assumed to derive it. The derived 60 μm flux density would be *raised* if the assumed spectrum were *steeper* than $\nu^{-2.5}$ [e.g., $\nu^2 B(\nu, 15\text{ K})$ or $\nu B(\nu, 18\text{ K})$] within the bandpass of the measurement.

c) *Source Luminosity and Intensity*

The integrated flux from B335 is 1.6×10^{-12} W m^{-2}, slightly larger than the value quoted in Paper I. The difference stems primarily from the improved short-wavelength data. It was determined by integrating under the solid curve in Figure 1 for $\lambda \geq 110$ μm and under the dotted curve for $\lambda < 110$ μm. The corresponding source luminosity is approximately 7.6 $L_\odot$ $(D/400\text{ pc})^2$. Since the source is much smaller than was assumed in Papers I and II on the basis of the visual extent of the globule, the derived surface brightness is much larger. If the source is a uniform disk with a diameter $\lesssim 30''$, the intensity is $\gtrsim 10^{-4}$ W m^{-2} sr^{-1}. This definitively rules out heating by the ISRF, which has an intensity of only approximately 1.8×10^{-6} W m^{-2} sr^{-1} (Werner and Salpeter 1969; see discussion in Paper II).

d) *Comparison with B361*

We reobserved B361 on the same KAO flight during which we made the new airborne observations presented here. In contrast with B335, its size in the far-infrared appears to be comparable to its extent in optical extinction and CO emission (see also Paper II). Our new measurements show that it has a cooler spectrum than B335. We did not detect it at 110 μm, and the ratio of its 140 and 200 μm signals (0.22 $\pm$ 0.06) is lower than the same ratio in B335 (0.35 $\pm$ 0.04) suggesting a value of approximately 11–13 K for the temperature.

IV. INTERPRETATION

a) *Possible Flux Contribution of ISRF*

Our new measurements of the flux from B335 definitely indicate the presence of another heat source besides the ISRF. Based on the results of Paper II, we estimate that the ISRF can contribute about 20%–60% of the flux into a 102″ beam at wavelengths longer than 160 μm but, based on our new data, only about 10%–30% of the bolometric flux in a 90″ beam. Since this heating by the ISRF is not likely to cause the observed, sharp central peak in intensity the remaining flux must be due to a central heat source.

In addition to the substantial component of approximately 15 K dust required by the peak of the observed spectrum near 200 μm, a component with temperature $\gtrsim 25$ K is required by the excess 60 μm radiation. As shown by our observations of B361, heating by the ISRF alone is not likely to produce such high temperatures. Our data cannot exclude the presence of dust cooler than 15 K.

b) *Mass, Density, and Extinction*

The central emission peak in B335 represents a sharp peak in dust column density as demonstrated by the sharpness of the intensity peak in the 400 μm spatial scan (Fig. 1*d*). Flux densities at 400 μm are less sensitive to differences in temperature than are those at shorter wavelengths. The sharp density peak is also seen in the near-infrared extinction data of Keene, Capps, and Whitcomb (1983).

We can estimate the mass in the central region of B335 from the 400 μm optical depth. The flux density at 400 μm is 20 $\pm$ 4 Jy within a 48″ beam. The source size, however, is smaller than the beam; the data indicate a diameter $\lesssim 30''$. The optical depth corresponding to a region $\lesssim 30''$ in diameter is $\gtrsim 0.02$ for $T = 15$ K. We use the relationship between 400 μm optical depth and hydrogen column density derived from the data of Whitcomb *et al.* (1981; see discussion by Hildebrand 1983) to estimate the column density and thus the mass of the central condensation.[6] We find a total mass of 6.5 $M_{\odot}$ $(D/400 \text{ pc})^2$ and an H_2 column density $\gtrsim 1.2 \times 10^{23}$ cm^{-2}. For a uniform spherical source $\lesssim 30''$ in diameter, this column density implies a volume H_2 density $\gtrsim 1.0 \times 10^6$ cm^{-3} $(D/400 \text{ pc})^{-1}$. The optical depth measurement also leads to an estimate for the visual extinction of $A_v \gtrsim 120$. The estimates of column density, volume density, and extinction are lower limits since we have not resolved the 400 μm source. The core mass estimate, however, is nearly independent of core size for small sizes, but it does not include any contribution from the more diffuse envelope whose visual extinction led Dickman (1978*a*) to deduce a mass ≥ 23 $M_{\odot}$.

