THE ASTROPHYSICAL JOURNAL, 316:265–274, 1987 May 1

INFRARED LINE OBSERVATIONS OF LOW-LUMINOSITY OUTFLOW SOURCES

HOWARD A. SMITH,[1,2] J. FISCHER,[1,2,3,4] T. R. GEBALLE,[5] AND P. R. SCHWARTZ[1,4]
Received 1986 August 14; accepted 1986 October 6

ABSTRACT

We have observed the low-luminosity young stellar objects B5 IRS 1, L1262, L1489, L1536, L1551 IRS 5, and L1582 in the infrared recombination lines of Brα and/or Brγ, and in the 5 GHz continuum. Line emission was detected from B5 IRS 1 in Brα, and from L1536 in Brα and Brγ. Limits to the line flux from other sources are $\leq 1 \times 10^{-20}$ W cm^{-2}. All have radio continuum fluxes <0.5 mJy at 6 cm. We have also set new upper limits of 1×10^{-20} W cm^{-2} to the Brα flux from the double radio source in L1455, and from NGC 2071 IRS 1, 2, and 3. The results indicate that low-luminosity outflow sources have strong ionized winds, despite the fact that their stellar ultraviolet production is relatively modest. The data also provide an indication that winds from low-luminosity objects possess a wide range of outflow parameters, with greater variation than is found in high-luminosity outflows.

In B5 IRS 1 conventional wind models provide a picture consistent with the measurements, and imply a mass loss rate of $\sim 4 \times 10^{-9}$ $M_\odot$ yr^{-1}. For the sources L1262, L1489, and L1582 the flux limits are also consistent with emission from a conventional stellar outflow. In contrast, the source L1536 has a Brα/Brγ line ratio less than unity, inconsistent with the usual model. We derive a general analytic expression for the emission from an ionized wind with a Sobolev flow and conclude that L1536 either has a rapidly decelerating flow or has a small emitting region like a low-luminosity Ae star, the first reported case of such a peculiar outflow. We show how a radio continuum spectral index $\alpha < 1$ could arise from a decelerating flow. L1455A and L1455B have measured spectral indices $\alpha = -0.8$ at 6 cm and might be other examples of this kind of flow.

No line emission is seen from the strong outflows associated with L1551 IRS 5 and NGC 2071 (a high-luminosity source), both of which are often considered prototypes of the class. Since shock excitation has been suggested to explain the radio continuum in L1551 IRS 5, we derive an expression for the emission-line intensity expected from such a region; it turns out to be large. We find that the limits we measure are consistent with emission from a conventional wind buried inside an obscuring disk.

Subject headings: infrared: sources — infrared: spectra — nebulae: H II regions — stars: emission-line — stars: formation — stars: winds

I. INTRODUCTION

a) Context of Infrared Line Observations

The phenomenon of outflows from young stellar objects (YSOs) has steadily become clearer over the last few years as CO millimeter-wave observations map more flows, and a variety of radio and infrared techniques probe the gas and dust components (for example, see the review in Lada 1985). In the majority of well-studied cases the stellar sources are of high luminosity ($L > 100\ L_\odot$), simply because these objects turn out to have larger mass loss rates and produce brighter flows. CO millimeter-wave observations have also provided evidence for mass loss in low-luminosity objects. While some of these weaker flows have also been mapped (Goldsmith *et al.* 1984), often the outflow is detected only by the broad extent of the wings of the CO emission (Frerking and Langer 1982) or is inferred from the presence of dense clumps of material traced by NH_3 (Myers and Benson 1983). These data indicate that the outflow seen in low-luminosity sources is analogous to that in high-mass, high-luminosity sources, and suggest that the outflow phenomenon occurs perhaps universally as stars evolve toward the main sequence.

High-luminosity sources are frequently found to have ionized winds at the inner portion of their flows, as evidenced by radio continuum and IR recombination line emission (e.g., Thompson 1981; Simon *et al.* 1981; Persson *et al.* 1984). For these objects the ionized material usually can be produced by Lyman continuum photons from the star according to zero-age main-sequence (ZAMS) models (Panagia 1973); however, the spectral index of the radio continuum and ratios of recombination line intensities are clearly different from those seen in normal H II regions. Some descriptions of winds show that even with an inadequate supply of stellar ionizing photons collisions or excitations from the $n = 2$ level are able to excite or ionize hydrogen (Krolik and Smith 1981; Simon *et al.* 1983). Other models of the outflows predict the presence of accretion disks that generate ample UV radiation (Thompson *et al.* 1977; Pudritz 1985). Finally, the association of shocked material with the flow, in H_2 for example, has led to the suggestion of shock-produced Lyman continuum photons (Torrelles *et al.* 1985). Therefore, low-luminosity sources might have weak but detectable evidence of such ionized winds even though UV radiation from their stellar components might be unable to sustain the ionization. Persson *et al.* (1984) found evidence for such a wind around HL Tau in their Brα observations.

The results of theoretical modeling of line and continuum radiation from winds by Krolik and Smith (1981, hereafter KS), Simon *et al.* (1983, hereafter SFCFM), Felli *et al.* (1984),

[1] E. O. Hulburt Center for Space Research, Naval Research Laboratory.
[2] Guest Observer at the United Kingdom Infrared Telescope.
[3] Applied Research Corporation.
[4] Visiting Astronomer, Kitt Peak National Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
[5] United Kingdom Infrared Telescope and Foundation for Astronomical Research in the Netherlands (ASTRON).

and others show that the detected radiation is generally optically thick, and therefore the line radiation at different wavelengths has arisen from different parts of the flow. One consequence is that the IR-line–to–radio-continuum ratio in wind sources is about 300 times greater than the ratio in H II regions, and measurements of a weak outflow—for example, with $\dot{M} \approx 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ at 1 kpc distance—while quite easy with existing IR instruments (if extinction is modest), are beyond the present capability of the VLA (see § II below). As a result, IR line observations offer the possibility of inferring an outflow from a source too weak for this to be done easily in the radio continuum. The small IR beamwidth also permits the identification of an outflow source in a confused field previously identified only by broad CO wings. Of course the IR lines have the additional advantage of providing kinematic information on the inner flow region. For all these reasons we have begun a program to detect and study ionized winds via the IR lines in a small selection of low-luminosity sources.

b) *Description of Individual Sources*

A selection of low-luminosity embedded sources was available from the work of Myers and Benson (1983), who surveyed in NH_3 the visually opaque regions of nearby dark clouds that were associated with T Tauri stars. They were looking for evidence of dense cores, and used the results of their CO survey (Myers, Linke, and Benson 1983) to identify those sources with high column densities. They found 27 regions with NH_3 condensations, in five of which they also found near-infrared point sources: B5, L1262, L1489, L1536, and L1582 (Benson, Myers, and Wright 1984). For these five they obtained near-IR photometry. The detection of the dense cores was important to our program because they signaled the presence of young stellar objects, and also because of suggestions that such spots were enhanced by the snowplow effect of winds (Schwartz, Waak, and Smith 1983; Torrelles *et al.* 1983). Accurate coordinates for the near-infrared point sources made observations with the small IR beam (5."4) possible.

i) *B5*

The dark cloud Barnard 5 had previously been identified as unusual by CO observations of Young *et al.* (1982). The cloud is about 40′ in extent, with a roughly circular appearance, and is located in the Taurus-Aurigae complex at a distance of about 350 pc (Herbig and Jones 1981). The CO observations of this region by Young *et al.* found a complicated kinematic structure which they suggested was due to rotation, with evidence for a counterrotating core but no evidence of outflow. Indeed, they pointed out that the data alone provide no evidence for star formation there. *Infrared Astronomical Satellite* (*IRAS*) observations of the region were analyzed by Beichman *et al.* (1984), who found four point sources embedded in the cloud separated by about 6′–20′, corresponding to 0.1–0.3 pc. IRS 1 (located very close to the center of the approximately spherical cloud) is the brightest, with $L_T \approx 10\ L_\odot$, and a grain temperature $\sim$30–150 K in the far-IR. Beichman *et al.* interpreted the *IRAS* data using the T Tauri–type star HL Tau as a model, and concluded that IRS 1 is about a 1 $M_\odot$ pre–main-sequence star. Benson, Myers, and Wright (1984) obtained a map in NH_3 of B5 IRS 1 which shows an elliptical ridge of dense material extending about 5′ in a north-south orientation. Although the CO line emission from the source showed no wings, the presence of the NH_3 core and the identification of a stellar source made it a good low-luminosity candidate for an outflow, and suitable for IR line emission observations. In more recent observations, however, Goldsmith, Langer, and Wilson (1986) obtained high spatial resolution, high-sensitivity CO 1–0 maps of the B5 cloud, and found that IRS 1 does have broad CO wings and a roughly bipolar structure. They also found outflow activity around the other *IRAS* sources in the cloud, IRS 2, 3, and 4, and make a case for sequential star formation in which IRS 1 is the youngest object.

