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THE DETECTION OF HIGH-VELOCITY OUTFLOWS FROM M8E-IR

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ABSTRACT

We present and discuss a high-resolution (0.059 cm^{-1}) *M* band (4.6 μm) spectrum of the embedded young stellar object M8E-IR. The spectrum shows strong absorption to large blueshifts in the rotational lines of the fundamental vibrational band, $v = 1$–0, of CO. We interpret the absorption as being due to gas near to ($\leq 10^{16}$ cm) and flowing from the central object. The outflowing gas is warm (95–330 K) and consists of discrete velocity components with the very high velocities of 90, 130, 150, and 160 km s^{-1}. On the basis of a simple model, we estimate that the observed outflows are less than 100 yr old.

Subject headings: stars: pre–main-sequence — stars: winds

I. INTRODUCTION

Observation of CO in emission at millimeter wavelengths has shown that many infrared objects embedded in molecular clouds are centers of molecular outflows having velocities of, typically, several tens of kilometers a second (Lada 1985). Microwave CO emission-line observations have limited sensitivity to gas very near the embedded object because of the dilution resulting from a finite beam size. Absorption spectroscopy is sensitive to gas near the source because only a single line of sight is probed. Furthermore, the interpretation of Doppler shifts is unambiguous in the sense that a blueshifted line must indicate gas approaching us from the near side of the object. In this *Letter*, we report the first result of a program to study gas flows near young stellar objects by infrared absorption spectroscopy. We have found outflows from the embedded source M8E-IR with velocities ranging from 90 to 160 km s^{-1}.

M8E-IR (also known as AFGL 2059) displays a number of properties which indicate that it is probably a massive star in a pre–main-sequence stage. It is an embedded object with broad (but not extremely deep) absorption at 3.0 and 9.7 μm (Willner *et al.* 1982). Its bolometric luminosity of $2 \times 10^4 L_\odot$ is equal to that of a B0 ZAMS star (Thronson, Loewenstein, and Stokes 1979). Microwave CO emission lines of M8E-IR exhibit wings of total width ~ 16 km s^{-1} (Bally and Lada 1983). On this basis it is classed as a high-velocity source, but it is certainly not an extreme one. The red and blue wings of CO are not spatially separate in the sky (Simon *et al.* 1984), so M8E-IR is not a known source of bipolar flow. Broad recombination lines of Brα and Brγ (Simon *et al.* 1981; Persson *et al.* 1984; Simon *et al.* 1984) are evidence of a dense stellar wind. Lunar occultation observations of M8E-IR at 3.8 and 10 μm have been interpreted to indicate a disk several tens of AU in diameter seen almost edge-on (Simon *et al.* 1985). Lacy *et al.* (1984) found two broad, shallow absorption features at 4.6 μm. Larson, Hofmann, and Fink (1986), on the basis of a higher resolution (1 cm^{-1}) spectrum, argue that these features are produced by gaseous CO which is warm ($T \geq 650$ K), has a large velocity spread ($\gg 10$ km s^{-1}), and has a large column density (10^{18}–10^{19} cm^{-2}).

II. OBSERVATIONS

The infrared spectrum of M8E-IR [$\alpha(1950) = 18^h01^m48^s.8$; $\delta(1950) = -24°26'56''$] was obtained on the 3.6 m Canada-France-Hawaii Telescope on Mauna Kea, Hawaii, on the night of 1986 September 17–18, using a Fourier transform spectrometer (Maillard and Michel 1982) at the Cassegrain focus. The astronomical source was alternately placed in each of the two input apertures, 53″ apart, to subtract the residual background emission. There were cooled InSb detectors at each of the two outputs. We employed an *M* band filter with a usable passband extending from 2080 to 2180 cm^{-1}. A spectral resolution of 0.059 cm^{-1} after apodization was used, corresponding to a velocity resolution of 8 km s^{-1}. A small aperture of 2″.5 was used to limit the thermal background. The total integration time was 56 minutes over a range in airmass of 1.4 to 1.5. The 2 σ signal-to-noise ratio in the spectrum is ~ 11.

