THE ASTROPHYSICAL JOURNAL, 271:L79–L83, 1983 August 15

SPECKLE INTERFEROMETRY OF IRC +10216 IN THE FUNDAMENTAL VIBRATION-ROTATION LINES OF CO

H. M. DYCK[1]
Institute for Astronomy, University of Hawaii; and Max-Planck-Institut für Astronomie
S. BECKWITH[1, 2]
Department of Astronomy, Cornell University
AND
B. ZUCKERMAN[1]
Astronomy Program, University of Maryland; and Astronomy Department, University of California, Los Angeles
Received 1983 January 3 1983; accepted 1983 April 27

ABSTRACT

Measurements have been made of the spatial distribution of five fundamental vibration-rotation lines of ^{12}CO and ^{13}CO in the carbon star IRC +10216 by combining high angular (1″) and spectral (45 km s^{-1}) resolution. All five lines were spatially resolved and found to be larger in size than the stellar continuum radiation at the same wavelengths.

Subject headings: interferometry — stars: circumstellar shells

I. INTRODUCTION

Red giants probably provide the largest fraction of the matter returned by stars to the interstellar medium. Mass loss rates vary greatly among individual giant stars depending on position on the giant branch; some stars lose more than 10^{-5} $M_{\odot}$ yr^{-1} (Zuckerman 1980; Knapp *et al.* 1982). Although the evidence for mass loss is by now overwhelming, the underlying physical mechanism that accelerates the gas is still not understood.

The carbon star IRC +10216 is an example of an evolved giant with a large mass loss rate. Because it is luminous (10^4 $L_{\odot}$) and nearby (~ 300 pc), it has been well studied at infrared and radio wavelengths. Infrared observations of NH_3, CH_4, CO, and C_2H_2 and HCN indicate that the gas has already reached terminal velocity (~ 15 km s^{-1}) at about eight stellar radii (~ 10^{15} cm) (references in Zuckerman 1980). This is in agreement with general theoretical ideas that the primary acceleration of the gas should occur within a few stellar radii.

One plausible acceleration mechanism in stars like IRC +10216 is radiation pressure on dust grains which then collide with and transfer their momentum to the gas. Using interferometric and lunar occultation techniques, various groups have measured the distribution of dust within a few arc seconds of IRC +10216 and other cool giant stars (e.g., McCarthy, Howell, and Low 1980). However, the intensity of infrared emission as a function of distance from the central star is determined by the combined effects of dust density and temperature. The two are not uniquely separable given the present state of the art for circumstellar shell models. This problem, combined with the fact that the dust may be forming as far as 10^{16} cm from the star (Werner *et al.* 1980) corresponding to a few arc seconds at the distance to IRC +10216, has made it impossible to establish the detailed distribution of material in the inner portions of the stellar envelope. In particular, based on studies of the dust, we still do not know if matter leaves the central star in a series of puffs or is ejected continuously in a steady wind.

Existing studies of the gas are also of limited value in distinguishing between these two possibilities. At a few hundred stellar radii and beyond, millimeter-wavelength radiation from CO and other molecules is readily observable in many stars. Because of large beamwidths and the differential ejection velocities of various shells which would smear together at large distances from the stars, it would, however, be very difficult to decide between continuous and pulsed ejection based on millimeter-wavelength observations. Infrared and visual observations of molecules and atoms in absorption against the central star often show multiple velocity components. Although this result may imply pulsational ejection, other interpretations appear possible.

At the present time neither infrared nor microwave observations provide a clear picture of the distribution of matter near cool red giant stars.

[1]Visiting Astronomer at the Infrared Telescope which is operated by the University of Hawaii under contract through the National Aeronautics and Space Administration
[2]Alfred Sloan Fellow.

