THE ASTROPHYSICAL JOURNAL, 277:L13–L16, 1984 February 1

FAR-INFRARED AND SUBMILLIMETER OBSERVATIONS OF THE LOW-LUMINOSITY PROTOSTARS L1455 FIR AND L1551 IRS 5: THE CONFINEMENT OF BIPOLAR OUTFLOWS

J. A. DAVIDSON[1,2,3] AND D. T. JAFFE[1,3,4]
Received 1983 August 23; accepted 1983 October 19

ABSTRACT

We present detailed broad-band 40–400 μm observations of two low-luminosity pre–main-sequence (PMS) objects: L1455 FIR ($L = 1.5\ L_\odot$) and L1551 IRS 5 ($L = 23\ L_\odot$). Compact ($< 7 \times 10^{16}$ cm), dense ($n_{H_2} \geq 4 \times 10^5$ and 1×10^6 cm^{-3}) dust cores surround both exciting stars and have masses (0.2 and 0.7 $M_\odot$) comparable to the stellar masses. The temperatures of these cores ($\sim$ 35 K) are intermediate between those of the low-luminosity PMS star in B335 and the far-IR emitting dust shells around visible PMS stars. We investigate the role the cores can play in channeling the high-velocity molecular outflows seen in both sources and find that the core of L1551 can channel an intrinsically isotropic stellar wind to produce the observed bipolar flow only if it has a radius $\leq 7.5 \times 10^{15}$ cm. This limit rules out *interstellar* ($\geq 10^3$ AU), as opposed to circumstellar ($\leq 10^3$ AU), material as the cause of the outflow's bipolar appearance.

Subject headings: infrared: general — photometry — stars: circumstellar shells — stars: pre–main-sequence — stars: winds

I. INTRODUCTION

Deeply embedded, low-luminosity ($L \leq 100\ L_\odot$) pre–main-sequence (PMS) objects have been studied extensively in the near-infrared (Strom 1977; Elias 1978*a*, *b*; Cohen and Kuhi 1979; Hyland 1981, and references therein). Extensive high-resolution far-infrared and submillimeter mapping and photometry, however, exist for only one such object: B335 (Keene *et al.* 1983). We present here broad-band far-IR and submillimeter (SMM) observations of two other low-luminosity PMS objects: L1455 FIR and L1551 IRS 5.

L1455, an extended dark cloud in the Taurus complex (distance $\sim$ 160 pc), contains an approximately 4′ region where ^{12}CO velocities in the wings of the line profiles exceed the ambient cloud velocity by ± 10 km s^{-1} (Frerking and Langer 1982). We have detected a warm ($T_d \sim 34$ K), compact ($\leq 30''$) far-IR source (L1455 FIR) near the center of the region containing high-velocity gas. This source has a luminosity of only about 1.5 $L_\odot$. There are no published near-IR observations of this source. L1551, another Taurus cloud, contains a compact 1.2–20 μm object (IRS 5: Strom, Strom, and Vrba 1976; Beichman and Harris 1981) with many of the characteristics common to high-luminosity PMS objects. The far-IR luminosity of the 5′ diameter region around IRS 5, however, is only 25 $L_\odot$ (Fridlund *et al.* 1980). Centered on IRS 5 is a large, well-defined, double-lobed molecular outflow extending over 25′ (Snell, Loren, and Plambeck 1980, hereafter SLP). By studying these two sources, we wish to determine the nature of the deeply embedded, low-luminosity PMS sources, characterize the dense cores surrounding the young stars, and evaluate confinement mechanisms for the apparently bipolar high-velocity outflows.

[1]Enrico Fermi Institute, University of Chicago.
[2]Department of Physics, University of Chicago.
[3]Visiting Astronomer at the Infrared Telescope Facility which is operated by the University of Hawaii under contract with the National Aeronautics and Space Administration.
[4]Space Sciences Lab, University of California, Berkeley.

II. OBSERVATIONS

We used the 0.91 m telescope of the NASA Kuiper Airborne Observatory (KAO) with the Yerkes Observatory H-1 and G-2 bolometer systems (Harper *et al.* 1984) to observe far-IR emission from L1551 in 1981 December and from L1455 in 1982 September and 1983 January. For these observations, the H-1 system had an effective wavelength of 190 μm and a measured beam profile with a full width at half-maximum (FWHM) of 92″. The G-2 system has five filters with effective wavelengths of 37 μm, 58 μm, 103 μm, 120 μm, and 168 μm (Jaffe *et al.* 1984). This system contains a spatial array with six 49″ beams in a closely packed hexagonal pattern around a central 49″ beam. The combined effects of cross-talk and optical spillover are approximately 1% at 40 μm and approximately 6% at 168 μm. In 1981 December, the separation of the two chopped beams was 6′ NW–SE. In 1982 September and 1983 January, we chopped 4′ in cross-elevation. The absolute pointing accuracy was approximately 15″. We derived the flux calibration from observations of W3(OH), OMC-1, and NGC 7027 (D. A. Harper, private communication).

