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INFRARED SPECTROSCOPY OF CARBON MONOXIDE IN GL 2591 AND OMC-1:IRc2

T. R. GEBALLE[1, 2] AND RICHARD WADE[3]

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ABSTRACT

Spectra of 4.7 μm fundamental band absorption lines of carbon monoxide in GL 2591 and OMC-1:IRc2 are presented. In GL 2591 the observed lines have total velocity widths of about 100 km s^{-1}, far larger than that in the 2.6 mm CO line seen toward this object. The spectra indicate ejection of material at ~ 100 km s^{-1} at a distance of ~ 10^{15} cm from the central object, followed by deceleration. The single CO line profile observed in IRc2 appears similar to those seen previously in BN except for the possible presence of a faint blue wing. The lack of strong absorption at highly blueshifted velocities in IRc2 implies that if IRc2 is the source of the high-velocity molecular outflow in OMC-1, then that outflow must be oriented so that little or no high-velocity gas is along the line of sight to IRc2.

Subject headings: infrared: sources — infrared: spectra — line profiles — stars: pre–main-sequence

I. INTRODUCTION

Newly forming, massive stars are usually embedded in the dense and visually obscuring molecular clouds which have spawned them. Recently, it has become clear that these stars return much material to the parent cloud during or soon after their formation. This phenomenon has been observed in several ways:

1. At the position of the star, broad infrared recombination lines of hydrogen are often found. These arise in a high-velocity, dense, ionized wind at or just outside the stellar surface (Simon *et al.* 1983; Persson *et al.* 1984).

2. Over an extended (0.1–1 pc) region surrounding the star, broad or shifted millimeter lines of CO and other molecules are observed (Bally and Lada 1983). These imply that a cooler, generally lower velocity and often bipolar outflow extends far beyond the star and well into the molecular cloud.

3. Spatially extended infrared line emission from shocked molecular hydrogen is often seen surrounding the star (see, e.g., Shull and Beckwith 1982). Apparently, these lines are emitted largely at the interface of the cool molecular outflow and the molecular cloud.

Except for the Becklin-Neugebauer (BN) object (Hall *et al.* 1978; Scoville *et al.* 1983) the molecular outflows have been probed only by millimeter and radio techniques, which necessitate the use of large (~ 1′) beams. Such observations cannot isolate that portion of the molecular flow which is relatively close to the star. This inner region may be of critical importance in understanding the outflow as a whole. For example, orders of magnitude larger mass loss and momentum deposition rates frequently are derived from the millimeter CO lines than from the hydrogen recombination lines (Persson *et al.* 1984). It is not clear at present whether and to what extent the differences can be explained by geometry, different acceleration mechanisms operating at different distances from the star, or evolution/time variability of the outflow (see, e.g., Königl 1982; Pudritz and Norman 1983).

An additional way to observe the molecular outflows, and one which may sample this critical inner region, is to measure absorption lines against the bright infrared continua of these obscured stars. In this method an outflow is examined along the entire line of sight to the continuum source, and the denser, inner region of the flow is expected to show up most prominently. The velocities and profiles of the absorption lines, when compared with those of the millimeter lines, can indicate the dependence of flow velocity on distance from the central object. By observing infrared lines covering a wide range of lower state energies and optical depths, the temperature and density structures of the flows may also be determined. Information on the surrounding molecular cloud along the line of sight may also be obtained because the absorption lines formed in the flow will be blueshifted from those formed in the cloud.

We have recently begun a survey of 4.7 μm fundamental band ($V = 1$–0) CO spectra in bright, embedded, young stellar objects in order to study their mass loss from this new perspective. In the survey we plan to make accurate measurements of a few suitably chosen lines of $^{12}C^{16}O$ and rarer isotopic species. Here initial spectra are presented of two objects in the survey, GL 2591 and OMC-1:IRc2.

II. OBSERVATIONS

The spectra were obtained at the United Kingdom Infrared Telescope on Mauna Kea, Hawaii, using a cooled seven channel grating spectrometer in series with ambient temperature, piezoelectrically scanned Fabry-Perot interferometers (Wade 1983). In this configuration only one channel of the grating spectrometer is employed, the grating being used to block all but one of the orders of the Fabry-Perot while both are scanned simultaneously by computer across a specified spectral interval. Successive spectra obtained in this manner are summed in the computer. For all observations reported here an aperture of diameter 5″ and an east-west chop of ~ 30″

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[1] Kapteyn Astronomical Institute, Rijksuniversiteit te Groningen.