The spectrum, without correction for telluric absorption, without apodization, and without correction for the shape of our bandpass, is shown in Figure 1. The lines of the fundamental vibrational band, $v = 0$–1, of CO are labeled in Figure 1, and their rest positions are indicated by vertical lines. The strong and narrow line to the red (left) of the telluric line is at the velocity of the ambient gas found by CO microwave emission. In addition, strong CO absorption, extending approximately 1.2 wavenumbers to the blue, can be seen in all lines from P15 to R7. The breadth of the absorption is indicated by the horizontal bars in Figure 1. Eight individual CO lines are displayed on a larger scale in Figure 2.

III. RESULTS AND DISCUSSION

At our velocity resolution of 8 km s^{-1}, we can distinguish five discrete absorption components. One, at $v_{LSR} = +11$ km

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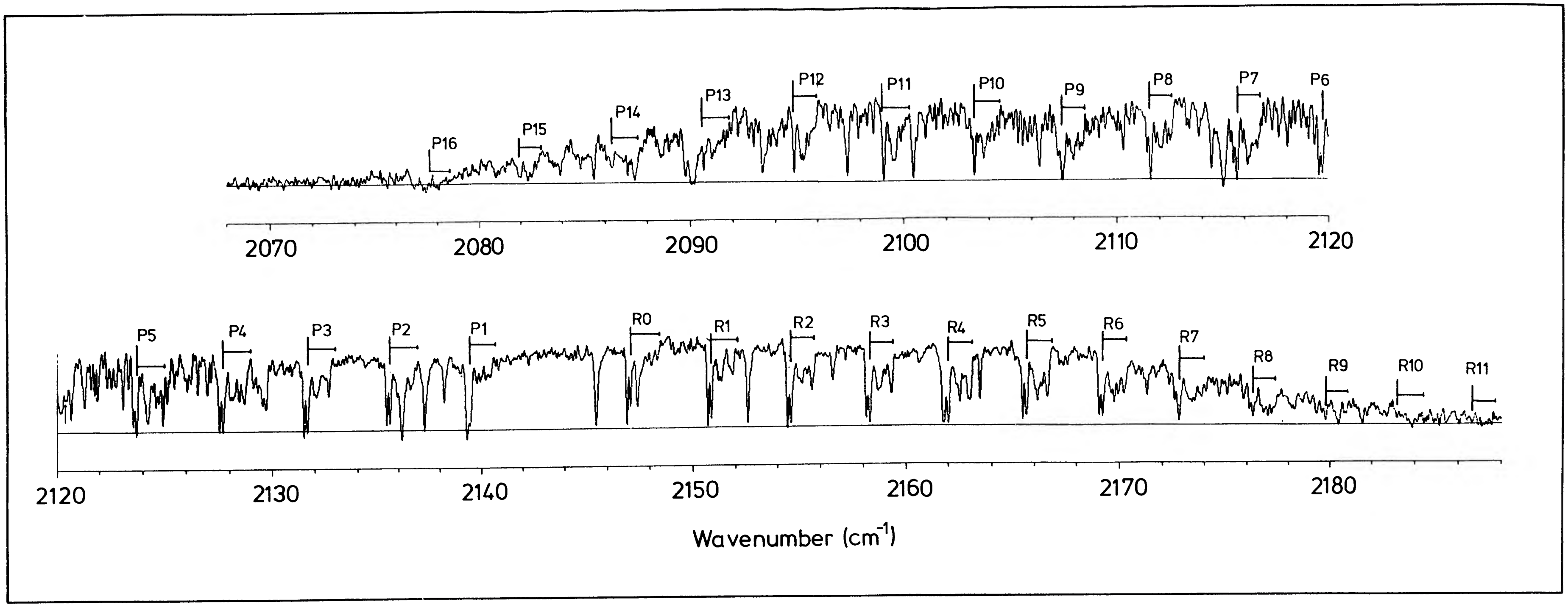

FIG. 1.—The spectrum of M8E-IR is shown over our complete filter passband. The spectrum is uncorrected for atmospheric absorption and is unapodized. The overall curvature that is apparent reflects the shape of the filter passband. The rest positions of CO $v = 1$–0 lines are labeled. The horizontal bar at each CO line position shows the breadth of the blueshifted absorption in each line.

