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IRAS[1] OBSERVATIONS NEAR YOUNG OBJECTS WITH BIPOLAR OUTFLOWS: L1551 AND HH 46–47

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ABSTRACT

A 6 $L_\odot$ dust-embedded precursor of a low-mass (about 1 $M_\odot$) pre–main-sequence star has been discovered with *IRAS* near the northeast lobe of the bipolar outflow region in the dust cloud L1551 and designated L1551 NE. Star formation is proceeding in at least two locations in L1551, reminiscent of the situation in regions of more massive star formation. If the position of NE in the flow from IRS 5 is indicative of the flow having initiated star formation in NE, then the object can be only about 2.4×10^4 years old. Alternatively, NE could appear by chance to lie in the flow from IRS 5. In the globule ES 0210-6A, we find a 12 $L_\odot$ dust-embedded precursor of a low-mass (about 1 $M_\odot$) pre–main-sequence star which drives the bipolar flow responsible for the string of Herbig-Haro objects HH 46–47 A–D. In this globule, there is only one region of active star formation.

Subject headings: infrared: sources — stars: formation

I. INTRODUCTION

In recent years it has become apparent that many young, dust-embedded stellar or protostellar objects show evidence of outflows indicated by shock-excited Herbig-Haro (HH) objects, high-velocity molecular outflows, and shocked molecular hydrogen emission (see, e.g., Bally and Lada 1983; Schwartz 1983). These flows are often bipolar, probably a consequence of the distribution of the surrounding interstellar material (Königl 1982). Infrared observations provide the locations and luminosities of the heavily dust-embedded objects that are presumed to drive the outflows. *IRAS* is being used to study such objects and their surroundings, and we present results for L1551 and HH 46–47, both of which are associated with HH objects.

II. OBSERVATIONS

Both regions were observed using the *IRAS* survey array whose center wavelengths (and in-scan by cross-scan rectangular fields of view) are 12 μm (0'.75 × 4'.5), 25 μm (0'.75 × 4'.6), 60 μm (1'.5 × 4'.7), and 100 μm (3'.0 × 5'.0). Higher spatial resolution (1'.2) was obtained with the chopped photometric channel (CPC) at 50 and 100 μm. The L1551 region was also mapped using the smaller survey edge detectors to enhance cross-scan resolution at 12 and 25 μm (cross-scan fields of view 1'.2 and 2'.3). The instruments are described by Neugebauer *et al.* (1984, hereafter Paper I). All observations were repeated at least twice to remove any possible effects of moving objects such as asteroids and space debris. The observations are listed in Table 1.

Positions are uncertain by about 15″. Fluxes have been converted from in-band powers to spectral densities using the conversion factors and color corrections given in Paper I. The uncertainty in the absolute photometric calibration is estimated to be approximately 30%. The quoted survey positions and flux densities are preliminary and may differ slightly from those appearing in the final *IRAS* catalog. The *IRAS* luminosity is derived by integration of the observed spectrum between 12 and 100 μm, and the estimates of the bolometric luminosities either assume blackbody emission at the appropriate color temperatures beyond the *IRAS* wavelength limits or, for L1551 IRS 5, use other data in the literature. L1551 IRS 5 and NE are assumed to be in the Taurus cloud at a distance of 160 pc, and HH 46–47 is placed at 300 pc following the argument of Schwartz (1977).

III. DISCUSSION

In Figure 1 the fluxes are plotted in the form log νS_ν against log ν to emphasize the contribution of different spectral regions to the luminosity. The blackbody color temperatures, $T_{\rm bb}$, range from 40 K to 145 K (35–120 K if the grain emissivity, Q, is proportional to ν). In no source will a single-temperature blackbody or $Q \propto \nu$ grain component fit the observed flux densities, and we conclude that a range of dust temperatures exists in each object, as expected for an embedded object heating surrounding dust (see e.g., Harvey, Thronson, and Gatley 1979). All objects are pointlike to our beams, although all are also embedded in more diffuse, low-level emission.