The column density and extinction inferred from the 400 μm optical depth are an order of magnitude larger than those inferred from molecular line measurements (Dickman 1978*b*; Martin and Barrett 1978; Snell, Langer, and Frerking 1982); the density is two orders of magnitude larger. Undoubtedly some of the discrepancy arises because the core of B335 is highly condensed. Since the peak in column density is very sharp, large beam sizes (typically greater than 1′ for the lines of isotopic CO which are used to determine column densities) mask the degree of line saturation. With our estimate of the column density of the core, even the lowest rotational line of $C^{18}O$ would be saturated. Other potential sources of discrepancy are inaccuracies in the assumed gas and dust temperatures, uncertainties in the calibration of the submillimeter and molecular line data, and the assumptions of isothermal source structure, constant gas to dust ratio, and constant CO to H_2 ratio.

c) *Source of Luminosity*

Our measured total flux and the distance estimate of ≤ 400 pc yield an upper limit of 7.6 $L_{\odot}$ for the total luminosity of the embedded object powering B335.

If the embedded power source were a main-sequence star, the observed luminosity would imply a spectral type F0 or later and a mass of less than 1.7 $M_{\odot}$. However, the time scale for pre–main-sequence evolution of such a low-mass star is so long ($> 10^7$ yr), it is unlikely that it would have reached the main sequence while remaining so deeply embedded in the globule. If the source is a pre–main-sequence star on the Hayashi track, it could be 2 $M_{\odot}$ or less (e.g., Iben 1965).

It is possible that the central source is a protostar still in its accretion phase. Such a source derives its luminosity from free-fall collapse of the parent cloud onto an accretion shock (e.g., Winkler and Newman 1980).

Frerking and Langer (1982) have shown that the CO line profiles in B335 indicate that there is a nonspherically symmetric flow in B335. The flow resembles those seen in many other regions which are believed to contain pre–main-sequence mass-loss objects except that this flow is much less energetic. Its total velocity extent is only about ± 4 km s^{-1}. Frerking and Langer conclude that the most likely mechanism for producing this flow is mass loss at the rate of 10^{-8} $M_{\odot}$ yr^{-1} from an embedded low-mass star or protostar. Using the A array of the VLA, Frerking and Schwartz (private communication) have searched B335 for a 6 cm continuum source. They found none to a 3 σ limit of 0.17 mJy. The absence of a continuum source is consistent with the estimated mass loss rate (e.g., Cohen, Bieging, and Schwartz 1982). It is not clear that the presence of the CO flow can eliminate the possibility that the source is a protostar in its accretion phase.

There is no near-infrared (2.2 μm) source within approximately 20″ of the far-infrared source, to a limit of $K = 15$ mag (Keene, Capps, and Whitcomb 1983). This implies that, if the embedded source is an F0 star, there must be at least 5 mag of extinction at 2.2 μm ($A_v \gtrsim 55$). If the source is cooler than an F0 star (i.e., pre–main-sequence) but still hotter than approximately 1500 K (thus having an emission peak shortward of 2.2 μm), it would require even more extinction, up to $A_v \gtrsim 85$ for a 1500 K object. Our estimate for the total extinction through the globule, $A_v \gtrsim 120$, confirms that the source is still very heavily enshrouded in dust.

V. CONCLUSIONS

We have detected a very cold, compact far-infrared source in the center of B335. Its luminosity implies that, if this object is a star or pre–main-sequence star on the Hayashi track, it has a mass of less than 2 $M_{\odot}$. This source is the first example of what may prove to be a large class of low-luminosity protostars which are visible only in the far-infrared and submillimeter wavelength regions. These sources will appear in the IRAS survey as unresolved sources with a ratio of 100 μm and 60 μm flux densities $\gtrsim 4$. High angular resolution at submillimeter wavelengths will be critical in further studies of low-mass star formation.

[6]Estimates of column density, mass, volume density, and extinction are linearly proportional to the 400 μm optical depth. For these estimates, we use $\tau_{400} = 0.02$ which was derived for $T = 15$ K. The corresponding values for $T = 18$ K are smaller by a factor of 0.63.

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