ii) *L1262, L1489, L1536, and L1582*

The Lynds sources L1262, L1489, L1536, and L1582 are also dark clouds having NH_3 cores around low-luminosity sources (Benson, Myers, and Wright 1984). L1489 and L1262 had been studied by Frerking and Langer (1982), who found no evidence of CO "pedestal" features suggestive of winds. Myers, Linke, and Benson (1983) examined all four in CO as part of a general study of opaque clouds, and, while they also failed to detect any direct evidence for outflow, they noted that L1536 and L1489 have HC_5N sources indicative of cold dense regions. Thus the CO limits could not exclude the presence of low mass loss winds, while the presence of dense cores suggested that a wind might be operating. Recently Myers *et al.* (1986) have found a small, weak CO outflow in L1489, but no evidence of CO outflow in the others. Independently Fischer, Smith, and Mozurkewich (1986) obtain the same result from CO observations of L1489 and L1582.

iii) *L1551 IRS 5*

Lynds 1551 IRS 5, unlike these other low-luminosity sources, has a strong, well-studied bipolar flow associated with it (e.g., Snell, Loren, and Plambeck 1980). Despite its role as a virtual prototype of bipolar flows having well-separated and well-collimated lobes (e.g., Lada 1985), no IR recombination line detections of it have been reported. It does, however, have a strong radio continuum. Bieging, Cohen, and Schwartz (1984) measured the peak flux density from IRS 5 as 1.7 ± 0.2 mJy at 6 cm, and < 1.8 mJy at 20 cm. They found the radiation arising from an extended, elliptical source about 3″ × 1″ in extent and aligned with the CO lobes. Bieging and Cohen (1985) resolve this core into two pointlike sources. Snell *et al.* (1985) subsequently obtained an integrated flux density of 4.3 ± 0.5 mJy at 5 GHz in their VLA map, in good agreement with the result of Bieging, Cohen, and Schwartz (1984). Torrelles *et al.* (1985) obtained a significantly larger value for the continuum, 17 mJy at 1.3 cm, and argued that the continuum strength is larger than expected from a ZAMS star of $\sim 30\ L_\odot$. They noted that the strength is also difficult to reconcile with the lower value of 1.7 mJy measured by Bieging, Cohen, and Schwartz (1984). They estimated that shock-produced ionization could produce this intensity of continuum radiation. In more recent VLA observations Rodríguez (1986) and Rodríguez *et al.* (1986) maintain that the double radio source is actually two excited peaks in a torus of material of radius 25 AU which is orientated perpendicular to the CO lobes, and which is shocked by a wind from a central unseen stellar source. Such a process should also produce considerable IR recombination line emission.

iv) *NGC 2071*

NGC 2071 is a high-luminosity source ($L \approx 3.3 \times 10^3\ L_\odot$; Mozurkewich, Schwartz, and Smith, 1986) which we include here because of some observational similarities it has to L1551 IRS 5. The source has been very well studied, both in continuum and millimeter line observations, and contains three infrared continuum sources IRS 1, 2, and 3. CO maps of the flow (Bally and Lada 1983; Snell *et al.* 1984) reveal a well-collimated outflow seen approximately normal to our line of sight. Recent high angular resolution line maps (40″) of IRS 1 in NH_3 (Takano *et al.* 1986) and in CS (Takano 1986) show the presence of dense material in an elongated structure about 0.4×0.15 pc in extent and aligned in a northwest-southeast direction, orthogonal to the CO flow axis. The authors argued that this material forms a disk around the star, and they interpreted their data as supporting a model of anisotropic outflow from the star. Bally and Predmore (1983) found that NGC 2071 IRS 1 has relatively strong radio continuum emission for an outflow source, 8 mJy at 6 cm. They reported the total IR luminosity as 750–1000 $L_{\odot}$, and noted that this luminosity is consistent with a B3 ZAMS star, with ample ultraviolet to produce the observed ionization. The luminosity obtained by Mozurkewich, Schwartz, and Smith (1986) is even larger, so that the observed ionization could result from stellar UV production. However, as noted by Bally and Predmore (1983), ionization effects associated with the wind and/or accretion are also possible. On the basis of the strong radio continuum flux, one would anticipate a strong IR line flux, yet SFCFM set surprisingly low limits, $< 10^{-18}$ W cm^{-2} for Brα. Our line detection sensitivity was considerably better than this, permitting us to improve the limit.

v) *L1455A and L1455B*

Frerking and Langer (1982) detected broad-winged CO emission in this low-luminosity source, and subsequently Levreault (1985) and Goldsmith *et al.* (1984) mapped the outflow, finding it to be large and complex, and containing perhaps three separate outflow sources. Cohen (1980) found a red reflection nebula in the complex (designated RNO 15), while Davidson and Jaffe (1984) discovered a far-IR source near the center of one of these flows but not coincident with RNO 15. Schwartz, Frerking, and Smith (1985) mapped the region in NH_3, and also searched for radio continuum emission with the VLA. They reported a strong double radio source near the focus of the flow, with 6 cm flux densities of 14 mJy each. However, the pair are not coincident with either RNO 15 or the far-IR source, and furthermore the spectral index of each source was about $\alpha = -0.8$, indicative of a nonthermal, possibly extragalactic, radio source. The obvious conclusion would be that the radio sources are a chance superposition of extragalactic sources. They pointed out, however, that because the location of the sources is so close to the focus of the CO flow, and because their orientation is also closely aligned with the CO outflow axis, such a coincidence is unlikely ($1:< 10^{-4}$). Instead the radio peaks might be a double source excited by a single wind in a configuration similar to the double peaks seen in L1551 IRS 5 by Rodríguez (1986; see above), or perhaps some other unusual winds are present. The great intensity of the emission suggests that there should be enough IR line radiation for measurements to help clarify the mechanism.

II. RESULTS

a) *Infrared Line Measurements*

We observed B5, L1536, L1582, L1551, L1455, and NGC 2071 in the Brα recombination line of hydrogen at 4.05 μm using the UKIRT 3.8 m telescope on Mauna Kea and the cooled grating spectrometer CGS 2 with a resolution of 550 km s^{-1} at 4 μm. The beam size of 5″.4 was set with a cold aperature stop, and the chopper throw was 30″ in a north-south direction. The line was detected in B5 IRS 1 and L1536, with profiles corresponding to the instrumental resolution, indicating that the lines were unresolved. We obtained 2 σ upper limits to the flux of $< 5 \times 10^{-21}$ W cm^{-2} from each of the sources L1551 IRS 5, L1455A and L1455B, and NGC 2071 IRS 1, 2, and 3. These measurements were taken between 1983 December and 1984 December. We also searched for the Brγ line at 2.12 μm in B5, L1536, L1582, L1262, and L1489 using the Kitt Peak National Observatory 4 m telescope and the Fourier transform spectrometer (FTS) with a resolution of 2 cm^{-1}, corresponding to a velocity resolution of 130 km s^{-1}. The beamwidth was 3″.8. The FTS can also obtain simultaneous measurements at Brα using a cooled narrow-band prefilter in front of the second input Dewar. Only L1536 gave a positive detection, of 1.3×10^{-20} W cm^{-2} in Brγ. The other sources had a 2 σ limit of $\leq 10^{-20}$ W cm^{-2} in Brγ. The KPNO data were obtained in 1984 November. The fluxes were calibrated by observing selected reference stars. Table 1 summarizes the results for all the sources observed.