One method which may give us significantly more information about the distribution of matter very close to the star is to measure the spatial extent of near-infrared lines using a combination of very high spatial and high spectral resolution. This method is the subject of the present *Letter*. Using speckle interferometry, we have measured the radial distribution of CO molecules on angular scales of 1″ near IRC +10216. Briefly, the idea is as follows. At distances of a few stellar radii from the photosphere, the CO gas temperature will be sufficiently low that most of the molecules will be in the ground vibrational state. An element of gas will absorb radiation traveling outward from the star and emit it isotropically. When observed away from the star in the light of an isolated CO line, the element will appear bright. By mapping this brightness as a function of distance from the star and observing lines originating from different levels, we eventually expect to establish the run of gas density, temperature, and velocity close to the star.

We have discussed the importance of the density distribution above. A measurement of the temperature distribution should also be of great interest. Indeed, at present, there is no really reliable observational or theoretical way to determine the radial temperature distribution of the gas. If we can measure it by means of "speckle spectroscopy," we can better constrain physical and chemical models of the circumstellar envelopes.

The purpose of the present *Letter* is to report the first infrared speckle spectroscopy measurements. Although our present spatial and spectral resolutions are inadequate to yield definitive answers to the problems posed above, we expect substantial improvements shortly, and the technique holds great promise for the future.

II. OBSERVATIONS

The CO line observations were obtained at the Infrared Telescope Facility (IRTF) on the nights of 1982 January 30, 31, and February 1 (UT) using a cooled grating spectrometer (Beckwith *et al.* 1983) and a speckle interferometry system similar to the one described by Dyck and Howell (1982). The entrance slit of the spectrometer was 0.1 mm wide corresponding to 0″.2 in the focal plane of the telescope. The chopping secondary mirror was driven by the observatory's PDP 11/45 computer in a sawtooth pattern north-south, sweeping the image across the slit at a rate of ~ 20″ per second with a total scan length of either 10″ or 5″. Each scan was divided into 128 segments of equal length. Typically 128 scans were obtained, the discrete Fourier transform of each scan was computed, and the power spectra of the scans were averaged together to produce a single data set. Data sets were taken alternately on the object or wavelength of interest and a calibrator (either a star or a different wavelength as described below). The power spectra of the object and the calibrator were ratioed to remove the effects of the instrument and atmosphere on the size of the image.

Figure 1 shows a portion of the spectrum in the vicinity of the ^{12}CO (1–0) $R(6)$ line. The spectral resolution of the spectrometer was approximately 0.3 cm^{-1} corresponding to 45 km s^{-1} for the CO line measurements. This relatively high resolution (for a cooled grating instrument) was possible because of the narrow entrance slit used for the speckle scans. The grating position readout allowed us to set the wavelength with a precision of about one-quarter of a resolution element.

In the usual method of speckle interferometry, the effects of the atmosphere and telescope on the image size are removed by comparing the object scans with scans of a nearby star whose angular diameter is smaller than the diffraction limit of the telescope. For the present experiment, we chose to compare the scans of spectral lines to scans of the same object at wavelengths in the stellar continuum close to the line. This method does not give an absolute size for the line-emitting region, but rather the size relative to the size of the continuum-emitting region. We were mainly interested in the relative sizes, but we also measured the absolute size of the region producing 4.8 μm continuum flux using normal broad-band speckle techniques on both the IRTF and the University of Hawaii 2.2 m telescope.

At the wavelength of the CO fundamental vibration-rotation bands (4.7 μm ≈ 2100 cm^{-1}), the diffraction-limited spatial frequency (f) transmitted by the 3 m IRTF is 3 cycles arcsec^{-1} corresponding to 0″.33 spatial resolution. The data beyond 1 cycle arcsec^{-1} were badly distorted by the telescope, and we have disregarded all spatial frequencies higher than this value. From subsequent simulation tests of the chopping secondary, we believe that the distortion can be attributed to poor control of the sweep rate of the secondary mirror at high frequencies and can be corrected in future observations. Observations of visual double stars during January-February and again in June on the IRTF indicated that the distortion at spatial frequencies below 1 cycle arcsec^{-1} was insignificant for the present experiment.