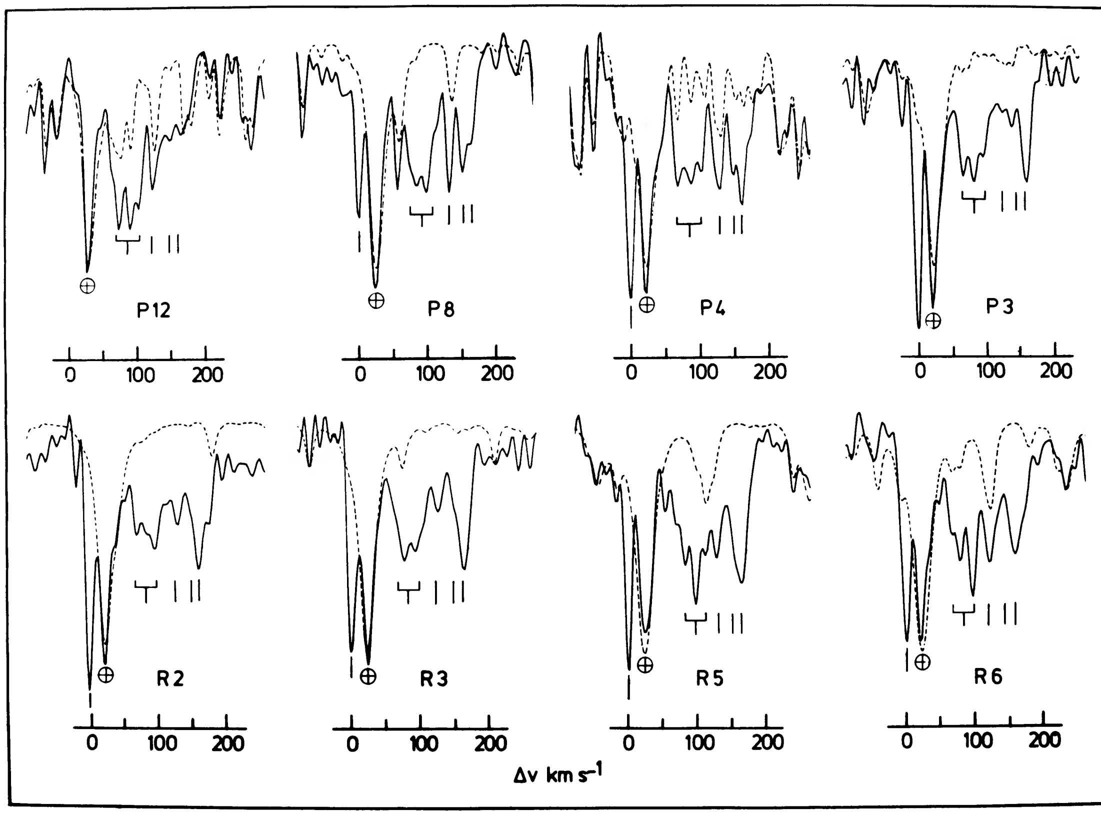

FIG. 2.—Portions of the spectrum near several CO lines are shown. The solid curves are the observed M8E-IR spectrum. The dashed curves are the spectrum of a model terrestrial atmosphere computed for 4.2 km. Velocity displacements, Δv, are measured from the absorption feature with $v_{LSR} = +11$ km s^{-1}. Source absorption features are labeled with vertical lines. Telluric CO lines are indicated by the symbol ⊕.