Included in Table 1 are estimates of the extinction associated with the various sources, so that the intrinsic intensities can be found. The mass loss rates are dependent on the absolute values of the intensity and such a correction is important, although many other model parameters depend only on line ratios not absolute fluxes. We have converted A_V to $A_{4\,\mu m}$ using the relation $A_{4\,\mu m}/A_V \approx 0.038$, based on the extinction data of Rieke and Lebofsky (1985). Our estimates for A_V are taken from the literature, where authors have usually derived them from optical observations of the whole cloud. These estimates at best provide a lower limit to the extinction to the IR line emitting regions because of the possibility of local dust. We note however that should the IR source lie near the front of the molecular cloud it could have less extinction than these estimates indicate.

b) *Infrared Continuum Values*

The continua at 2 and 4 μm can be useful diagnostics of the flows if the dust emission does not dominate. Our grating and FTS observations also measured the continuum baselines, with the major flux uncertainties being in the calibrations. Selected nearby reference stars were chosen for calibrations; the final results are listed in Table 1. We used two different reference stars with L1536 and obtained continuum values differing by $\pm 25\%$, providing an indication of the calibration accuracy. The continuum fluxes we obtained for B5 IRS 1, L1536, and L1582 differ from those of Benson, Myers, and Wright (1984) by about a factor of 2, not enough to effect our conclusions.

c) *Radio Continuum Observations and Analysis*

We observed B5 IRS 1, L1262, L1536, L1489, and L1582 with the NRAO VLA[6] in the B configuration. No continuum emission was seen from any of the sources, to a limit of < 0.5 mJy at 4.8 GHz and < 0.8 mJy at 1.4 GHz. Table 1 includes all the radio continuum observational data. The continuum measurements in the table for L1551 IRS 5 are taken from Cohen, Bieging, and Schwartz (1982), L1455 from Schwartz, Frerking, and Smith (1985), and NGC 2071 from Bally and Predmore (1983).

[6] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

DATA ON LOW-LUMINOSITY OUTFLOWS

Source	Distance (pc)	L ($L_\odot$)	Observed ($\times 10^{-20}$ W cm^{-2}) Brα	Brγ	A_V (mag)	Intrinsic ($\times 10^{-20}$ W cm^{-2}) Brα	Brγ	Continuum 6 cm (mJy)	4.05 μm (Jy)	$\dot{M}$ ($M_\odot$ yr^{-1}) From Brα[a]	From Radio[b]
B5 IRS 1	330	10	1.9 ± 0.2[c]	<1.6	6.1	2.4 ± 0.3	<3.0	<0.4	0.47	$\sim 4 \times 10^{-9}$	$<28 \times 10^{-9}$
L1262	200	12	...	<1	3	...	<1	<0.5	...	$<3 \times 10^{-9}$	$<15 \times 10^{-9}$
L1489	140	40	...	<1	5.2	...	<1.7	<0.5	...	$<3 \times 10^{-9}$	$<9 \times 10^{-9}$
L1536	140	0.6	0.5 ± 0.2	1.3 ± 0.4	3	0.6 ± 0.2	1.8 ± 0.5	<0.5	1.5	$\sim 1 \times 10^{-9}$	$<9 \times 10^{-9}$
L1582	460	10	<0.7	<1	6	<0.9	<2	<0.5	0.22	$<3 \times 10^{-9}$	$<54 \times 10^{-9}$
L1551 IRS 5	160	30	<0.5	...	30	<1.4	...	1.7[d]	0.73	$<1 \times 10^{-9}$	2.8×10^{-8}
NGC 2071	500	3.3×10^3	...	...	...	...	...	...	...	...	...
IRS 1	...	...	<0.5	...	30	<1.4	...	7.7[e]	...	$<5 \times 10^{-9}$	4.7×10^{-7}
IRS 2	...	...	<0.5	...	30	<1.4	...	...	...	...	...
IRS 3	...	...	<0.5	...	30	<1.4	...	...	...	...	...
L1455A	350	16	<1	...	30	<2.9	...	14[f]	...	$<5 \times 10^{-9}$	7×10^{-7}
L1455B	350	16	<1	...	30	<2.9	...	14	...	...	...

[a] Eq. (3), with $v = 100$ km s^{-1}.
[b] Eq. (4), with $v = 100$ km s^{-1}.
[c] 2 σ uncertainty level throughout.
[d] Bieging, Cohen, and Schwartz 1984.
[e] Bally and Predmore 1983.
[f] Schwartz, Frerking, and Smith 1985.

III. SOURCE ANALYSIS AND DISCUSSION

a) B5 IRS 1: Line Intensities in a Conventional Flow

The detection of Brα emission in B5 IRS 1 is the first reported evidence that ionized material surrounds it, while the absence of detectable 6 cm radio continuum emission is a clear indication the recombination line is not arising in a normal H II region. On the basis of this result, and considering its overall properties and the NH_3 clumps found nearby by Benson, Myers, and Wright (1984), it is reasonable to conclude that IRS 1 is a flow source. Since our observations Goldsmith, Langer, and Wilson (1986) have directly measured broad CO wings and bipolar extent there (see § I*b*[i] above).

The theoretical strength of the radio free-free continuum emission and IR line emission in a flow has been discussed by Panagia and Felli (1975), KS, SFCFM, Felli *et al.* (1984), and others. SFCFM in particular present the results of numerical calculations on a few representative sets of outflow parameters, and show line intensities as a function of inner and outer ionized radius, optical depth, mass loss rates, and wind velocities. KS formulate an approximate but analytic expression for the intensity which will be useful in the subsequent discussion. They calculate the intensity by considering the detected emission as having come from the surface where the optical depth of the radiation, produced by the dense ionized gas flowing outward, equals unity. The expression for the optical depth, $\tau_\nu(R_\nu)$, is given by their equation (4), which is adapted from Castor (1970); the surface is defined by the locus of points with $\tau_\nu(R_\nu) = 1$. The largest surfaces, farthest from the star, occur at wavelengths at which the optical depth becomes thick soonest. Lines with strong transition strengths are therefore seen arising from the largest surfaces farthest out from the star. All these authors assume that a Sobolev approximation is valid, and in the KS description this implies that distinct features of the line are produced by electrons radiating from equivalent surface regions. The line shape is therefore determined by the particular geometry of each isovelocity surface.

The expression for the flux density emitted from the $\tau = 1$ surface is given by

$$I_\nu \approx \pi B_\nu(T) R_L^2 , \qquad (1)$$

where R_L is a measure of the dimensions of the surface $\tau \approx 1$ and $B_\nu(T)$ is the Planck function at temperature T. In the case of a constant-velocity, spherically symmetric outflow, for which the electron density n_e is proportional to $1/r^2 V$, the expression R_L is given by KS's equation (15a) in terms of atomic constraints, and the flow parameters mass loss rate $\dot{M}$ and velocity V. R_L has dimensions $\sim 3 \times 10^{13}$ cm for typical outflows. The total intensity in the line, F_L, is found by integrating equation (1) over frequency, which corresponds to integration over an angle to the surface (see the discussion in KS and in Ambartsumyan 1958):

$$F_L = \int_0^\infty I_\nu d\nu = \frac{\nu V}{c} \int_{-1}^{+1} I(x) dx , \quad x \equiv \frac{(\nu - \nu_L)c}{\nu_L V} . \qquad (2)$$

The resultant formula for the line intensity in Brα is

$$F_L(\text{Br}\alpha) \approx 3.8 \times 10^{-18} \left(\frac{\dot{M}}{10^{-6}\ M_\odot\ \text{yr}^{-1}}\right)^{4/3} \left(\frac{V}{100\ \text{km s}^{-1}}\right)^{-1} \times \left(\frac{D}{\text{kpc}}\right)^{-2} \text{W cm}^{-2} . \qquad (3)$$

This expression assumes a uniform excitation temperature T throughout the flow, and neglects aspheric effects in the $\tau = 1$ surface and details of the geometry of the outflow. The numerical calculations of SFCFM derive a coefficient in this expression which has been shown to be in good agreement with observations, somewhat closer than the coefficient given in KS (Persson *et al.* 1984). We have therefore used the SFCFM value in the above expression. An analogous expression for the radio continuum emission is

$$S_\nu \approx 15.2 \left(\frac{\dot{M}}{10^{-6}\ M_\odot\ \text{yr}^{-1}}\right)^{4/3} \left(\frac{V}{100\ \text{km s}^{-1}}\right)^{-4/3} \times \left(\frac{D}{\text{kpc}}\right)^{-2} \left(\frac{\lambda}{\text{cm}}\right)^{-0.6} \text{mJy} . \qquad (4)$$

The numerical coefficient here is also taken from SFCFM.