We measured the north-south visibility in the light of several lines of ^{12}CO and ^{13}CO in the v = 1–0 vibration-rotation band; these lines are listed in Table 1. We attempted to find lines which would be uncontaminated by other nearby CO lines at the present spectral resolution based on the published spectra and discussion of Geballe, Wollman, and Rank (1973). More recent spectra by Hall (1982) indicate that some contamination from v = 2–1 transitions probably did occur, and remarks about possible contamination are included in Table 1.

High-resolution spectra of the lines measured here show P Cygni profiles (Ridgway and Hall 1980). At the present resolution, both the emission and absorption

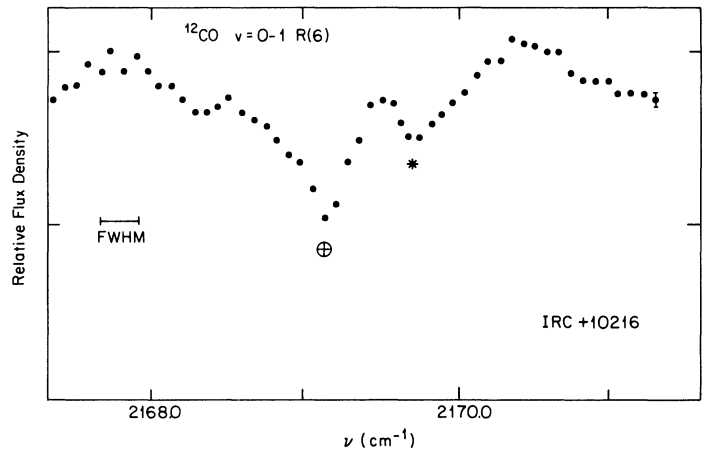

FIG. 1.—Spectrum of IRC +10216 near the $^{12}CO(1-0)\,R(6)$ line. The marked positions correspond to the telluric (⊕) and stellar (*) CO absorption lines. This spectrum was made at slightly higher spectral resolution than that used for the speckle scans. The bandpass for the speckle scans was centered 0.1 cm^{-1} lower than the position of the maximum stellar absorption to accept the P Cygni emission in the line.

TABLE 1

A SUMMARY OF THE CO LINES AND CONTINUUM REFERENCE POSITIONS

Line	ν_l(cm^{-1})	ν_c(cm^{-1})	Blends
^{13}CO $P(3)$	2084.95	2083.77	^{13}CO(2–1) $R(3)$
^{12}CO $P(14)$ ...	2086.32	2083.77	...
^{13}CO $R(9)$	2131.01	2131.98	...
^{12}CO $P(3)$	2131.63	2132.98	^{12}CO(2–1) $R(3)$
^{12}CO $R(6)$	2169.20	2167.32	...

parts of each line are included in the measurement at the line wavelength, and in some cases telluric absorption of the stellar continuum was also present within the bandpass. Because there may be systematic effects on the image size due to the Earth's atmosphere, we tested to determine if the image size would be altered by the presence of a telluric line by ratioing spectra of the stellar continuum at wavelengths inside and outside of strong telluric lines, but away from any stellar lines. Three telluric lines were checked in this way, and there was no evidence of any change in image size within or near telluric lines at the 1″ level. An example of such a ratio is shown in Figure 3.

III. DISCUSSION

Figure 2 shows the north-south visibilities of the CO lines plotted as the ratio of line to adjacent continuum; these are relative visibilities. Scan lengths of 5″ and 10″ are plotted separately to demonstrate that the results are insensitive to scan length. The data represent the mean