[2] United Kingdom Infrared Telescope.

[3] Royal Observatory, Edinburgh.

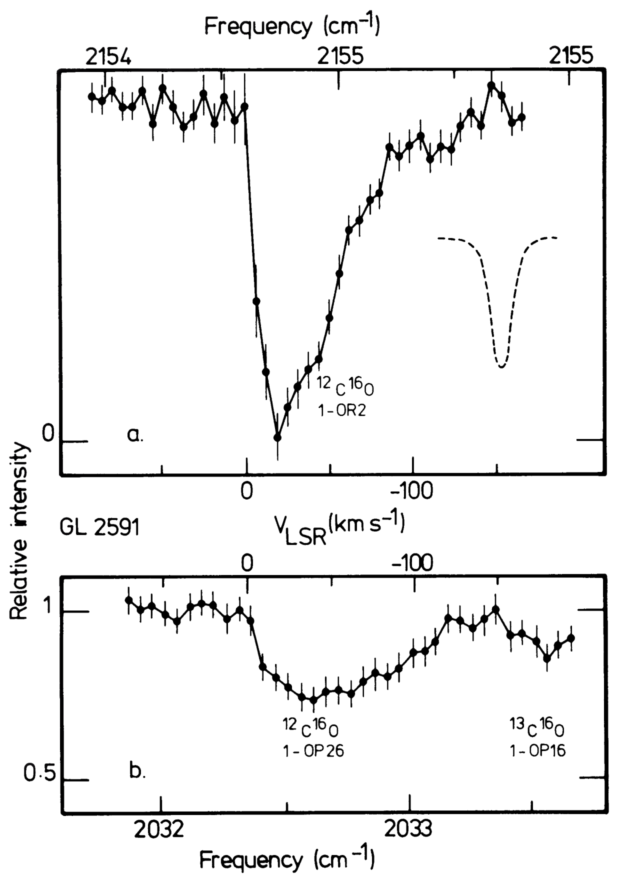

FIG. 1.—Ratioed spectra of GL 2591 in two narrow-frequency intervals in the 5 μm atmospheric window. The velocity resolution (FWHM) was ~ 12 km s^{-1}; the instrumental profile is indicated by the dashed line in the upper panel. The $^{12}\mathrm{C}^{16}\mathrm{O}$ and $^{13}\mathrm{C}^{16}\mathrm{O}$ lines in GL 2591 are labeled. Velocity scales relative to LSR are given in between the two panels for each $^{12}\mathrm{C}^{16}\mathrm{O}$ line. Error bars are $\pm 1\ \sigma$. (*a*) Spectrum near 2155 cm^{-1}. (*b*) Spectrum near 2033 cm^{-1}.

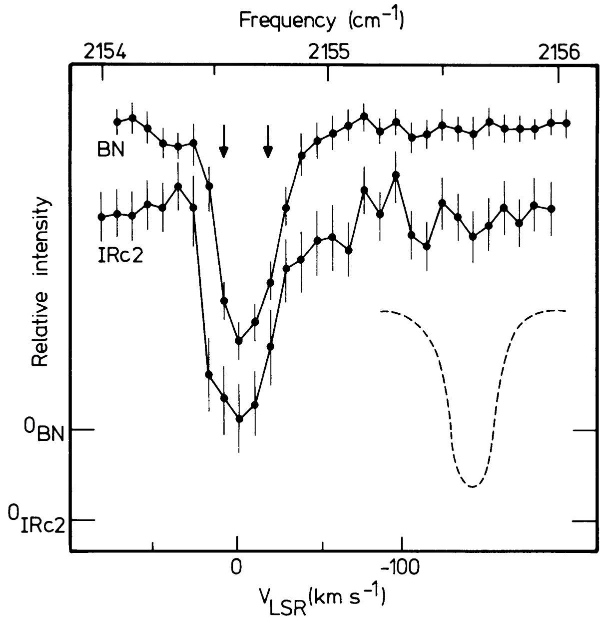

FIG. 2.—Ratioed spectra of IRc2 and BN near 2155 cm^{-1} in the region of the $^{12}\mathrm{C}^{16}\mathrm{O}$ 1–0 *R*2 line. The velocity resolution was ~ 24 km s^{-1}. Error bars are $\pm 1\ \sigma$. The positions of the absorption components at 9 and -18 km s^{-1} found by Hall *et al.* (1978) are indicated by vertical arrows.

were used. Frequency calibration, obtained from atmospheric lines and from a CO absorption cell mounted in front of the instrument, is accurate to ± 3 km s^{-1}.