We made the SMM observations of L1551 on the 3.75 m United Kingdom Infrared Telescope (UKIRT)[5] on Mauna Kea in 1981 November with the University of Chicago f/35 SMM photometer (Whitcomb, Hildebrand, and Keene 1980). A combination of metal mesh interference filters, atmospheric transmission, and source spectra resulted in an effective wavelength of approximately 400 μm. The measured beam profile

[5]The UKIRT is operated by the Royal Observatory, Edinburgh, an establishment of the Science and Engineering Research Council.

TABLE 1

PROPERTIES OF L1455 AND L1551

Parameter	L1455	L1551
Distance	160 pc[a]	160 pc[b]
Position of peak flux at 400 μm	$\alpha(1950) = 03^h24^m36^s.2$ $\delta(1950) = 30°02'40''$	$\alpha(1950) = 04^h28^m40^s.5$ $\delta(1950) = 18°01'42''$
Luminosity	$1.5(\frac{D}{160\,pc})^2\,L_\odot$	$23(\frac{D}{160\,pc})^2\,L_\odot$
100 μm/60 μm dust color temperature	(34 ± 3) K for $\nu B_\nu(T)$ (43 ± 4) K for $B_\nu(T)$	(37 ± 3) K for $\nu B_\nu(T)$ (47 ± 5) K for $B_\nu(T)$
Size of core at 120 μm, ϑ_c	$\leq 30''$	$\leq 30''$
Size of core at 400 μm	...	$\leq 35''$
Mass of core for $\vartheta_c = 30''$	$0.2(\frac{D}{160\,pc})^2\,M_\odot$	$0.7(\frac{D}{160\,pc})^2\,M_\odot$

[a]Frerking and Langer 1982.
[b]Snell 1979.

had a FWHM of 37″. The positional accuracy was ±6″ and the chopping secondary mirror gave us two beams separated by 2′.7 E–W. We derived the flux calibration from observations of OMC-1 and Mars. We observed L1455 at 400 μm in 1982 November on the 3 m NASA infrared telescope (IRTF) with the same photometer. At the IRTF, the beam size was 48″, the positional accuracy was ±8″, and the chopper throw was 2′ E–W.

We used an iterative procedure to calculate the flux densities from the observed signals (Jaffe *et al.* 1984). Systematic uncertainties due to diffraction effects, atmospheric transmission, spectral response, and the fluxes of the calibrators usually dominate the random errors. We estimate a total uncertainty of ±30% in both airborne and ground-based flux density measurements.

Table 1 gives a summary of the observed properties of both L1455 and L1551. For L1455, we derived the 120 μm size limit from the upper limit to the fluxes in the outer channels of the G-2 array when the center channel was on the source. We derived the upper limit to the 120 μm and 400 μm size of L1551 from cross scans. Our 120 μm map over an approximately 5′ diameter region indicates that IRS 5 must be the only embedded source in the core of L1551. Neither source was resolved to a limit of 30″ (7×10^{16} cm at 160 pc). The source positions for L1551 at 120 μm and 400 μm agree to better than the nominal positional accuracy (±15″ and ±6″) with the position of the 1.2–20 μm source IRS 5 (Beichman and Harris 1981). Figure 1 shows the source spectra.