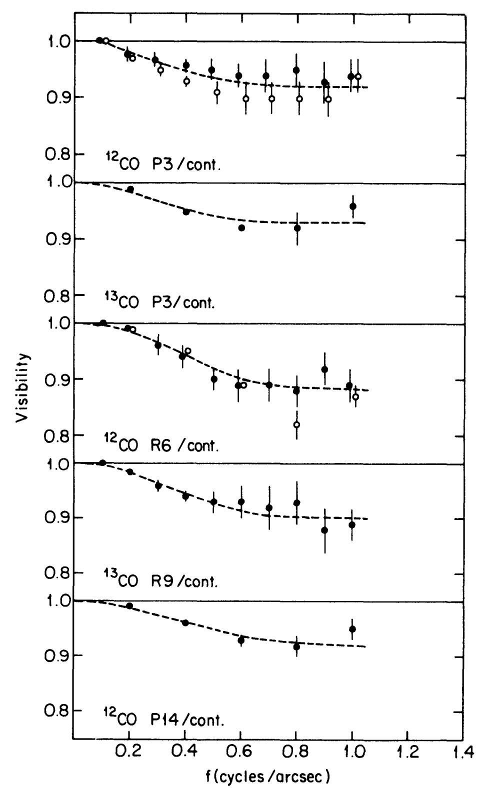

FIG. 2.—Relative visibility data for five CO fundamental vibration-rotation lines taken with a spectral resolution of 0.3 cm^{-1}. Each set of data has been divided by the visibility of a nearby continuum frequency. Data taken on different nights are shown with different symbols. Two-component Gaussian models (discussed in the text) are shown as dashed lines in the figure.

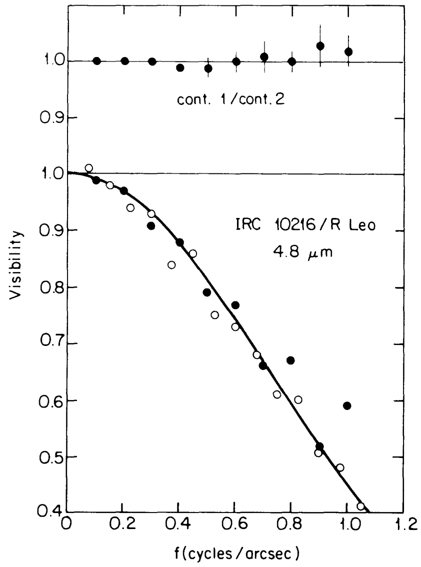

FIG. 3.—(a) The ratio of two different continuum points near the ^{12}CO $R(6)$ line. One of these lay inside the telluric $R(6)$ line. These observations show that the presence of telluric lines has no effect upon the measured visibility. (b) The north-south 4.8 μm continuum visibility for IRC +10216 (ratioed to R Leo). The filled circles are data obtained on 1982 February 1 (UT) on the IRTF, and the open circles, on 1982 June 12 (UT) on the 2.2 m telescope.

and standard deviation of the mean of several data sets for each line. One feature is clearly common to the five CO line visibility curves: the visibility of each line drops to ~ 90% at $f \sim 0.6$ cycles arcsec^{-1} and remains constant within the uncertainties to 1 cycle arcsec^{-1}. Our interpretation is that the P Cygni emission region in each CO line is more extended that the continuum emission region produced by thermal radiation from dust.

To fix the absolute size of the CO emitting region, it is necessary to measure the continuum visibility relative to a point source. In Figure 3, we show the 4.8 μm continuum visibility. The data obtained in January–February on the IRTF and those obtained in June on the 2.2 m telescope are plotted separately. A Gaussian visibility model, shown as a solid curve in the figure, has been fitted to the data; for this model, the full width at half-maximum is 0''.48. Our speckle data are consistent with those of Howell (1980), Mariotti *et al.* (1983), Ridgway (1982), and McCarthy, Howell, and Low (1980).

The absolute size of each CO line emission region can be calculated from the results above. One of the difficulties in obtaining a quantitative estimate of the CO brightness distribution arises from the relatively broad spectral passband used in this experiment. The equivalent width of R-branch ^{12}CO lines near the $R(6)$ line seen in absorption against the star is 0.07 cm^{-1} or about 20% of our passband (Ridgway and Hall 1980). This is approximately the expected fractional energy to be seen in emission from CO off the star. Thus, at least 80% of the measured energy—when the spectrometer is centered on the CO line—must come from the dust continuum. The line-to-continuum contrast (and, hence, the signal-to-noise ratio for the deconvolved CO brightness distribution) is greatly reduced, making it difficult to obtain a unique model for the visibility. It is nonetheless possible to fit the brightness distributions in a simple model which is outlined below.