The ratio of the 6 cm continuum to Brα line intensities is now given by

$$\frac{S_\nu(6\ \text{cm})}{F_L(\text{Br}\alpha)} = 1.4 \times 10^{18} \left(\frac{V}{100\ \text{km s}^{-1}}\right)^{-1/3} \frac{\text{mJy}}{\text{W cm}^{-2}} . \qquad (5)$$

For comparison, the corresponding value in a normal H II region, $T = 10^4$ K, and assuming Menzel's case B recombination, is (e.g., Osterbrock 1976)

$$\frac{S_\nu(6\ \text{cm})}{F_L(\text{Br}\alpha)} = 3.7 \times 10^{20} \frac{\text{mJy}}{\text{W cm}^{-2}} . \qquad (6)$$

This result is instructive. In an outflow source of $V = 100$ km s^{-1} whose flux in Brα is given by 5×10^{-20} W cm^{-2}, a readily detectable value about 1 order of magnitude above the limits in this study, the corresponding 6 cm continuum flux from a wind is ~ 70 μJy, below the present limits of detection. Consequently, the nondetections in our VLA results are consistent with the picture of a wind source, as will be more fully discussed below. As pointed out in § I, this relatively strong IR line emission makes a particularly powerful tool for detecting and measuring flow parameters.

The ratio of the line strengths of Brα and Brγ in ionized winds depends on details of the flow processes, many of which (like characteristics of geometry and velocity gradients) are uncertain. An approximate value for the line ratio can be obtained from the formulation of equation (1), an expression which should be somewhat more accurate for calculating the ratio than it is for calculating the flux itself. The ratio turns out to be (see also SFCM, Fig. 3)

$$\frac{F_L(\text{Br}\alpha)}{F_L(\text{Br}\gamma)} \approx 1.3 . \qquad (7)$$

In a usual H II region, assuming that Menzel's case B applies, $F_L(\alpha)/F_L(\gamma) = 2.86$. Observations of high-luminosity sources give an intrinsic ratio around the wind value (e.g., Persson *et al.* 1984).

The presence of Brα in B5 IRS 1 at a level of $1.9 \pm 0.2 \times 10^{-20}$ W cm^{-2} and the absence of 6 cm continuum emission indicate that a wind is the likely line-producing mechanism. A mass loss rate of $\dot{M} = 4 \times 10^{-9}$ $M_\odot$ yr^{-1} is derived using expression (3) above with $D = 0.33$ kpc and $V = 100$ km s^{-1}. This rate results in a 5 GHz continuum level of 0.03 mJy (eq. [5]), a level well below our VLA limit. The nondetection of Brγ in B5 IRS 1 with an upper limit of 1.6×10^{-20} W cm^{-2} yields a ratio of $F_L(\alpha)/F_L(\gamma) > 1.1$, consistent with expression (7) and the observed range of values. The inferred extinction to IRS 1 from measurements of its CO and dust column density is about $A_V \geq 3$ mag (cf. Benson, Myers, and Wright 1984), and implies an intrinsic $F_L(\alpha)/F_L(\gamma)$ ratio >0.8. P. Myers (private communication) indicates the extinction within 30 AU of B5 might be $A_V \approx 30$ mag or more, bringing the lower limit on the intrinsic line ratio to >0.1 and raising the value of $\dot{M}$ to $8 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$. In their detailed study of Brα from more luminous outflow sources, Persson *et al.* (1984) also found that the line intensities and (where available) line ratios are in agreement with wind models. IR line observations of the other three sources associated with CO outflows in the B5 cloud (Goldsmith, Langer, and Wilson 1986) would now be valuable, since these four are thought to comprise an evolutionary set.

From the recently obtained CO maps of the B5 cloud by Goldsmith, Langer, and Wilson (1986) we can estimate mass loss in the molecular material, $\dot{M}_{\mathrm{CO}}$. Its approximate value, from their Table 2, is $\dot{M}_{\mathrm{CO}} \approx M_{\mathrm{CO}}/\tau = 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, where M_{CO} is the mass in swept up CO and τ is the time scale of the flow. This value for $\dot{M}$ is 1000 times larger than that seen in the ionized flow, but because this includes swept-up material, the difference is not surprising. The ratio is similar to that seen in other sources (e.g., Persson *et al.* 1984; Bally and Lada 1983).

b) L1262, L1489, and L1582: Outflow Sources with Upper Limits

These sources were suspected of being associated with outflows, but only L1489 has a detected CO outflow (see § I*a*[ii]). They have neither detectable IR lines nor radio continuum. We observed L1262 and L1489 in Brγ only, and assuming that these sources have flow parameters resembling those in other sources, the limits provide limits to the mass loss rates. From equation (3) we find that both sources have $\dot{M} < 3 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$. In the case of L1582 we have upper limits to both $F_L(\mathrm{Br}\alpha)$ and $F_L(\mathrm{Br}\gamma)$, with the somewhat most stringent limit on mass loss rate coming from $F_L(\mathrm{Br}\alpha)$, also giving $\dot{M} < 3 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$.

For all these sources the limits provided by the radio continuum data are even less restrictive. If the sources resemble B5 IRS 1, the expected ionized flow would be $\approx 10^{-9}\ \dot{M}_\odot\ \mathrm{yr}^{-1}$, with the emission from this low value falling well below the detection capability of radio receivers, but being marginally accessible to the IR systems. Our current limits are consistent with this conclusion. The IR continuum values we obtained are larger than expected from the free-free and bound-free radiation, but are consistent with dust around the sources.

c) L1536: Line Intensities from an Unusual Flow

In L1536 we measured both the Brγ and Brα lines, and found the intensity ratio $F_L(\mathrm{Br}\alpha)/F_L(\mathrm{Br}\gamma) = 0.3 \pm 0.1$. This value is about 4 times less than that expected using the model above (eq. [7]). The presence of line emission together with the absence of detectable radio continuum indicates the influence of an ionized wind, but this wind cannot be explained by the model used for B5 IRS 1 and high-luminosity sources. The value we see is less than that of any other reported wind source. Additional extinction would decrease the ratio even more.

One possible scenario is that the observed lines do not arise from the regions of $\tau_\nu \approx 1$, as they seem to do in usual flow sources and as is assumed in the derivation of equation (7). The line strengths in the extreme limits of τ can be estimated easily in the case of a constant-velocity outflow model. When $\tau_\nu \gg 1$, the emission is observed arising from a surface of dimension approximately r_0, the physical radius of the outer ionized zone where the gas recombines, rather than from the surface defined by R_L. When this situation arises, the value of r_0 will be small compared with the usual value for R_L ($\approx 10^{13}$ cm; KS, eq. [15a]). Then

$$I_\nu \approx \pi B_\nu(T) r_0^2 \tag{8}$$

and

$$\frac{F_L(\mathrm{Br}\alpha)}{F_L(\mathrm{Br}\gamma)} \approx \frac{\nu_\alpha}{\nu_\gamma} \frac{B_\alpha(T)}{B_\gamma(T)} \approx 0.18 \quad (T = 10^4\ \mathrm{K}) \tag{9}$$

(see SFCFM, eq. [11] and figures). While this value is less than what we have measured, it suggests that a more detailed model of the flow in the limit of large τ could fit the observations.