s^{-1}, we identify with the cold gas within which M8E-IR is embedded (Wright *et al.* 1977). A low temperature for the +11 km s^{-1} component is supported by the fact that the lines weaken for higher rotational levels and are absent for $J > 10$. The other four components have large negative velocities ranging from $v_{LSR} \approx -80$ to -150 km s^{-1}. The broad feature centered at $v_{LSR} = -76$ km s^{-1} appears to have internal structure, with possibly three components superposed on continuous absorption. We have treated this broad feature as a single line. The two features at $v_{LSR} = -142$ and -152 km s^{-1} are partially blended because their intrinsic widths are comparable to their separation.

It is natural to interpret these components as lines formed in molecular gas flowing toward us from M8E-IR. If M8E-IR shares the velocity of the gas cloud within which it is embedded, and if the outflow is isotropic (so that projection effects can be neglected), then we have detected molecular gas with outflow velocities of 90, 130, 150, and 160 km s^{-1}. To our knowledge, these are the highest velocity molecular gas outflows yet found from a young stellar object.

The high-velocity lines are resolved in velocity and are not highly saturated. To obtain the column density of CO molecules in each rotational level accessible to us ($J = 0$ to $J = 15$), we have applied a curve-of-growth analysis (e.g., Spitzer 1978). Before equivalent widths can be determined from the spectrum, it is, of course, necessary to correct for atmospheric absorption features. The usual practice is to ratio the source spectrum with the spectrum of a reference star. This procedure can be imprecise because of changes in atmospheric conditions in the time interval between observation of the program object and the reference object. Furthermore, in order to divide out the telluric features without degrading the final result, a low noise reference spectrum is required. In *M* band, rather long integration times are needed to achieve a high *S*/*N* because the early-type stars which must be used (to avoid stellar lines) are intrinsically faint at 4.6 μm. For these reasons we chose to remove the atmospheric absorption by using a model atmosphere computed for the 4.2 km altitude of Mauna Kea. The program used for these computations was developed in support of the upper atmosphere research project ATMOS (Atmospheric Trace Molecule Spectroscopy; Farmer and Raper 1986). In this program, Earth's atmosphere is divided into 150 concentric shells of 1 km thickness, to each of which can be assigned a temperature, a pressure, and a density using a variety of widely accepted model atmospheres. A similar database of volume mixing ratios of all known infrared active atmospheric species is also provided. The spectra are synthesized for the geometry of observation (including refraction) on a line-by-line basis using the Air Force Geophysics Laboratory line parameters compilation and some updates developed specifically for the ATMOS project. Tests against high-quality atmospheric spectra acquired both from the ground and from space show that, over most of the infrared, the atmospheric spectrum can be synthesized to better than 1%. We validated the modeling procedure by reproducing the spectrum of a reference star, α Aquilae, observed close in time to M8E-IR. The dashed curves in Figure 2 show the model spectrum for the conditions of the M8E-IR observations. The atmospheric absorption was removed to obtain the equivalent widths of the CO absorption features. Linewidth parameters, *b*, were

TABLE 1

PROPERTIES OF THE HIGH-VELOCITY ABSORPTION FEATURES IN M8E-IR

v_{LSR} (km s^{-1})	Δv_{FWHM}	T (K)[a]	N(CO) (cm^{-2})[a]
−76	44	330(+63, −50)	$(6.9 \pm 0.9) \times 10^{17}$
−117	17	320(+60, −48)	$(2.3 \pm 1.1) \times 10^{17}$
−142	12	255(+37, −30)	$(1.8 \pm 0.9) \times 10^{17}$
−152	15	95(+9, −8)	$(2.0 \pm 0.6) \times 10^{17}$

[a] Quoted errors are 1 σ.

obtained from the measured velocity widths after correction for instrumental resolution, viz. using $\Delta v^2 \approx \Delta v_{obs}^2 - \Delta v_{inst}^2$. In all cases, linewidths are full widths at half-maximum. The measured width of each velocity component is an average over all observed rotational lines. The corrected linewidths are shown in Table 1.