Observations of fundamental band CO in GL 2591 were made on the nights of 1983 October 27–28 and 1984 September 17, using a Fabry-Perot of resolution 0.085 cm^{-1} (12 km s^{-1}). Spectral intervals observed included 2154-2156 cm^{-1}, which contains the 1–0 *R*2 line of $^{12}\mathrm{C}^{16}\mathrm{O}$, and 2032–2034 cm^{-1}, which contains both the 1–0 *P*26 line of $^{12}\mathrm{C}^{16}\mathrm{O}$ and the 1–0 *P*16 line of $^{13}\mathrm{C}^{16}\mathrm{O}$. Total integration times were 20 and 40 minutes, respectively. IRc2 was observed twice in the 2154-2156 cm^{-1} interval, on 1984 February 16–17 and 1984 September 19–20. On these occasions a Fabry-Perot of resolution 0.17 cm^{-1} (24 km s^{-1}) was employed, and BN was also observed. Total integration times were approximately 300 minutes for IRc2 and 20 minutes for BN. The final spectra of these objects, ratioed by suitably chosen standards observed on the same nights, are shown in Figures 1 and 2.

In the 2154–2156 cm^{-1} interval, absorption by the telluric $^{12}\mathrm{C}^{16}\mathrm{O}$ *R*2 line partially obscures the same line in GL 2591, IRc2, and BN. Complete recovery of a source spectrum by ratioing to a standard is possible only if the telluric line is fully resolved and not totally opaque. In our observations the telluric CO *R*2 line is almost fully resolved at 0.085 cm^{-1} resolution but is only partially resolved at 0.17 cm^{-1} resolution. At the higher resolution, it had a FWHM of 0.17 cm^{-1} and a fractional depth of 0.65 at maximum. Therefore the ratioed spectrum of GL 2591 in Figure 1*a* should represent the intrinsic spectrum to within the limits imposed by spectral resolution and sensitivity. For the lower resolution spectra of BN and IRc2, the two sets of spectra are shifted from each other by 0.36 cm^{-1} due to Earth's orbital motion, so that all portions of the source spectra were well transmitted during at least one of the measurements. The data points in Figure 2 are signal-to-noise–weighted averages of the data points in the individual ratioed spectra, and thus should represent the actual spectra to within the above limits. The interval 2032–2034 cm^{-1} was found to be nearly transparent, except for a strong line of H_2O at the high-frequency edge. This line obscures part of the $^{13}\mathrm{C}^{16}\mathrm{O}$ *P*16 line in GL 2591, which is omitted in Figure 1*b*. No telluric absorption due to the high-excitation $^{12}\mathrm{C}^{16}\mathrm{O}$ *P*26 line was detected.

III. RESULTS AND DISCUSSION

a) *GL 2591*

Early infrared observations of GL 2591 demonstrated its general similarity to BN. Both objects have strong 3.1 μm ice and 9.7 μm silicate absorptions on continua of similar shapes and apparent intensities (Merrill and Soifer 1974). More recent higher spectral resolution observations reveal some striking differences, as do the present data. BN is a source of strong infrared recombination line emission, whereas in GL 2591 no lines are observed at one-tenth the intensities seen in BN (Hall *et al.* 1978; Thompson and Tokunaga 1979; Simon, Simon, and Joyce 1979). The limit for radio continuum emission at the position of the GL 2591 continuum source (Campbell 1984) is also roughly one-tenth of that seen at BN (Moran *et al.* 1983). A second difference concerns the appearance of the infrared CO bands. In GL 2591 absorption lines of the fundamental band were detected easily by Lacy *et al.* (1984) using an instrument with a velocity resolution of ~ 350 km s^{-1}. Their detection demonstrates that the absorption lines are both strong and broad. In BN, the CO lines have a much smaller equivalent width (Hall *et al.* 1978) and detection would be difficult at the low resolution of Lacy *et al.* (1984).