The absolute fluxes in the lines are very small, as would be expected from a small value of r_0. A value of $r_0 \leq 10^{11}$ cm is derived from the Brα flux. While this is much smaller than the usual R_L, and smaller than the ionized region of $\geq 10^{14}$ cm postulated around a wind source in the model of Pudritz (1985), it is comparable to the dimensions of the envelope of Be stars. Be stars also have recombination line emission that is optically thick (e.g., Marlborough 1969). Smith, Larson, and Fink (1979) pointed out that there could be some similarity between pre–main-sequence objects with outflow and Be stars, and more recently Persson *et al.* (1984) have explored in some detail the relative IR recombination line morphologies. However the total IR luminosity of L1536 is much less than that of a Be star, only 0.6 $L_\odot$ as measured by *IRAS* (Mozurkewich, Schwartz, and Smith 1986) versus 10^3–$10^5\ L_\odot$ for the range of Be stars. It may be that an A-type shell star (Strom *et al.*, 1972; Slettebak, 1979) can provide a closer analog to the star in L1536. Since these emission-line stars are rapid rotators as well as being high mass loss objects, high-resolution spectra of their line shapes show a wealth of detail and variability (e.g., Ulrich and Knapp 1979). Representative velocity widths for Ae stars are ~ 400 km s^{-1} FWHM (Garrison 1978). Our FTS spectrum, with a resolution of 120 km s^{-1} at Brγ, shows no evidence for such a broad line, although it does appear marginally resolved. Improved high-resolution spectra of L1536 are needed to settle this question. Finally, we also note that a small emitting radius will only result in a small continuum flux at 2 and 4 μm, whereas we detect a substantial IR continuum, presumably because of the presence of warm dust.

We next consider the possibility that the line radiation arises in a region of the opposite limit, where $\tau_\nu \to 0$. In this case

$$I_\nu \approx \pi B_\nu(T) R_L^3 r_0^{-1} \tag{10}$$

and

$$\frac{F_L(\mathrm{Br}\alpha)}{F_L(\mathrm{Br}\gamma)} \approx \frac{f_{nn'}(\alpha)}{f_{mm'}(\gamma)} \frac{B_\alpha(T)}{B_\gamma(T)} \frac{e^{I_n/kT}}{e^{I_m/kT}} \frac{(1 - e^{-h\nu(\alpha)/kT})}{(1 - e^{-h\nu(\gamma)/kT})} = 3.0 \tag{11}$$

(see SFCM, eq. [13] and figures). Here $f_{nn'}$ is the oscillator strength for the transition from level n' to level n, I_n is the energy required to ionize the atom from level n (KS, eq. [15]), and T is the excitation temperature. This ratio of 3 is even larger than the unacceptable value from the conventional wind model with $\tau_\nu \approx 1$. We conclude that the $\tau_\nu \to 0$ limit is not a viable explanation for the observation.

The apparent difficulty the usual models encounter in explaining the emission from this source, even with some extension of the usual limits prompts us to generalize the discussion of intensities presented in § III*a*. One can extend the approach of KS to produce analytic expressions for the intensities in the case when the emission arises from a surface with $\tau_\nu \approx 1$ but with the flow velocity given by the general expression with the free parameter s,

$$V = V_i(r/r_i)^s , \quad (12)$$

rather than the constant-velocity case described before. V_i is the initial velocity at the inner ionized radius r_i. The general expression for τ_ν (see KS, eq. 4), including a term for the radial dependence of the velocity, results in an expression for the characteristic radius of the optically thick zone:

$$R_L = \left[\left(\frac{r_i^s}{r}\right)^3 \frac{\pi e^2}{m_e} \frac{f_{nn'}}{\nu} \left(\frac{h^2}{2\pi m_e kT}\right)^{3/2} \left(\frac{\dot{M}}{4\pi\mu}\right)^2\right]^{1/3(s+1)} \times [b_n g_n e^{I_n/kT}(1 - e^{-h\nu/kT})]^{1/3(s+1)} . \quad (13)$$

In this expression m_e is the electron mass, b_n the standard thermodynamic departure coefficient, g_n the degeneracy of level n, and μ the mass per free electron. The excitation temperature T is evaluated at the surface R_L. Using equations (1) and (2), it is clear that

$$I_\nu \propto \nu^3(e^{h\nu/kT} - 1)^{-1}\left[\frac{f_{nn'}}{\nu} \frac{\dot{M}^2}{V_i^3} e^{I_n/kT} g_n(1 - e^{-h\nu/kT})\right]^{2/3(s+1)} \quad (14)$$

and

$$F_L \propto \nu^4(e^{h\nu/kT} - 1)^{-1}\left[\frac{f_{nn'}}{\nu} \frac{\dot{M}^2}{V_i^3} e^{I_n/kT} g_n(1 - e^{-h\nu/kT})\right]^{(2+s)/3(s+1)} , \quad (15)$$

so that, assuming that the excitation of the Brα and Brγ lines is about the same,

$$\frac{F_L(\mathrm{Br}\alpha)}{F_L(\mathrm{Br}\gamma)} \approx 0.18(18.3)^{(2+s)/3(s+1)} . \quad (16)$$

Felli *et al.* (1985) have pointed out this dependence of the emission on s for this regime, and have discussed in detail the behavior of the radiation in the millimeter and radio limit. When $s = 0$, the usual case, the ratio equals 0.8, in reasonable agreement with the more detailed model results of SFCFM. When $s > 0$, the ratio becomes ~ 1 (see the "hybrid model" calculations of SFCFM, for example). For our measured value of $F_L(\mathrm{Br}\alpha)/F_L(\mathrm{Br}\gamma) = 0.33$ the above expression yields a formal value of $s = -3.7$, with the negative sign of s indicating a decelerating flow. The magnitude of s should only be taken as indicative of a strong deceleration until better spectroscopic data are obtained and modeled.

These measurements of L1536 provide the first evidence that a flow from a low-luminosity source may be decelerating. In the case of the highly luminous source S106, Garden and Geballe (1986) suggest that deceleration may be present, on the basis of their high spectral resolution observations of the line profiles of Brα and Pfγ. Scoville *et al.* (1983) also concluded (on the basis of their line profile observations) that deceleration was present in the BN source in Orion. Additional confirmation of a strong deceleration could be obtained from intensity measurements of other recombination lines. Using the preceding formulation and the intensity for the Pfund γ line at 3.75 μm, for example, one can show that

$$\frac{F_L(\mathrm{Br}\alpha)}{F_L(\mathrm{Pf}\gamma)} \approx 0.8 \times (4.64)^{(2+s)/3(s+1)} . \quad (17)$$

For the usual case of $s = 0$, the ratio is ~ 2.2, whereas in a strongly decelerating flow the ratio is only 1.1. Since the two lines are relatively close together in wavelength and differential extinction is minimized, it should be possible to distinguish between these two cases.

The reason for a possible deceleration in L1536 is not discernible from our present data. It might be thought that the flow only has the appearance of deceleration, as the result of a peculiar geometry, but it has been shown that a nonspherical outflow would have only minor effects unless the outflow collimation were extreme (Schmid-Burgk 1982). Alternatively, we note that a decelerating velocity law is the result of an electron distribution

$$n_e(r) = \frac{\dot{M}}{4\pi r^2 V(r)} \propto r^{-(s+2)} . \quad (18)$$

Therefore, because the measurements are sampling the electron density distribution, an apparent deceleration could in principle result if the mass loss rate of the star were decreasing, although this condition could not last very long, only about $\dot{M}_0/\dot{M} \approx R_L/V$ yr ($\dot{M}_0$ is the initial mass loss rate). In the case of physical deceleration, gravity offers one possible mechanism when it dominates the outward pressure from radiation as measured by the total luminosity L. A rough estimate can be made by setting

$$\frac{\tau L}{c} < \frac{M_* M_g G}{r^2} , \quad (19)$$

where M_* is the stellar mass, and M_g is the mass of gas in the wind. If $\tau = 0.1$, and using $L = 0.6\, L_\odot$ and $r \approx 10^{13}$ cm, we find that gravity will dominate if $M_g > 10^{-12}\, M_\odot$. If τ or r are larger, M_g is correspondingly larger. However, gravitational deceleration, even in a free-fall condition, will only make s equal to -0.5, smaller than is inferred from the line intensities. A second possible mechanism for deceleration is from collisions with material already surrounding the star, a process which could produce a wide range of values for s. Garden and Geballe (1986) also discuss such effects in the case of S106. Until more detailed results on L1536 become available, it is premature to attribute possible deceleration to any particular process.