Several lines of evidence (see Schwartz 1984*a* for a review) suggest that the exciting stars powering the shocked flows that excite HH objects are related to young, relatively low-mass stars such as T Tauri stars. Cohen *et al.* (1984*a*) argue that the bolometric luminosities of the exciting stars of HH objects indicate protostars of about 1 $M_\odot$ still in their accretion phase. Our bolometric luminosities (Table 1) and temperatures are consistent with dust-embedded pre–main-sequence precursors of stars having mass of the order of 1 $M_\odot$ (see, e.g.,

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TABLE 1

FLUX DENSITIES AND LUMINOSITIES OF OBSERVED SOURCES

NAME	POSITION (1950.0) R.A.	POSITION (1950.0) Decl.	SURVEY FLUX DENSITY (Jy) 12 μm	25 μm	60 μm	100 μm	LUMINOSITY ($L_\odot$) *IRAS*	Bol.
L1551 IRS 5	$04^h28^m41^s.2$	$+18°01'46''$	13	150	470	530	29	38
L1551 NE	04 28 51.2	+18 02 10	1.2	16	80	130	4	6
HH 46–47 IRS ...	08 24 16.2	−50 50 43	1.0	8.2	34	78	7	12

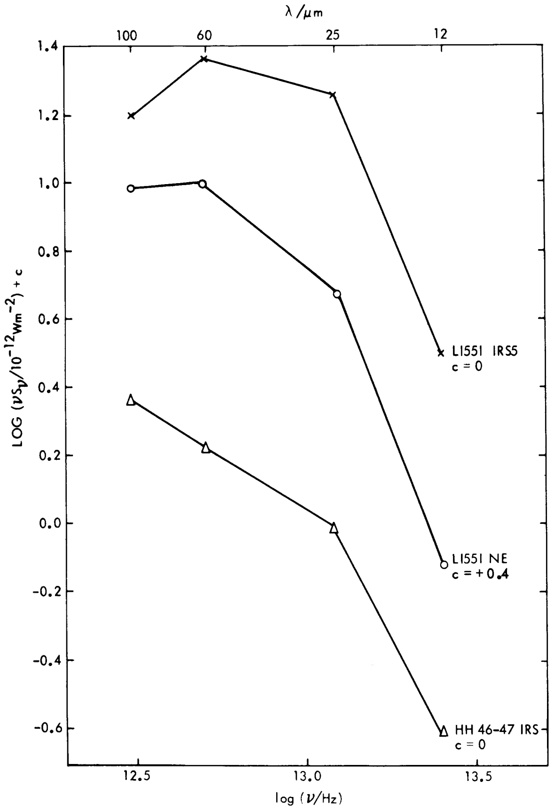

FIG. 1.—Log($\nu S_\nu/10^{-12}$ Wm^{-2}) vs. log infrared spectra of L1551 IRS 5 (*cross*, $c = 0$), L1551 NE (*circle*, $c = +0.4$), and HH 46–47 IRS (*triangle*, $c = 0$).

Cohen and Kuhi 1979), and we adopt this interpretation in what follows. We now discuss each object in turn.

a) *L1551*

L1551 is a dark cloud containing a bipolar flow associated with HH 28, 29, and 102 (Snell, Loren, and Plambeck 1980) and has a known embedded driving source, L1551 IRS 5. Our fluxes for L1551 IRS 5 are consistent with those reported by others (e.g., Beichman and Harris 1981; Fridlund *et al.* 1980; Cohen *et al.* 1984*a*) taking account of uncertainties and beam size effects. Our spectrum (Fig. 1) indicates a T_{bb} range of 65–135 K (45–110 K if $Q \propto \nu$).

Using the CPC and the small survey edge detectors, we detected a second object, which we designate L1551 NE, some 0'.4 north and 2'.4 east of L1551 IRS 5. L1551 NE is about 30 and 10 times brighter than the low-level, extended diffuse emission from the L1551 cloud at 60 and 100 μm respectively. NE is pointlike to the smallest dimensions for our beams at all wavelengths (0'.75 at 12 μm and 25 μm, 1'.2 at 60 μm and 100 μm), allowing us to set a conservative upper limit on its size of 0'.75.

