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THE FORMATION OF SOLAR TYPE STARS: *IRAS*[1] OBSERVATIONS OF THE DARK CLOUD BARNARD 5

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ABSTRACT

Observations of the dark cloud Barnard 5 show two compact sources of radiation within the dense core. IRS 1 is associated with 30–800 K dust, has a total luminosity of about 10 $L_\odot$, and is presumably a newly formed star of roughly solar mass. IRS 2 has a much cooler color temperature, approximately 25 K, and emits only 1.3 $L_\odot$. Its status is unclear, but IRS 2 may be at a very early stage of gravitational collapse or a density enhancement within the cloud heated by the interstellar radiation field. Also within the confines of the cloud are two point sources, which, if associated with the cloud, each emit about 0.5 $L_\odot$ in the *IRAS* bands. These may be T Tauri stars, separated from the cloud but still enshrouded in dust shells.

Subject headings: infrared: sources — stars: circumstellar shells — stars: formation

I. INTRODUCTION

Observations at infrared wavelengths have provided crucial data on the earliest stages of stellar evolution. Young stars ranging in mass from OB stars to T Tauri stars have been found within dense clouds of molecular gas (see, e.g., Wynn-Williams 1982). Many fundamental mysteries remain, however, and perhaps chief among these are the typical conditions that determine when a cloud will collapse to form stars. We present here the first results from *IRAS* of a study of star formation in one nearby molecular cloud, Barnard 5. Future papers will deal with the large statistical sample that the sky survey makes possible.

II. OBSERVATIONS AND RESULTS

The observations described in this *Letter* were all taken with the *IRAS* survey array (Neugebauer *et al.* 1984, hereafter Paper I) using a combination of observations from the mini-survey (Rowan-Robinson *et al.* 1984) and special pointed observations (Paper I). Table 1 lists the properties of four compact sources found within the central 0°.5 of B5.

IRS 1 appears pointlike in all four wavelength bands with an upper limit to its size (FWHM) at 25 μm, where the spatial resolution and signal-to-noise ratio are greatest, of about 20″.

A second source, denoted IRS 2, is found at 60 and 100 μm 5′ southeast of IRS 1. A computer algorithm that matches signals to the signature of a point source extracted IRS 2 from the general background emission at 60 μm on each of 10 observations. The source is unresolved along the narrow dimension of the 60 μm aperture, implying a size less than 1′. At 100 μm, confusion from the rest of B5 makes it difficult to assign a flux density to IRS 2. An estimate of the emission above the general cloud background at the position of IRS 2 is 7 Jy in a 3′ × 5′ beam.

[1]The *Infrared Astronomical Satellite* was developed and is operated by the Netherlands Agency for Aerospace Programs (NIVR), the US National Aeronautics and Space Administration (NASA), and the UK Science and Engineering Research Council (SERC).

IRS 3 and 4 are detected at 12, 25, and 60 μm, but not at 100 μm. Confusion with emission from the rest of the cloud at the longest wavelength may have prevented our detecting weak 100 μm fluxes from these sources. Examination of the Palomar Observatory Sky Survey (POSS) plates reveals the presence of two stellar images within about 1′ of IRS 4, but nothing at the positions of IRS 1, 2, or 3.

Figure 1 shows the energy distributions of the sources detected within the confines of the B5 dark cloud. Corrections of approximately 20% have been applied to account for the shape of each source's energy distribution within the *IRAS* passbands (Paper I). The absolute accuracy of the preliminary *IRAS* photometry is estimated to be 30%.

III. DISCUSSION

a) *Sources Within B5*

i) *IRS 1*

Comparison of the *IRAS* results with maps in a variety of molecular lines shows that IRS 1 is located within the dense core of the B5 molecular cloud, 2′ southeast of the position of maximum $C^{18}O$ column density (Young *et al.* 1982) and at the center of the southern of two clumps observed in NH_3 (Myers and Benson 1983; Benson 1983). The position of the source agrees within 1″ with that of an object with a very red energy distribution detected by Benson, Myers, and Wright (1984, hereafter BMW) at 1.65–5.0 μm. The *IRAS* results imply the presence of grains with temperatures ranging from 30 to 150 K, values typical of molecular clouds heated by an embedded energy source. The near-infrared emission requires the presence of material as hot as 800 K. Table 2 lists the luminosity emitted in these two wavelength regions. Also included in the table is an estimate of the power emitted at wavelengths longer than those observed by *IRAS*, obtained by integrating from 100 μm to infinite wavelength the spectrum of grains with a ν^β emissivity at a temperature derived from