The continuum emission in the IR may become an important diagnostic in trying to determine flow parameters. Using the generalized velocity law in equation (12), and estimating the continuum strength in an approach analogous to that for the lines, it is straightforward to show that

$$S_\nu \propto \nu^3(e^{h\nu/kT} - 1)^{-1} \times \left[\nu^{-3} T^{-1/2} G(\nu)(r_i)^{2s} \frac{\dot{M}}{V_i^2}(1 - e^{-h\nu/kT})\right]^{2/3(s+1)} , \quad (20)$$

where $G(\nu)$ is the Gaunt factor. Then

$$\frac{F_L(\mathrm{Br}\alpha)}{S_\nu(4\ \mu\mathrm{m})} \approx \frac{[5.75 \times 10^{38} \dot{M}^2 V^{-3}(r_i)^{3s}]^{2/3(s+1)}}{[5.86 \times 10^{36} \dot{M}^2 V^{-2}(r_i)^{2s}]^{2/(2s+3)}} . \quad (21)$$

This line-to-continuum ratio can be substantially larger than unity when a large negative value is taken for s. Our measured line–to–IR continuum value is 0.3, but as noted earlier it is expected that a substantial contribution from dust emission at 4 μm will be present to overwhelm this process.

With the appropriate Gaunt factor a similar expression can be derived for the radio continuum. SFCFM point out that the largest part of the radio continuum arises in the outer envelope of the flow, by which time the flow must approach an $s = 0$ condition. In practice we take this point of view as well here, even though there is no measurable 6 cm continuum in L1536. In principle, however, a radio spectral index α is possible (where $S_\nu \propto \nu^\alpha$), with

$$\alpha = 2 - \frac{4.2}{2s+3} . \quad (22)$$

When $s = 0$, the spectral index α is 0.60, in agreement with usual wind theories (e.g., Panagia and Felli 1975; Felli and Panagia 1981).

d) L1551 IRS 5: Shock Excitation of Infrared Recombination Lines Considered

L1551 is of particular interest because of its strong, well-separated, and highly collimated CO lobes. It has been observed with a variety of probes in the radio (e.g., Snell, Loren, and Plambeck 1980; Torrelles *et al.* 1985) and IR (e.g., Snell *et al.* 1985; Strom *et al.* 1985). In particular, Bieging, Cohen, and Schwartz (1984) and Torrelles *et al.* (1985) find strong radio continuum radiation. The latter discuss the fact that the low IR luminosity of the source, if a ZAMS star, indicates a spectral class unable to produce enough UV to ionize the material seen in the radio continuum, and they invoke the shock excitation model of Cox (1972) to explain the large radio continuum they see. Since this ionized gas will also produce line radiation, we first investigate briefly the implications of the Cox model for our results.

In the shock ionization scenario an atom moving with velocity v crossing a shock front into a medium of density n_0 and surface area A_s emits U photons capable of ionizing hydrogen, where (Cox 1972)

$$U = 4.0 v_{100}^2 - 1.4 , \quad (23)$$

where v_{100} is the velocity in units of 100 km s^{-1}. As the hydrogen so ionized recombines, it emits both continuum and line radiation with the usual cascade efficiency for H II regions. Cox discusses the case where the emission is optically thin and therefore closely resembles the emission processes in normal H II regions. The predicted 6 cm continuum value is about

$$S_\nu \approx 2.8 \times 10^{-17} \frac{U n_0 v_0 A_s}{\alpha_0 D^2} \text{ Jy} , \quad (24)$$

where α_0 is the recombination coefficient (Osterbrock 1976). Torrelles *et al.* (1985) note that this shock mechanism is capable of producing more than enough radio continuum radiation, and in fact conclude that only 40% of the material need be processed by the shock.[7]

From the same recombination and cascade analysis the predicted Brα value is

$$F_L(\text{Br}\alpha) \approx 2.68 \times 10^{-21} \frac{n_0 v_0 A_s}{D^2} (2.7 v_{100}^2 + 0.27) \text{ W cm}^{-2} . \quad (25)$$

Line fluxes for other transitions can be obtained with reference to $F_L(\text{Br}\alpha)$ by noting that the recombination process behaves like that in conventional H II regions. The resultant ratio of continuum to line is

$$\frac{S_\nu(6 \text{ cm})}{F_L(\text{Br}\alpha)} \approx 2.9 \times 10^{19} \frac{4 v_{100}^2 - 1.4}{2.7 v_{100}^2 + 0.27} \frac{\text{mJy}}{\text{W cm}^{-2}} . \quad (26)$$

[7] Unpublished shock calculations by J. Raymond (private communication) using parameters suitable for Herbig-Haro objects indicate the 6 cm radio continuum emission is larger than given by our eq. (24), perhaps by a factor of 10. The line-to-continuum ratio for such shocks will therefore be the same as for an H II region.

This ratio is relatively small compared with the line-to-continuum ratios obtained for the normal H II region case, equation (6). With a flux density of 1.7 mJy and $V_{100} = 1$ (Bieging, Cohen, and Schwartz 1984) the shock model predicts $F_L(\text{Br}\alpha) = 7 \times 10^{-20}$ W cm^{-2}, much more than our current limit of $F_L(\text{Br}\alpha) < 5 \times 10^{-20}$ W cm^{-2}. The shock mechanism as described therefore could not be responsible unless A_V were > 270 mag. Another serious argument against this scenario is that unless L1551 IRS 5 is peculiar, then other shocked sources, having less extinction, should show a shock-excited line-to-continuum ratio. But no outflow sources appear to do so.

Like the shock model, an ionized wind can produce the radio continuum flux seen in L1551 IRS 5. A mass loss rate of $\sim 10^{-7}$ $M_\odot$ yr^{-1} is needed (see eq. [4]) and, as in the shock-front excitation model, more line radiation would then be expected. Other possible ionization scenarios, especially ionization from the $n = 2$ level (SFCFM), might also explain the radio continuum from this low-luminosity source, but these too should produce detectable line emission from the subsequent recombination cascade. One possible explanation for the absence of the line is the presence of unusually heavy extinction surrounding the line-producing region and reducing the Brα line flux by over an order of magnitude. An objection to invoking heavy extinction was raised against the shock model because no sources show the model's predicted line ratio. Many sources do agree with the wind model, demonstrating its applicability, and heavy extinction could be possible in this source.

Snell *et al.* (1985) have obtained CCD images which address the extinction argument. They observed the L1551 nebulosity and the region around IRS 5 in Hα emission and find an Hα line flux of 3×10^{-21} W cm^{-2} in a 4″ × 10″ area around the brightest portion of the southern "jet" from IRS 5, with the total flux in a 10″ × 20″ box being about 6.1×10^{-21} W cm^{-2}. Curiously, they see no emission northeast of the star, despite the prominent CO lobe that extends in that direction. They argue that the absence of Hα emission northeast of the star might indicate the presence of a tilted disk of material around IRS 5 with an inner radius of 1″ and an outer radius of $\geq 10''$ capable of blocking the visible light. Now an optically thin gas with case B parameters, and an Hα flux of 6×10^{-21} W cm^{-2}, should produce a Brα flux of 1.4×10^{-16} W cm^{-2} assuming Snell *et al.*'s (1985) extinction estimate of $A_V = 20$ mag. That we see no Brα emission, even from the extended nebulosity, is consistent with their result because we did not look along the jet but only directly at IRS 5, where they report that the Hα image is "pinched" and possibly partially blocked. The absence of Brα emission from directly around the source could be explained by their tilted disk if it obscured all of the dense ionized flow around the star, including some gas toward the southwest. Further evidence in support of this general idea comes from Rodríguez (1986) and Rodríguez *et al.* (1986), who report new VLA continuum observations that suggest that IRS 5 is located between the vertices of two collinear cones separated by about 50 AU, the tips of which are being excited by the wind from the star. The "pinched" Hα emission may occur around IRS 5, with the bulk of the Hα emission and radio continuum arising from the wind-shocked "cones" rather than in the wind directly.