L1551 NE lies almost on the highest (2 K) CO antenna temperature contour line of the northeast bipolar lobe of Snell, Loren, and Plambeck (1980), only 0'.6 off the line joining IRS 5 and the center of the northeast lobe, which presumably indicates the projected direction of the bipolar flow. L1551 NE is 0'.9 from IRS 4 (Strom, Strom, and Vrba 1976), but IRS 4 does not have a very red $H - K$ color, and this fact, together with the lack of positional coincidence with NE, indicates that IRS 4 is probably not the source of the far-infrared flux. This conclusion should be checked by high spatial resolution mid-infrared photometry. Nothing is apparent on the Palomar Observatory Sky Survey plates at the position of L1551 NE. The T_{bb} range is 50–130 K (40–110 K if $Q \propto \nu$), significantly hotter than the approximately 30 K 60–100 μm color temperature of the diffuse cloud emission. Detailed maps of dust color temperature and optical depth in the L1551 cloud must await a better understanding of the calibration of the total flux measured by *IRAS* and a model of the zodiacal background whose contribution is significant at the low ecliptic latitude of L1551.

The observed CO velocities around L1551 IRS 5 show that the flow is channeled in two oppositely directed streams, one away from the observer toward the northeast and the other toward the observer to the southwest, with the southwest lobe having apparently reached the front surface of the cloud as indicated by the optical emission in that region (Snell, Loren, and Plambeck 1980). We can explain the presence of L1551 NE toward the embedded lobe either as a projection effect, a chance coincidence, or as an indication of a causal relationship.

We consider that the observed position of NE toward the more deeply obscured part of L1551 and its spectral similarity to a dust-embedded object argue against the possibility of it being a background or foreground object unrelated to the L1551 cloud but seen in projection toward it.

If the existence of NE is a result of the bipolar flow, it could be interpreted as a region of the dust cloud that has been heated by direct radiation and shocks from the wind or from embedded HH objects whose line and continuum radiation are thermalized by the dense surrounding dust cloud. Cohen *et al.* (1984*a*) have shown that HH 1 and HH 25 are themselves infrared sources, which would seem to support this suggestion. However, the requirement that IRS 5, whose measured bolometric luminosity is 38 $L_\odot$, deposit 6 $L_\odot$ in a small region 0.1 pc away seems incompatible with the estimate by Bally and Lada (1983) of 0.2 $L_\odot$ for the present mechanical luminosity in the wind from IRS 5. If IRS 5 produced much stronger flows in the past or went through eruptive stages, NE might be a remnant of these events (as suggested by Cohen *et al.* 1984*a* for the far-infrared emission from HH 1 and HH 25), although the energetics and time scales required are unclear. However, such regions are likely to be extended, whereas our results suggest a size of less than 0$'$.75.

Adopting the view that the observed luminosity is ultimately generated within NE itself, the object could be a precursor of a pre–main-sequence star which has formed out of another fragment of the L1551 cloud and which is seen near the northeast CO lobe merely by chance. This suggests that L1551 fragmented into at least two cores (IRS 5 and NE which are 0.1 pc apart) in which star formation occurs. (Note also that the T Tauri star HL Tau [Cohen 1983] is only 0.25 pc away from IRS 5.) This situation is reminiscent of the tendency for infrared sources which are high-mass (OB) stars at an early stage of formation to occur in molecular clouds in groups of two or more with a characteristic separation of 0.1 pc (Beichman, Becklin, and Wynn-Williams 1979) and might suggest (if found to be true in general) that similar mechanisms are involved in the fragmentation of clouds leading to both high-mass and low-mass star formation.

The location of NE in the flow from IRS 5 suggests that the flow was involved in triggering the formation of NE. In this scenario, the age of NE is approximately given by the time interval between the flow from IRS 5 reaching the present position of NE (0.1 pc from IRS 5) and expanding to its present radius of 0.5 pc. Edwards and Snell (1983) estimate that the flow reached its present extent in 3×10^4 years, assuming a constant flow velocity and motion in the plane of the sky, which yields an age for NE of 2.4×10^4 years. At this very young age, the radiation emitted from NE must be largely from a protostellar dust photosphere, and we take the 12–25 μm color temperature of 130 K as our best available estimate of the effective dust temperature. We can then use the observed bolometric luminosity to locate NE on the theoretical evolutionary track in the H-R diagram of the dust photosphere of a protostar accreting mass at a typical rate of 10^{-5} $M_{\odot}$ yr to find that it is about 1×10^4 years since formation of its hydrostatic core (Stahler, Shu, and Taam 1980). In the remaining 1.4×10^4 years that would then be available between the passage of the flow from NE and the formation of the hydrostatic core, the cloud must have been compressed from its initial density and collapsed to form the core. A cloud with an initial hydrogen density of roughly 10^7 cm^{-3} has a free-fall time corresponding to 1.4×10^4 years. If the flow did initiate NE, it must have compressed the original cloud material from its initial density to 10^7 cm^{-3}, which may be achievable with a realistic initial density, Mach number, and an isothermal shock. Further theoretical work on this possibility is desirable.