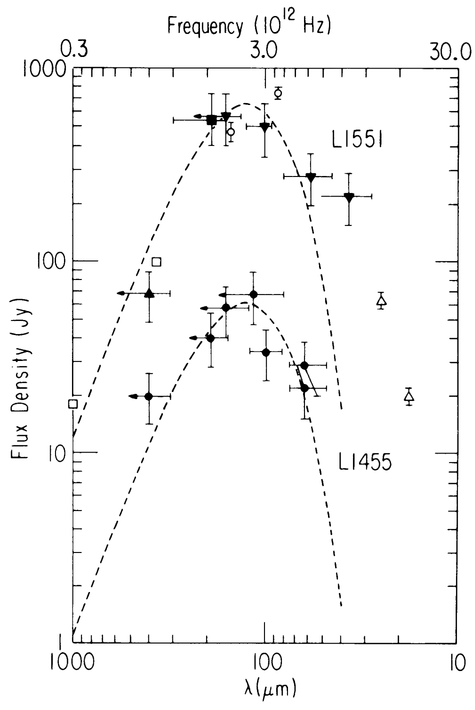

FIG. 1.—Source spectra of L1455 FIR and L1551 IRS 5. All measurements are made at the positions of the compact sources. Both curves have the form νB_ν(30 K). The filled circles show our measurements of L1455 with a 49″ (FWHM) beam. The filled square, triangle, and inverted triangles show our measurements of L1551 IRS 5 with beam sizes of 92″, 37″, and 49″ respectively. The other points of L1551 are as follows: *open triangles*, Beichman and Harris (1981; 3″.8 beam); *open circles*, Fridlund *et al.* (1980; 270″ beam); *open square*, Phillips *et al.* (1982; 86″ beam). For our measurements, the vertical bars represent the total errors. The horizontal bars indicate the half-power points of the filter passbands. The horizontal bars with arrows indicate that low-pass filters were used. For the measurements made by others, the vertical bars represent the flux errors as given in their papers.

III. DISCUSSION

a) *Comparison with Other Objects*

The 60–100 μm temperatures of L1455 and L1551 are comparable to the temperatures of dense clumps surrounding newly formed early B stars with far-IR luminosities 10^3–10^4 times larger (Jaffe *et al.* 1984) and considerably hotter than the other low-luminosity PMS object we have investigated, B335 (Keene *et al.* 1983). B335 has a 60–100 μm temperature of only about 23 K. The luminosity and mass of B335, however, are comparable to those of L1455 and L1551. If B335 is at its upper limit distance of 400 pc (Bok and McCarthy 1974), its luminosity and mass are 7.6 $L_\odot$ and 6.5 $M_\odot$. If its distance is 160 pc, these values become 1.2 $L_\odot$ and 1.0 $M_\odot$ (Keene *et al.* 1983).

b) *Nature of the Central Stars*

The bolometric luminosities of L1455 (1.5 $L_\odot$) and L1551 (23 $L_\odot$) would imply embedded stars of type F8 and type A5, if these stars were already on the main sequence. The long PMS lifetimes of late-type stars, however, make it unlikely that they would remain embedded in their dense cocoons all the way to the main sequence. As in the case of B335, if they are still descending the Hayashi track and lie well above the main sequence, as do visible T Tauri stars with similar luminosities (see Strom 1977), they could be considerably less massive. Harvey, Thronson, and Gatley (1979) and Cohen (1983) have made far-IR observations of less deeply embedded PMS stars with similar luminosities. The clouds around these already optically visible stars generally have higher 60–100 μm color temperatures and emit a substantial fraction of their energy at $\lambda \leq 40$ μm. This suggests that there may be a correlation between evolutionary state and dust temperatures, with the youngest objects (B335) having the coolest surrounding clouds.

c) *Nature of the Clouds*

The breadth of the peak in the spectrum of L1551 between 60 μm and 200 μm implies a large amount of dust with $T_d \leq 35$ K within approximately 5×10^{16} cm of IRS 5. In both sources, the mean temperature of the dust emitting at 400 μm may be less than that given by the 60–100 μm dust color temperature. For this reason, and since we have only upper limits to the source sizes, the values of the peak 400 μm optical depths (≥ 0.005 for L1455 and ≥ 0.016 for L1551, using eq. [1] of Jaffe *et al.* 1983) are only lower limits. Using a ratio of visual extinction, A_v, to 400 μm optical depth, $A_v/\tau_{400\ \mu\mathrm{m}} \sim 6000$, derived from the results of Whitcomb *et al.* (1981), we can place lower limits on A_v toward the cloud cores of ≥ 30 for L1455 and ≥ 100 for L1551. The 1.25–1.65 μm data for L1551 IRS 5 (Strom, Strom, and Vrba 1976) imply $A_v \sim 30$ for an underlying Rayleigh-Jeans spectrum. The SMM optical depths result in lower limits for the densities at the source peaks (Hildebrand 1983) of $n_{\mathrm{H}_2} \geq 4 \times 10^5$ $(D/160\ \mathrm{pc})^{-1}$ for L1455 and $n_{\mathrm{H}_2} \geq 1 \times 10^6$ $(D/160\ \mathrm{pc})^{-1}$ for L1551. We derive a mass of 0.2 $(D/160\ \mathrm{pc})^2$ $M_\odot$ for L1455 and 0.7 $(D/160\ \mathrm{pc})^2$ $M_\odot$ for L1551, assuming $\tau_{400\ \mu\mathrm{m}} \ll 1$. These masses are comparable to the probable masses of the exciting stars.