Figure 1 shows the 1–0 $R2$ and $P26$ lines of ${}^{12}C^{16}O$ in GL 2591. The $R2$ line is especially strong with an equivalent width consistent with the estimate of Lacy *et al.* (1984). The most remarkable feature of these lines in GL 2591 is their large-velocity widths. The lines extend approximately from $V_{LSR} = -10$ km s^{-1} to -110 km s^{-1}, with the strongest absorption in each line occurring at the less blueshifted velocities. In contrast, millimeter CO line emission was detected only over the range 14 km $s^{-1} > V_{LSR} > -28$ km s^{-1} by Bally and Lada (1983). The two velocity ranges only partially overlap. Clearly, much of the CO detected at infrared wavelengths is moving much more rapidly than all of the CO seen at millimeter wavelengths. The broad infrared lines may be composed of several features at different velocities. Examination of Figure 1 suggests that discrete components may be present. Observations at higher sensitivity and perhaps higher resolution are required for confirmation.

The differences between the millimeter and infrared CO spectra can be understood as follows: The millimeter observations detect extended line emission from both the front and back of the flow. The velocity of the source of the flow is given approximately by the central velocity, or peak of the millimeter emission line; for GL 2591 this is $V_{LSR} \approx -5$ km s^{-1} (Lada *et al.* 1984). The presence of infrared CO absorption only at velocities more negative than $V_{LSR} = -5$ km s^{-1} verifies that gas along the line of sight is moving outward from the source at velocities as high as 100 km s^{-1}. That the highest velocities are not detected in the millimeter line implies that the filling factor of the high-velocity gas is very small, and thus that it is found close to the continuum source. This in turn implies that the gas has been ejected from GL 2591.

Comparison of the profiles of the two ${}^{12}CO$ lines, whose lower state energies differ by 1900 K, gives additional information on the outflow. A crude excitation temperature may be determined at each velocity from the ratio of these line profiles. At the highest expansion velocities the temperature is ~ 1000 K; at the lower velocities it is less than ~ 400 K. (The upper limit here is due to uncertainty in the degree of saturation of the $R2$ line.) It is also apparent from the absence in the spectra of prominent CO lines from higher vibrational levels that observed temperatures are not much higher than 1000 K.

The high-velocity gas appears therefore to be hotter than the low-velocity gas. This, together with the velocity extent of the millimeter CO line, implies that the CO has been strongly decelerated before it reaches distances from the central source ($> 10^{17}$ cm) at which the filling factor at millimeter wavelengths is significant. Rough assumptions for the innermost radius at which temperatures of ~ 1000 K would occur (5×10^{14} cm assuming Lada *et al.*'s 1984 value for the luminosity of GL 2591), and the mass within this radius ($\gtrsim 30$ $M_\odot$, the mass of a star having this luminosity) suggest that gravity may not account for all the deceleration. Lada *et al.* (1984) find evidence for constant or increasing velocity with distance from the source of the flow. Taken together these results could indicate deceleration due to either a compact dense region or a shell within ~ 10^{17} cm of the source and could suggest that the increasing velocities seen by Lada *et al.* are due to rotation of the molecular cloud.

Without further observations and a detailed model of the outflow, only a crude column density and mass-loss rate can be estimated from the present observations. We obtain $N_{CO} \approx 2 \times 10^{19}$ cm^2 and $M \approx 10^{-4}$ $M_\odot$ yr^{-1}, where the uncertainties are at least a factor of 3 and an order of magnitude, respectively. It is important to refine both estimates and to obtain for comparison a mass-loss rate from the spatially resolved millimeter line emission.

b) *IRc2*

The source, IRc2, situated within OMC-1 and only a few arc seconds distant from the apparently much brighter source, BN, is thought to be more heavily obscured, more luminous, and in an earlier evolutionary state than BN (Downes *et al.* 1981). Evidence presented by Wynn-Williams *et al.* (1984) suggests that a wind from IRc2 has created a low-density cavity within OMC-1; the broad (FWZI ≈ 200 km s^{-1}) millimeter CO lines observed in this region are widely suspected to be emitted in that wind. Mass-loss rates estimated from these lines are typically greater than 10^{-3} $M_\odot$ yr^{-1} (e.g., Bally and Lada 1983).