The curve-of-growth analysis yields column densities of CO in each rotational level. On the assumption that the rotational states are populated according to a Boltzmann distribution with a unique temperature, we can apply the relation $N_J \propto (2J + 1) \exp(-E_J/kT)$ to obtain the rotational temperature: N_J is the column abundance of CO molecules in rotational state J, E_J is the energy of level J above $J = 0$, and T is the rotational temperature. Figure 3 illustrates this for each velocity component: a least-squares fit is made to the calculated N_J values. As plotted in Figure 3, the slopes of the lines are equal to $1/T$. Once the temperature is known, the calculation of the total CO column density from any N_J is straightforward. The resulting gas temperatures and CO column densities are given in Table 1. In the analysis, we have neglected vibrationally excited CO: No significant errors should be introduced by this assumption. The gas properties we find are, in general, consistent with the more qualitative conclusions of Larson, Hofmann, and Fink (1986).

Even with beams as small as 23″ (Simon *et al.* 1984), the maximum microwave emission line widths observed in CO are no broader than 16 km s^{-1}. The high-velocity CO, with a total column density of 1.3×10^{18} cm^{-2}, would be easily seen at millimeter wavelengths if it filled the beam. Its nondetection at millimeter wavelengths implies that the high-velocity gas fills only a small fraction of a 23″ beam and must be, therefore, close to the infrared source. At the distance of 1500 pc, a 23″ beam has a diameter of 5×10^{17} cm. The high-velocity gas is, therefore, likely within $\sim 10^{17}$ cm (or $\leq 10^4$ AU) of the central object. A natural implication is that the high-velocity gas has been ejected by the source. The existence of several velocity components suggests discrete ejection events.

On the basis of lunar occultation experiments at 3.8 and 10 μm, Simon *et al.* (1985) have proposed a two-component model for M8E-IR: a disk with dimensions 20 × 60 mas and an effective temperature of 700 K is surrounded by a larger spherical component with a color temperature in the range 300–500 K. It is possible to identify the warm CO we observe with the spherical component. In this picture, we are seeing CO in absorption against the inner 700 K background. Models have been developed for the variation of dust temperature with distance from a star (e.g., Kwok, Bell, and Feldman 1981; Jiang, Perrier, and Lena 1984). If we assume that the densities are sufficiently high for the gas and dust to be in temperature equilibrium, we can use our deduced gas temperatures to estimate the distances of the gas from the central source. Applying