d) *Nature of the Outflow*

The ^{12}CO observations of L1551 reveal that the high-velocity gas has a pronounced double-lobed distribution that extends approximately 0.5 pc (10′) from IRS 5 (SLP). The CO radial velocities together with transverse velocities for Herbig-Haro objects within the lobes (Cudworth and Herbig 1979) imply that the material flows away from IRS 5. The channeling mechanism for the outflow is unknown. A number of models of stellar-wind–driven outflows attempt to account for the apparently bipolar structure present in many molecular flows (Cantó *et al.* 1981; Hartmann and MacGregor 1982; Königl 1982; Draine 1983). These models discuss both extrinsically channeled flows, i.e., flows that are initially isotropic and are channeled by the matter around the star, and intrinsically anisotropic flows where the generation and shape of the wind are causally connected. If the flow is initially isotropic, we can use the current observations to place an upper limit on the size scale of the matter that channels the flow.

Consider a cloud core with an isotropic matter distribution. We can estimate the momentum flux per sterdian $\dot{P}(\Omega)$ of the part of the wind that drives the outflow from the mass, M_L, velocity, V_L, and angular and linear extent, Ω_L and r_L, of the swept-up material in the lobes by balancing forces

$$\int_{\mathrm{Lobe}} \dot{P}(\Omega)\, d\Omega \approx \frac{M_L V_L^2}{r_L}\ \mathrm{g\ cm\ s^{-2}}. \qquad (1)$$

We have ignored gravitational forces due to the mass of the molecular core and the star since these are small for values of r_L that are large compared with the core size.

To obtain a lower limit to the outward motion of the quiescent material in the core due to the momentum deposited by an isotropic stellar wind $[\dot{P}(\Omega) = \dot{P}]$, we consider only the counteracting gravitational force, F, and ignore thermal and magnetic pressure. The velocity of the core, V_C, which has mass M_C and solid angle $\Omega_C \approx 4\pi$ is then

$$V_C \approx \frac{M_L}{M_C}\left(\frac{\Omega_C}{\Omega_L} - \frac{F}{\Omega_L \dot{P}}\right) V_L, \qquad (2)$$

where $\Omega_L \dot{P}$ is the result of the integral in equation (1). The gravitational force binding the core is given by

$$F = \left(\frac{4 \ln 2}{\pi}\right)^{3/2} \frac{\pi G M_c}{r_c^2}\left[\left(\frac{\pi}{\ln 2}\right)^{1/2} M_\star + \frac{0.56}{(\pi \ln 2)^{1/2}} M_c\right] \qquad (3)$$

where G is the gravitational constant, r_c the half-width to half-maximum of the core density distribution (assumed to be Gaussian), and $M_\star$ the mass of the exciting star. (Eq. [3] can be modified to account for other possible core geometries by changes in the dimensionless scaling constants.) For the southwest outflow lobe in L1551, we obtain values of $\Omega_L \dot{P} \sim 6 \times 10^{26}$ dyn and $\Omega_C/\Omega_L \sim 50$ from the data of SLP. In the absence of gravity, we therefore derive a velocity for the material in the core of $V_C \sim 100$ km s^{-1}, larger even than the velocity of the swept-up material in the lobes and therefore not physically reasonable. The observed velocity of this material is ≤ 3 km s^{-1} (SLP). Inserting $M_\star = 1.5$ $M_\odot$ and a total gas mass in the core of 0.7 $M_\odot$ into equation (3), we obtain a radius of 7.5×10^{15} cm ($\vartheta_C = 6''$) for a core where the thrust of an isotropic wind balances the force of gravity and makes the core static, as observed. At this size, the core would have a 400 μm optical depth of 0.3 and $n_{\mathrm{H}_2} \sim 10^8$ cm^{-3}. On this size scale, both thermal and milligauss range magnetic pressures are small compared with the wind pressure. If part of the core of L1551 were optically thick, its mass and density could be larger than we have estimated from the SMM measurements. The measured 400 μm flux and bolometric luminosity place a lower limit on the density of any optically thick core component and an upper limit on its size. If all of the 400 μm flux comes from a blackbody source around IRS 5, its temperature is $\gtrsim 75$ K and its size is $\leq 4 \times 10^{15}$ cm (2″). It will therefore have $n_{H_2} \geq 10^9$ cm^{-3}. This size is the same as the size of the 5 GHz continuum source of Cohen, Bieging, and Schwartz (1982). Our observations are therefore consistent with the possibility that a small, dense "circumstellar" ($r < 10^{16}$ cm) core surrounding the exciting star channels an initially isotropic stellar wind in L1551. They do not favor this possibility, however, over a model with a larger "interstellar" ($r_c > 10^{16}$ cm) cloud core and an intrinsically anisotropic outflow. The small mass of the cloud core in L1551 measured at 400 μm rules out models in which an interstellar matter distribution with $r_d > 10^{16}$ cm channels an initially isotropic flow.