A deep absorption feature due to the 1–0 $R2$ line of ${}^{12}C^{16}O$ is seen in Figure 2 in the spectra of both BN and IRc2. The CO absorption in BN is known to be produced primarily by gas at $V_{LSR} = +9$ and -18 km s^{-1} (Hall *et al.* 1978; Scoville *et al.* 1983). These components would not be resolved from one another at the resolution used here; however, the measured line center velocity of $V_{LSR} = -4 \pm 4$ km s^{-1} and FWHM of 40 ± 5 km s^{-1} in BN is clearly consistent with their presence. The observed line profile in IRc2 is similar to that of BN, except for the probable presence of a faint component or wing extending to $V_{LSR} \approx -60$ km s^{-1}. The core of the line is centered at $V_{LSR} = -2 \pm 8$ km s^{-1} and has a FWHM of 45 ± 10 km s^{-1}, which within the uncertainties are identical to those of BN. This together with the proximity of IRc2 to BN suggests that the principal absorption components seen in the BN spectrum are also present along the line of sight to IRc2. Hall *et al.* (1978) and Scoville *et al.* (1983) interpreted the $+9$ km s^{-1} feature as arising in quiescent OMC-1 gas and the -18 km s^{-1} feature as arising in the high-velocity flow. Our interpretation of the spectrum of IRc2 is not inconsistent with theirs, as it implies that most of the absorbing gas is local to neither source. It must be stressed that our interpretation of the CO line profile in IRc2 requires confirmation based on measurements at higher spectral resolution. We did not attempt such measurements because of the faintness of IRc2.

The faint blue wing of CO absorption, if real, suggests that a cool outflowing wind may be associated with IRc2, as it is with GL 2591. It generally has been assumed that IRc2 is the source of the massive high-velocity outflow in OMC-1. If this is indeed the case, then it is perhaps surprising that there is so little blueshifted CO absorption seen toward IRc2. The rate of mass loss estimated from the strong and broad lines in GL 2591 is probably at least an order of magnitude *less* than that inferred from the outflow in OMC-1, and thus, one might have expected stronger and more blueshifted absorption lines in IRc2 than in GL 2591. A possible explanation for the paucity of infrared evidence for the outflow is the existence of a thick disk or doughnut-like structure close to IRc2, oriented such that it prevents the outflow of material from IRc2 along the line of sight. The surface of the disk would emit the continuum which we have observed, and the bipolarity of the millimeter CO outflow, established by Erickson *et al.* (1982), would be a natural consequence of the structure. Chelli, Perrier, and Léna (1984) and Lester *et al.* (1984) have determined dimensions of $1\farcs4 \times 0\farcs8$ for IRc2 at various mid-infrared wavelengths, which presumably are the outer dimensions of the structure. Chelli *et al.* have proposed that the structure is a doughnut which is tilted such that its interior can be seen from our line of sight. However, the lack of highly blueshifted CO absorption may demand a more nearly edge-on orientation than they suggest.

Although the above explanation for the rather narrow CO absorption feature in IRc2 appears plausible, the possibility that IRc2 is not the source of the high-velocity outflow is also raised by the present observation and should be considered. In this case the blueshifted CO absorption could be explained as the outflow being seen in projection toward IRc2 and BN. However, the source of the outflow would have to be an additional luminous object within the OMC-1 core, and in this regard no candidates have been found from mapping out to 30 μm (Lee *et al.* 1983; Wynn-Williams *et al.* 1984). Luminosity arguments also tend to preclude the existence of such an object (Wynn-Williams *et al.* 1984). Therefore, it appears more likely that the explanation for the IRc2 line profile lies in the particular morphology of that object.

IV. CONCLUSION

Although simple interpretations of the observed infrared CO spectra of GL 2591 and IRc2 exist, the spectra appear almost contrary to naive expectations based on previous millimeter line spectroscopy. The infrared CO lines observed in GL 2591 have much higher velocities than those seen in the millimeter CO line spectrum. In contrast the millimeter CO lines in Orion imply a high outflow velocity and rate of mass loss, but these are not suggested by the single infrared CO line observed in IRc2.

A better understanding of the GL 2591 and IRc2 infrared CO spectra awaits measurements of a wider range of CO lines. The spectra presented here illustrate the exciting possibilities of this technique and the importance of extending it to more lines and other sources.

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T. R. GEBALLE: United Kingdom Infrared Telescope, 900 Leilani Street, Hilo, HI 96720

RICHARD WADE: Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, Scotland, United Kingdom