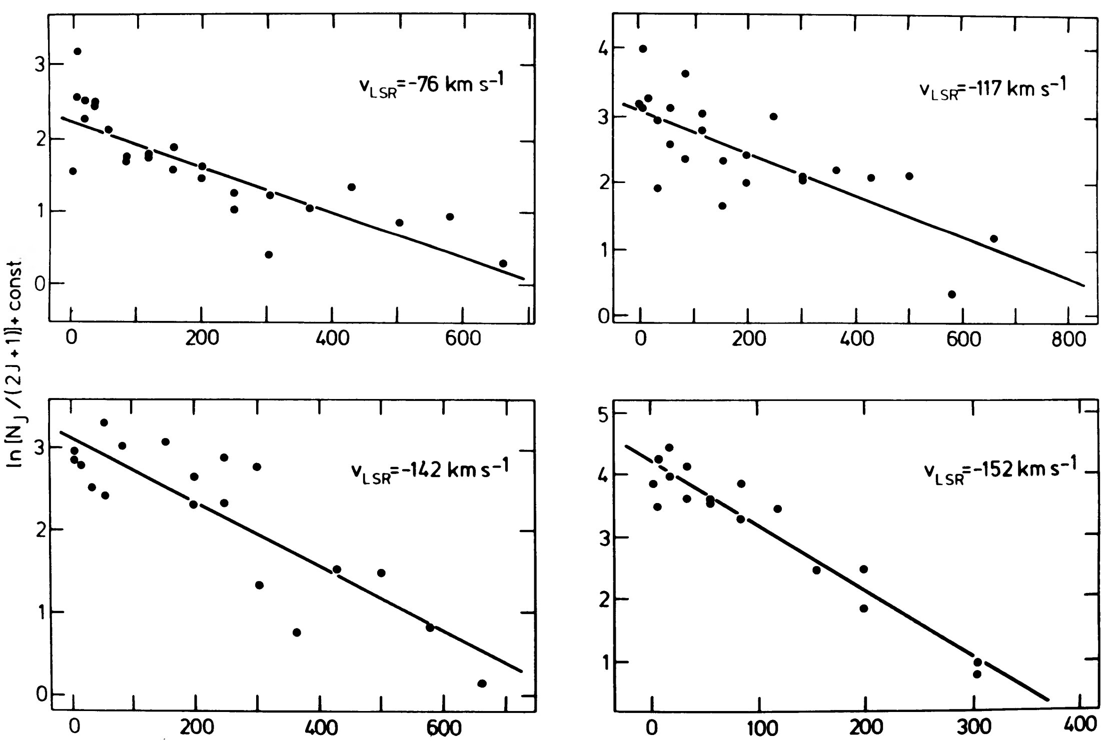

FIG. 3.—CO column densities in each rotational sublevel are plotted as a function of the rotational energy in K for the absorption features at $v_{LSR} = -76$, -117, -142, and -152 km s^{-1}. The lines are least-squares fits and indicate temperatures of 330 K, 320 K, 255 K, and 95 K, respectively.

the temperature dependence for silicate dust as proposed by Jiang, Perrier, and Lena (1984) for the similar source NGC 2024/IRS 2, $T \propto r^{-0.5}$, we find distances of $\sim$200 AU to $\sim$2700 AU ($\sim 3 \times 10^{15}$ to $\sim 4 \times 10^{16}$ cm) for the velocity components in Table 1. The largest radius, which applies to the 95 K component, is larger than the radius estimated for the dust envelope by Simon *et al.* (1985). There is no contradiction, however, because the outermost gas, with a temperature near 95 K, will radiate with a maximum at $\sim$30 μm and may not contribute significantly to the radiation at 3.8 and 10 μm. Assuming that each component has moved at constant speed since its ejection, we can use the above distances to estimate that the outbursts occurred from $\sim$10 to $\sim$80 yr ago. An alternative interpretation of the discrete absorption features is that they are due to clumps in a continuous wind rather than to ejected shells. Perhaps we are looking along a clumpy jet, like that of L1551/IRS 5 (Nickel and Staude 1987). A difficulty with this interpretation is that the knots seen in YSOs by optical emission are composed of hot, atomic gas which may be shock-heated. The high-velocity gas we see in M8E-IR is warm and molecular. No emission from shock-excited H_2 has been seen toward M8E-IR.

The multiple high-velocity absorption features we have found for M8E-IR are remarkably similar in appearance to absorption features seen in a visible spectrum of V1057 Cyg (Bastian and Mundt 1985). In V1057 Cyg, absorption features in the range -90 to -180 km s^{-1} are seen in the D lines of sodium. V1057 Cyg experienced an FU Ori–type outburst in 1969, increasing by 5 mag in visual brightness. The high-velocity absorption is probably due to gas ejected in that outburst. The preoutburst spectrum of V1057 Cyg shows that it is a T Tauri star (i.e., a low-mass, pre–main-sequence star). We suggest that M8E-IR may have recently experienced an FU Ori–type outburst. The FU Ori phenomenon may, therefore, span the entire range of stellar masses.

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