We thank M. Dragovan, I. Gatley, W. Glaccum, D. A. Harper, R. H. Hildebrand, R. F. Loewenstein, R. Pernic, T. Roellig, M. W. Werner, and B. Zuckerman for help with the observations, and R. Genzel and R. H. Hildebrand for helpful comments. This work was supported in part by NASA grant NSG 2057 and NSF grant AST 8117134 to the University of Chicago.

REFERENCES

Beichman, C. A., and Harris, S. 1981, *Ap. J.*, **245**, 589.
Bok, B. J., and McCarthy, C. C. 1974, *A.J.*, **79**, 42.
Cantó, J., Rodríguez, L. F., Barral, J. F., and Carral, P. 1981, *Ap. J.*, **244**, 102.
Cohen, M. 1983, *Ap. J. (Letters)*, **270**, L69.
Cohen, M., Bieging, J. H., and Schwartz, P. R. 1982, *Ap. J.*, **253**, 707.
Cohen, M., and Kuhi, L. V. 1979, *Ap. J. Suppl.*, **41**, 743.
Cudworth, K. M., and Herbig, G. H. 1979, *A.J.*, **84**, 548.
Draine, B. T. 1983, preprint.
Elias, J. H. 1978*a*, *Ap. J.*, **224**, 453.
______. 1978*b*, *Ap. J.*, **224**, 857.
Frerking, M. A., and Langer, W. D. 1982, *Ap. J.*, **256**, 523.
Fridlund, C. V. M., Nordh, H. L., Van Duinen, R. J., Aalders, J. W. G., and Sargent, A. I. 1980, *Astr. Ap.*, **92**, L1.
Harper, D. A., Glaccum, W., Loewenstein, R. F., and Pernic, R. 1984, in preparation.
Hartmann, L., and MacGregor, K. B. 1982, *Ap. J.*, **259**, 180.
Harvey, P., Thronson, H. A., and Gatley, I. 1979, *Ap. J.*, **231**, 115.
Hildebrand, R. H. 1983, *Quart. J. R.A.S.*, **24**, 267.
Hyland, A. R. 1981, in *IAU Symposium 96, Infrared Astronomy*, ed. C. G. Wynn-Williams and D. P. Cruikshank (Dordrecht: Reidel), p. 125.
Jaffe, D. T., Hildebrand, R. H., Keene, J., Harper, D. A., Loewenstein, R. F., and Moran, J. M. 1984, *Ap. J.*, submitted.
Jaffe, D. T., Hildebrand, R. H., Keene, J., and Whitcomb, S. E. 1983, *Ap. J. (Letters)*, **273**, L89.
Keene, J., Davidson, J., Harper, D. A., Hildebrand, R. H., Jaffe, D. T., Loewenstein, R. F., Low, F. J., and Pernic, R. 1983, *Ap. J. (Letters)*, **274**, L43.
Königl, A. 1982, *Ap. J.*, **261**, 115.
Phillips, J. P., White, G. J., Ade, P. A. R., Cunningham, C. T., Robson, E. I., and Watt, G. D. 1982, in *Regions of Recent Star Formation*, ed. R. S. Roger and P. E. Dewdney (Dordrecht: Reidel), p. 323.
Snell, R. L. 1979, Ph.D. Thesis, University of Texas, Austin.
Snell, R. L., Loren, R. B., and Plambeck, R. L. 1980, *Ap. J. (Letters)*, **239**, L17 (SLP).
Strom, S. E. 1977, in *IAU Symposium 75, Star Formation*, ed. T. de Jong and A. Maeder (Dordrecht: Reidel), p. 179.
Strom, K. M., Strom, S. E., and Vrba, F. J. 1976, *Ap. J.*, **81**, 320.
Whitcomb, S. E., Gatley, I., Hildebrand, R. H., Keene, J., Sellgren, K., and Werner, M. W. 1981, *Ap. J.*, **246**, 416.
Whitcomb, S. E., Hildebrand, R. H., and Keene, J. 1980, *Pub. A.S.P.*, **92**, 863.

J. A. Davidson: Enrico Fermi Institute, University of Chicago, 5630 South Ellis Avenue, Chicago, IL 60637

D. T. Jaffe: University of California, Space Sciences Laboratory, Berkeley, CA 94720