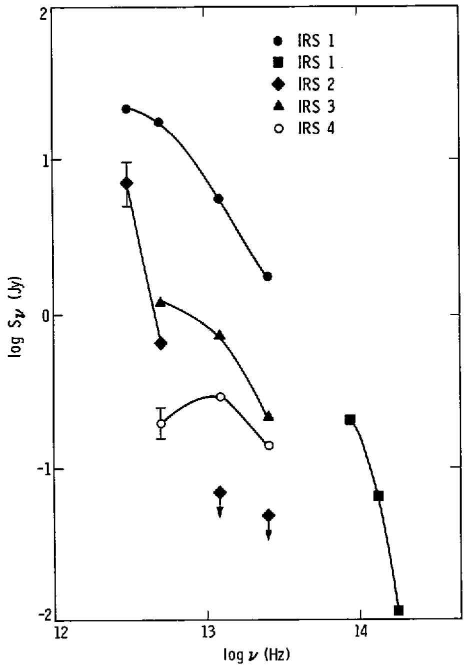

FIG. 1.—Energy distributions for sources found within the B5 cloud. *IRAS* observations of IRS 1 are shown as filled circles. Near-infrared observations of IRS 1 from BMW are shown as squares. Data for IRS 2, IRS 3, and IRS 4 are given as diamonds, triangles, and open circles respectively.

the 60-μm to 100 μm flux ratio. In all the discussions that follow, we assume $\beta = 1$. We adopt a distance of 330 pc to B5 based on the arguments of Sargent (1979) and Herbig and Jones (1983).

The evolutionary phase of B5 IRS 1 is, of course, uncertain. The luminosity and inferred grain temperatures of IRS 1 resemble those of the T Tauri star HL Tau (Cohen 1983) and the bright source found embedded within the dark cloud L1551 (Beichman and Harris 1981; Freidlund *et al.* 1980; Emerson *et al.* 1984). Models of 1 $M_\odot$ protostars (e.g., Stahler, Shu, and Taam 1980) are characterized by dust photospheres of 10^{14} cm radius at 200–400 K. The shell around IRS 1 seen in the near-infrared is hotter (~ 800 K) and smaller (3×10^{13} cm) than this, implying that IRS 1 may be at a later stage of evolution than described by the model. The vertical tracks of low-mass stars in the H-R diagram (Cohen and Kuhi 1979) make it difficult to assign a mass to an embedded source, although typically a 10 $L_\odot$ object is thought to be the pre–main-sequence precursor of a 1 $M_\odot$ star.

ii) *IRS 2*

IRS 2 lies near the edge of the 8′ diameter ^{13}CO maximum found in B5 (Young *et al.* 1982). Because the surface density of 60 μm sources is only 0.65 deg^{-2} at this sensitivity (Rowan-Robinson *et al.* 1984), it is extremely unlikely that IRS 2 is a foreground or background source unrelated to B5. The energy distribution shown in Figure 1 implies a color temperature of 25 K and a physical grain temperature of 22 K. In its temperature and size, IRS 2 is similar to, but fainter than, the compact source found in B335 by Keene *et al.* (1983).

If the emitting dust is optically thin, the mass of gas and dust present is given by (Hildebrand 1983)

$$M(M_0) \geq 4.8 \times 10^{-12} \lambda^4 F_\nu [\exp(14388/\lambda T) - 1] d^2 = 0.24\, M_0, \quad (1)$$

where λ is the observation wavelength in μm, F_ν is the flux density in Jy, T is the grain temperature, and d is the distance to the cloud in kpc. This estimate is a lower limit because material colder than approximately 20 K emits predominantly at wavelengths longer than those observed by *IRAS*. From the upper limit to the size of IRS 2, 1′ or 0.1 pc, the 60 μm optical

TABLE 1
COMPACT SOURCES WITHIN B5

Source	Position (1950) R.A.	Position (1950) Decl.	Flux Density (Jy) F_ν (12 μm)	F_ν (25 μm)	F_ν (60 μm)	F_ν (100 μm)
IRS 1	$3^h44^m31\overset{s}{.}9$	32°42′30″	1.8 ± 0.1	5.5 ± 0.3	18 ± 1	22 ± 2
IRS 2	3 44 53.5	32 40 17	< 0.05	< 0.07	0.65 ± 0.06	~ 7 ±2
IRS 3	3 43 55.6	32 33 54	0.22 ± 0.02	0.74 ± 0.06	1.2 ± 0.1	< 3
IRS 4	3 44 36.1	32 54 33	0.29 ± 0.03	0.61 ± 0.04	0.4 ± 0.1	< 10

TABLE 2
DERIVED PROPERTIES OF COMPACT SOURCES

Source	T (dust) (K)	L (12–100 μm) ($L_\odot$)	L (λ > 100) ($L_\odot$)	L (λ < 12 μm) ($L_\odot$)	L (total) ($L_\odot$)
IRS 1	43[a]	5.9	1.0	2.7	9.6
IRS 2	22[a]	0.3	1.0	...	1.3
IRS 3	85–150[a]	0.5	...	...	> 0.5
IRS 4	170–215[b]	0.3	...	...	> 0.3

[a]Physical temperature derived for $\beta = 1$ grains from 60 and 100 μm flux ratio.
[b]Physical temperature range for $\beta = 1$ grains from 12–60 μm data.

depth must exceed 0.003, and the average density of molecular hydrogen must exceed roughly 10^4 cm^{-3}. For typical grains (e.g., Hildebrand), the corresponding visual extinction lies between 1.5 and 5 mag.