Pudritz (1985) has modeled outflow regions as containing a hydrodynamic disk of neutral material which might be responsible for extinction. His estimated parameters for the neutral disk of material surrounding are $r \approx 5 \times 10^{16}$ cm, ellipticity 0.2, and $M \approx 100\ M_{\odot}$. With a 6 cm continuum flux value of 1.7 mJy, a wind with "conventional" parameters described by equation (5) would require an extinction of $A_V \approx$ 150 mag to mask the line flux. In the case of L1551 IRS 5 the model dimensions would result in a disk mass $\sim 1.5\ M_{\odot}$, in reasonable agreement with the model predictions given the uncertainties, although larger than the estimates of Snell *et al.* (1985) from their optical data. Finally, we note that while the optical emission forms a jet which the disk partially obscures, there is no clear evidence yet that the inner ionized wind is so collimated. Any evidence of such asymmetry would be very important, and help resolve the ongoing dispute over whether the bipolar flow is collimated by the external medium or by internal processes.

e) NGC 2071: Upper Limits to Lines from a High-Luminosity Source

NGC 2071 IRS 1 is a high-luminosity source, $L \approx 3300\ L_{\odot}$ (Mozurkewich, Schwartz, and Smith 1986) with a strong radio continuum of 8 mJy at 6 cm, and a predicted Brα flux (eq. [5]) of 8.6×10^{-18} W cm^{-2}. Our limit of $< 5 \times 10^{-21}$ W cm^{-2} is therefore surprising. The relations developed in the preceding sections show that even some variations on wind models, or the shock model, predict a line flux well above our limit. Therefore, as in the case of L1551 IRS 5, we investigate the possibility that the presence of a disk of material can explain the line's absence via extinction.

An extinction of $A_V \approx 200$ mag could account for the absence of the lines at intensities predicted from a conventional wind. Using the Pudritz (1985) model sizes as described in the case of L1551 IRS 5 and on the basis of the extinction requirements, a disk mass of $\geq 1\ M_{\odot}$ is derived, which is less than that predicted by Pudritz but within the uncertainties. The same order of magnitude disk mass was inferred from L1551 IRS 5 (primarily because the upper limits are the same). We note that for both these sources the clean separation of the molecular lobes and a line of sight that is approximately perpendicular to the flow direction indicate that we would be seeing such a disk edge-on, and therefore viewing the inner ionized material through maximum extinction. Lane and Bally (1986) find a gap in the distribution of shocked H_2 about 15″ southwest of the infrared cluster including IRS 1, and they conclude that it may indicate the presence of a dense sheet of gas with several magnitudes of extinction at 2 μm. It is unlikely that this material is the source of the extinction around IRS 1.

A second possibility can be considered. Herbig (1977) pointed out that T Tauri stars are likely to flare (see also Ulrich and Knapp, 1979), and more recently other observers have noted the similarity of these low-luminosity outflow sources to T Tauri stars. Furthermore, it is probable that outflows are episodic rather than continuous, in order to keep the total ejected mass down to observed values. If NGC 2071 IRS 1 were in a quiescent phase of its wind, the strength of the IR lines might be reduced below our detection limits, because the lines sample the inner, optically thick material rather than the thin gas sampled by the radio. The recombination coefficient of hydrogen, $\alpha_{\rm eff} \approx 4 \times 10^{-13}$ cm^3 s^{-1} (Osterbrock 1976), implies that the gas will recombine very quickly, on the order of days or less, in the high-density region around the star.

We have also obtained limits to the Brα emission from IRS 2 and IRS 3 in NGC 2071, located about 5″ north and 10″ northeast, respectively, of IRS 1. IRS 3 has a 6 cm continuum flux of 2.8 $\pm$ 1 mJy (Bally and Predmore 1983), while no radio continuum was detected from IRS 2. The absence of Brα emission from IRS 2 is consistent with the limit to the radio flux for an H II region. If IRS 3 were an outflow source, the absence of the IR line would be just as puzzling as its absence from IRS 1, but there is no evidence that it has any wind. Rather, we take the lack of Brα emission to imply that it is not a wind source, and the radio continuum is produced in a more conventional H II region.

f) L1455A and L1455B: Strong Nonthermal Radio Continuum Sources

Schwartz, Frerking, and Smith (1985) observe a 6 cm continuum flux density of about 14 mJy in each of the components A and B of L1455, with a spectral index in each of $\alpha = -0.8$, indicating that the emission is not coming from an H II region. Indeed, the predicted Brα flux is 4×10^{-20} W cm^{-2}, comfortably above our observed limit of $< 10^{-20}$ W cm^{-2} for each component. If a wind were responsible for the ionization, as is suggested by the source positions near the vertex of a strong CO bipolar flow, the Brα emission line should be very strong, $\sim 10^{-17}$ W cm^{-2} (eq. [5]), so any winds present must be unusual or highly extinguished. The "nonthermal" value for the spectral indices has already marked any winds as peculiar, requiring a velocity law with $s = -0.76$ (see eq. [22]). A self-consistent wind model can be found using the expressions in § III*c*, and can explain the observed results for both the radio and the line emission, although a very large mass loss rate ($\geq 10^{-3}\ M_{\odot}$ yr^{-1}) is required. However, neither the H II region model nor the wind model explains the most salient feature of the sources, their similarity. This almost certainly means that either a single process is exciting both peaks, such as the excitation of two facing vertices of coaxial cones suggested by Rodríguez *et al.* (1986) in L1551 IRS 5 (see above), or else some global parameter determines their properties. In the former case, however, shock excitation of the material, while capable of explaining the radio intensity, would also predict strong Brα unless the extinction were large. Since the distance and angular separation of the two sources imply a linear separation of around 5000 AU, as compared with the 50 AU inferred by Rodríguez *et al.* in L1551 IRS 5, an extinction of $A_V \approx 200$ mag is needed either over this whole region (a prohibitively large mass) or else clumped around the two sources. More complete data are needed to unravel the nature of this object.

IV. SUMMARY AND CONCLUDING REMARKS

1. The most straightforward model for an ionized wind, having a constant or accelerating velocity and an optical depth in the observed lines of the order of unity, enables us to identify B5 IRS 1 as the source of an outflow, and to estimate its mass loss rate. The model also provides a consistent picture for the sources L1262, L1489, L1536, and L1582 which have only limits to their IR line emission.

2. In L1536 the usual wind model parameters are inadequate to explain the line emission. Emission from a small, very optically thick region such as occurs around some emission-line stars, or a decelerating flow (or an electron distribution that simulates such a process) are possible.

3. A normal wind cannot explain the limits to the IR lines in L1551 IRS 5 unless the extinction is very great, a somewhat ad hoc requirement made more tenable by other published results in the visible and radio continuum. The suggestion that shock-excited atomic hydrogen is responsible for the radio emission

in this source similarly is shown to be possible only if a large amount of extinction were present to obscure the IR lines. Since no outflow source has been found with an IR line ratio approximating that predicted by the shock scenario, this second alternative is less likely.

4. The absence of detectable line emission from the high-luminosity source NGC 2071 IRS 1 can be explained with extinction, and the disk model of Pudritz (1985) provides a self-consistent description.

The data and their analysis indicate that the class of outflow objects with low luminosities shows a comparatively complex range of outflow parameters and local conditions, making the sources qualitatively different from the usual high-luminosity counterparts. From other work there is also evidence that low-luminosity sources are not simply weak copies of higher luminosity ones. Mozurkewich, Schwartz, and Smith (1986), using *IRAS* data and published radio maps, find that as a group low-luminosity outflows have a higher ratio of mechanical to radiative energy than do high-luminosity sources, and tend to have a higher degree of collimation and lower CO velocities. These differences may be due to differences in the cloud parameters, and indeed the cloud conditions that prompt a low-mass star to form rather than one of higher mass, while incompletely understood, involve more than simple differences in mass scaling. Our present results suggest that the wind and its environment in low-luminosity stars are also likely to be different. Further observations of these and similar sources, especially with the higher spectral resolution required to obtain line profiles, are needed to study the processes and refine the models of why and how such stars form.