b) *HH 46–47*

Photographs of HH 46–47 and the globule ES 0210-6A from which they appear to have been ejected are shown and discussed in Graham and Elias (1983) and Schwartz (1983). HH 46–47 IRS (Table 1) is 0$'$.2 southwest of the position of HH 46 (Schwartz 1977) and of its exciting star (Graham and Elias 1983), approximately on the projection toward HH 47 C of the nebulous bridge of material joining HH 47 A and HH 46. This suggests that HH 46–47 IRS is the embedded object driving the flow that produces the HH objects. Higher spatial resolution observations at 10 μm by Cohen *et al.* (1984*b*) independently confirm our position within 3$''$, although these authors failed to detect HH 46–47 IRS at 52 and 65 μm and observed about a third of our flux at 100 μm presumably because of beam size effects. HH 46–47 IRS lies toward the edge of the globule. Although extended emission at 60 and 100 μm is seen from the globule itself in the survey data, there are no other discrete sources resolved within it by *IRAS*, thus confirming the isolated nature of this star formation event (Schwartz 1977). The fact that HH 46–47 IRS is located toward the edge of the globule that faces the expanding Gum nebula is in qualitative agreement with the suggestion by Schwartz (1977) that the Gum nebula may have been a factor in triggering star formation in the globule. The spectrum (Fig. 1) indicates a T_{bb} range of 40–145 K (35–120 K if $Q \propto \nu$).

The globule ES 0210-6A within which HH 46–47 IRS has apparently formed is well delineated and detached from other dark material. The globule mass has been estimated as 25 $M_{\odot}$ by Bok (1978). Another estimate can be made from the H_2CO absorption results of Goss *et al.* (1980) using the relation given in Whiteoak and Gardner (1974), taking $T_s = 2.7$ K, an abundance $X(H_2CO) = N(H_2CO)/N(H_2)$ of $2\text{–}4 \times 10^{-9}$ (Evans *et al.* 1975), and a cloud projected area of 18 arcmin^2, which yields 7–15 $M_{\odot}$. Uncertainty in this mass arises because the abundance is related to the cloud density n (cm^{-3}) by $X(H_2CO) = 3.3 \times 10^{-4}\ n^{-1.26}$ (Wootten, Snell, and Evans 1980). However, we expect the cloud density to be around 10^4 cm^{-3}, a value typical for the cores of dark clouds, in which case the abundance range given by Evans *et al.* (1975) is appropriate. If we take a factor of 2 uncertainty in the mass of the newly forming stellar object (i.e., 0.5–2.0 $M_{\odot}$), the extreme values suggest that the local efficiency of mass conversion from cloud to star is between 2% and 30% in this globule, consistent with the star formation efficiency of approximately 10% estimated by Cohen and Kuhi (1979) in regions where T Tauri stars are optically visible. We recall that, in this case, *IRAS* shows that there is only one region of star formation activity in the cloud.

IV. CONCLUSIONS

In L1551 we find, in addition to L1551 IRS 5, a second source, L1551 NE, displaced from IRS 5 and located near the northeast CO lobe of the bipolar flow. The object appears to be a 6 $L_{\odot}$ dust-embedded precursor of a low-mass (about 1 $M_{\odot}$) pre–main-sequence star and indicates that star formation is occurring in more than one location in the L1551 cloud, similar to the situation found in regions of more massive star formation. The position of NE toward the northeast lobe of the bipolar outflow from IRS 5 could be by chance or may suggest some dynamical interaction in which case NE is about 2.4×10^4 years old. A detailed theoretical analysis is needed to assess whether this time scale is reasonable given the initial cloud conditions and the properties of the flow.

In the globule ES 0210-6A associated with HH 46–47, we find a single 12 $L_{\odot}$ dust-embedded pre–main-sequence precursor of a low-mass (about 1 $M_{\odot}$) star which drives the flow that produces the string of Herbig-Haro objects.

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