IRS 2 may be a prestellar object observed at a very early stage of gravitational collapse. Approximately 1.3 $L_\odot$ is emitted by a clump of gas and dust with a temperature of about 22 K and a mass larger than 0.25 $M_\odot$. Similar condensations are seen within Orion in NH_3 by Harris *et al.* (1983). The Jeans mass necessary for gravitational instability can be written as

$$M_J(M_\odot) = 12T^{3/2}n^{-1/2} = 7\ M_\odot, \qquad (2)$$

where T is the gas temperature, taken to be 15 K (Young *et al.* 1982), and n is the gas number density in cm^{-3}. The lower limit to the mass of IRS 2 inferred from the 60 and 100 μm data is less than the Jeans mass. In this sense, B5 IRS 2 differs from the source found within B335 which, because of its greater density (10^6 cm^{-3}) and smaller size (< 0.06 pc), has a mass in excess of its Jeans mass.

IRS 2 is similar in some respects to the infrared "cirrus" that is characteristic of the extended structure of the sky at 60 and 100 μm (Low *et al.* 1984). Calculations by Spencer and Leung (1978) suggest that the surfaces of dark clouds heated by the interstellar radiation field can reach temperatures in excess of 25 K. However, because the lower limit to the surface brightness of IRS 2 exceeds 2×10^{-6} W m^{-2} sr^{-1}, which is larger than typical values of the interstellar radiation field (Werner and Salpeter 1969; Mezger, Mathis, and Panagia 1981), an additional source of energy may be required.

No star is visible on the POSS plate at the position of IRS 2, making it unlikely that the 60 μm source is a hot spot on the face of B5 due to a nearby foreground star. To account for the strength of IRS 2, the star would have to emit more than 1 $L_\odot$, making it at least 12 mag visually. Even with 5 mag of extinction, such a star ought to be visible.

It is unlikely that IRS 2 is heated by radiation from IRS 1. Simple energy balance relations (e.g., eq. [9] of Scoville and Kwan 1976) show that the equilibrium grain temperature 0.5 pc away from IRS 1 (10 $L_\odot$) is only 12 K, far less than the observed 22 K. Heating from the nearby nebula IC 348 could increase the radiation field around a local density enhancement at B5 sufficiently to produce the observed source.

High spatial resolution measurements at 60 μm and observations in the lines of molecular species requiring high densities for excitation will determine or set more stringent limits on the size and density of IRS 2 and decide between an internally powered prestellar object or an externally heated clump of material.

iii) *IRS 3 and 4*

Additional measurements in the visual and near-infrared will be required to classify these sources and to determine their bolometric luminosities (Table 2). A strong possibility is that these are pre-main-sequence objects like T Tauri or emission-line stars which can have circumstellar dust shells (Cohen and Kuhi 1979; Harvey, Thronson and Gatley 1979; Harvey and Wilking 1982).

b) *Stability of B5*

B5 is a classic dark cloud with as many as four recently formed stars seen toward it. How can this fecundity be reconciled with the apparent quiescence of the cloud (Young *et al.* 1982; MLB)? MLB concluded that the dense cores of clouds like B5 could not be supported against collapse by the thermal energy characterized by the kinetic temperature of the gas but could be maintained in stable equilibrium by the energy associated with the turbulent motions inferred from the widths of optically thin molecular lines. The presence of IRS 1 in the core of B5 demonstrates that suprathermal motions do not wholly support the cloud. Because B5 is representative of the other clouds observed by MLB, it is likely that many of the other cores are also collapsing and harbor embedded infrared sources. The idea of a nonturbulent cloud with a contracting core conflicts with molecular line observations (Leung, Kutner, and Mead 1982; Myers 1983), so some middle ground between collapsing/nonturbulent and turbulent/noncollapsing clouds is required (e.g., Larson 1981; Scalo and Pumphrey 1982). Low-mass stars may form by the contraction and fragmentation of dense, turbulent cores of small, dark molecular clouds.

IV. CONCLUSIONS

B5 may contain as many as four newly forming or formed stars. The character of these sources ranges from a fully formed star embedded within the core of the cloud, to a dense clump of warm material at the position of a local density maximum, to stars separate from the cloud but enshrouded in luminous dust shells. This varied population is similar to that seen toward the Chamaeleon dark cloud (Baud *et al.* 1984). The formation of low-mass stars is an ongoing process within the cores of nearby dark clouds.

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