We thank D. Mozurkewich for his help in obtaining total source luminosities from the *IRAS* data set, and S. Odenwald for his assistance in obtaining the VLA limits to the sources reported here. We also thank S. Strom for his comments on the discussion of L1551 IRS 5. The data on NGC 2071 and L1551 IRS 5 were obtained in conjunction with G. White and R. Harten, who first proposed observing them at UKIRT.

REFERENCES

Ambartsumyan, V. A. 1958, *Theoretical Astrophysics* (New York: Pergamon).
Bally, J., and Lada, C. J. 1983, *Ap. J.*, **265**, 824.
Bally, J., and Predmore, R. 1983, *Ap. J.*, **265**, 778.
Beichman, C. A., *et al.* 1984, *Ap. J. (Letters)*, **278**, L45.
Benson, P. J., Myers, P. C., and Wright, E. L. 1984, *Ap. J. (Letters)*, **279**, L27.
Bieging, J. H., and Cohen, M. 1985, *Ap. J. (Letters)*, **289**, L5.
Bieging, J. H., Cohen, M., and Schwartz, P. R. 1984, *Ap. J.*, **282**, 699.
Castor, J. I. 1970, *M.N.R.A.S.*, **149**, 111.
Cohen, M. 1980, *A.J.*, **85**, 29.
Cohen, M., Bieging, J. H., and Schwartz, P. R. 1982, *Ap. J.*, **253**, 707.
Cox, D. P. 1972, *Ap. J.*, **178**, 143.
Davidson, J. A., and Jaffe, D. T. 1984, *Ap. J. (Letters)*, **277**, L13.
Felli, M., Oliva, E., Panagia, N., and Stanga, R. 1985, *Astr. Ap.*, **151**, 27.
Felli, M., and Panagia, N. 1981, *Astr. Ap.*, **102**, 424.
Felli, M., Staude, H. J., Reddmann, T., Massi, M., Eiroa, C., Hefele, H., Neckel, T., and Panagia, N. 1984, *Astr. Ap.*, **135**, 261.
Fischer, J., Smith, H. A., and Mozurkewich, D. M. 1986, in preparation.
Frerking, M. A., and Langer, W. D. 1982, *Ap. J.*, **256**, 523.
Garden, R., and Geballe, T. R. 1986, *M.N.R.A.S.*, preprint.
Garrison, L. A. 1978, *Ap. J.*, **234**, 535.
Goldsmith, P. F., Langer, W. D., and Wilson, R. W. 1986, *Ap. J. (Letters)*, **303**, L11.
Goldsmith, P. F., Snell, R. L., Hemeon-Heyer, M., and Langer, W. 1984, *Ap. J.*, **286**, 599.
Herbig, G. H. 1977, *Ap. J.*, **217**, 693.
Herbig, G. H., and Jones, B. F. 1981, *A.J.*, **86**, 1232.
Krolik, J. H., and Smith, H. A., 1981, *Ap. J.*, **249**, 623 (KS).
Lada, C. J. 1985, *Ann. Rev. Astr. Ap.*, **23**, 267.
Lane, A. P., and Bally, J. 1986, *Ap. J.*, **310**, 820.
Levreault, R. M. 1985, Tech. Report No. 85-1, Astronomy Department, University of Texas.
Marlborough, J. M. 1969, *Ap. J.*, **156**, 135.
Mozurkewich, D., Schwartz, P. R., and Smith, H. A. 1986, *Ap. J.*, **311**, 371.
Myers, P., and Benson, P. 1983, *Ap. J.*, **266**, 309.
Myers, P. C., Heyer, M., Snell, R., and Goldsmith, P. 1986, preprint.
Myers, P., Linke, R., and Benson, P. 1983, *Ap. J.*, **264**, 517.
Osterbrock, D. E. 1976, *Astrophysics of Gaseous Nebulae* (San Francisco: Freeman).
Panagia, N. 1973 *A.J.*, **78**, 929.
Panagia, N., and Felli, M. 1975, *Astr. Ap.*, **39**, 1.
Persson, S. E., Geballe, T. R., McGregor, P. J., Edwards, S., and Lonsdale, C. J., 1984, *Ap. J.*, **286**, 289.
Pudritz, R. E. 1985, *Ap. J.*, **293**, 216.
Rieke, G., and Lebofsky, M. 1985, *Ap. J.*, **288**, 618.
Rodríguez, L. F. 1986, in *IAU Symposium 115, Star-forming Regions*, ed. J. Jugaku and M. Peimbert (Dordrecht: Reidel).
Rodríguez, L. F., Cantó, J., Torrelles, J. M., and Ho, P. T. P. 1986, *Ap. J. (Letters)*, **301**, L25.
Schmid-Burgk, J. 1982, *Astr. Ap.*, **108**, 169.
Schwartz, P. R., Frerking, M. A., and Smith, H. A. 1985, *Ap. J.*, **295**, 89.
Schwartz, P. R., Waak, J., and Smith, H. A. 1983, *Ap. J. (Letters)*, **267**, L109.
Scoville, N. Z., Kleinmann, S. G., Hall, D. N. B., and Ridgway, S. T. 1983, *Ap. J.*, **275**, 201.
Simon, M., Felli, M., Cassar, L., Fischer, J., and Massi, M. 1983, *Ap. J.*, **266**, 623 (SFCFM).
Simon, M., Righini-Cohen, G., Fischer, J., and Cassar, L. 1981, *Ap. J.*, **230**, 127.
Slettebak, A. 1979, *Space Sci. Rev.*, **23**, 541.
Smith, H. A., Larson, H. P., and Fink, U. 1979, *Ap. J.*, **233**, 132.
Snell, R. L., Bally, J., Strom, S. E., and Strom, K. M. 1985, *Ap. J.*, **290**, 587.
Snell, R., Loren, R. B., and Plambeck, R. L. 1980, *Ap. J. (Letters)*, **239**, L17.
Snell, R., Scoville, N. Z., Sanders, D. B., and Erickson, N. R. 1984, *Ap. J.*, **284**, 176.
Strom, S. E., Strom, K. M., Grasdalen, G. L., Capps, R. W., and Thompson, D. 1985, *A.J.*, **90**, 2575.
Strom, S. E., Strom, K. M., Yost, J., Carrasco, L., and Grasdalen, G. 1972, *Ap. J.*, **173**, 353.
Takano, T. 1986, *Ap. J. (Letters)*, **300**, L85.
Takano, T., Stutzki, J., Fukui, Y., and Winnewisser, G. 1986, *Ap. J.*, submitted.
Thompson, R. I. 1981, in *IAU Symposium 96, IR Astronomy*, ed. C. G. Wynn-Williams and D. P. Cruikshank (Dordrecht: Reidel), p. 153.
Thompson, R. I., Strittmatter, P. A., Erickson, E. F., Witteborn, F. C., and Stecker, D. W. 1977, *Ap. J.*, **231**, 736.
Torrelles, J. M., Ho, P. T. P., Rodríguez, L. F., and Cantó, J. 1985, *Ap. J.*, **288**, 595.
Torrelles, J. M., Rodríguez, L. F., Cantó, J., Carral, P., Maraide, J., Moran, J. M., and Ho, P. T. P. 1983, *Ap. J.*, **274**, 214.
Ulrich, R. K., and Knapp, G. R. 1979, *Ap. J. (Letters)*, **230**, L99.
Young, J. S., Goldsmith, P. F., Langer, W. D., Wilson, R. W., and Carlson, E. R. 1982, *Ap. J.*, **261**, 513.

Jacqueline Fischer: Code 4138F, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5000

Thomas R. Geballe: United Kingdom Infrared Telescope, 665 Komohana Street, Hilo, HI 96720

Philip R. Schwartz: Code 4138, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5000

Howard A. Smith: Code 4138SM, E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5000