The visibility observed at the line wavelength consists of contributions from line and continuum. If we assume that each part can be modeled by a Gaussian brightness distribution, the ratio of line plus continuum to the continuum visibility has the form

$$V(f) = V_0 + (1 - V_0)\exp\left[-2\pi^2 f^2\left(\sigma_L^2 - \sigma_D^2\right)\right], \quad (1)$$

where σ_L and σ_D are the characteristic widths of the line and dust continuum emission regions, respectively, V_0 is the fraction of the flux radiated by the dust continuum into our spectral passband, and f is the spatial frequency in cycles arcsec^{-1}. Each of the visibilities plotted in Figure 2 has this model fitted to the data.

Using the value of σ_D derived from Figure 3 together with equation (1), we derive the values of σ_L for each of the CO lines from the models in Figure 2; the resulting parameters are given in Table 2. The spatial scale for the CO emission is larger than the dust emission scale by factors of 2.2–3.0. This result is consistent with the view that the optical depth in a CO line is much greater than that in the nearby dust continuum (Keady 1982).

One may use the temperature profile for gas in IRC +10216 calculated by Kwan and Linke (1982) to estimate radial optical depths for various CO transitions of interest. With an assumed local line width of 1 km s^{-1}, we find a $P(14)$ optical depth of ~ 1 between infinity

TABLE 2

GAUSSIAN FWHM FOR THE DUST CONTINUUM AND CO-LINE BRIGHTNESS PROFILES FOR IRC +10216

Observation	FWHM (″)	Projected Radius (cm)[a]
Dust continuum ...	0.48 ± .01	1.04×10^{15}
^{12}CO $P(3)$	1.46 ± .12	3.17×10^{15}
^{13}CO $P(3)$	1.36 ± .14	2.95×10^{15}
^{12}CO $R(6)$	1.06 ± .12	2.30×10^{15}
^{13}CO $R(9)$	1.29 ± .17	2.80×10^{15}
^{12}CO $P(14)$	1.18 ± .14	2.56×10^{15}

NOTE.—FWHM = 2.35 σ where σ is defined in text.
[a]Assumed distance of 290 pc.

and a radial distance that corresponds to $\sim 2''$ angular displacement from IRC +10216 (or $\sim 6 \times 10^{15}$ cm for Kwan and Linke's assumed distance, 200 pc, to IRC +10216). This is mainly due to the small population in the $J = 14$ level beyond 6×10^{15} cm where the gas temperature is less than 100 K. Given the various uncertainties in the circumstellar model and in the observations, the agreement between our observed size and the above estimate for scattering of $P(14)$ line photons appears reasonable.

For the $P(3)$ line the result of a similar calculation is strikingly different. The $J = 3$ level carries $\sim 15\%$ of the total CO population all the way from $2''$ to $30''$ (where $T \sim 15$ K). The $P(3)$ radial optical depth over this path is ~ 50, and we might have expected to measure a size for the $P(3)$ envelope that is much larger than that for $P(14)$. That the $P(3)$ size is at most only slightly larger than $P(14)$ can probably be explained by trapping of the CO vibrational radiation just outside of the region responsible for the 4.7 μm continuum radiation. Provided that the local velocity dispersion ($\Delta V \sim 1$ km s^{-1}) is much less than the terminal outflow velocity ($V_\infty \sim 15$ km s^{-1}), a number of possible fates await these trapped photons, the relative importance of which depends on the mass loss rate, $\Delta V/V_\infty$, and the dust-to-gas ratio (among other quantities). It appears that trapped photons cannot diffuse very far beyond the region that produces the 4.7 μm continuum emission before they are either destroyed by dust or escape along outward trajectories that are not in radiative contact with outflowing gas far from the star. Depending on the circumstellar parameters, this escape may result from diffusion in frequency (in the blue wing of locally produced profiles) or in space, or in both, and takes place in a nonradial direction where the spherical outflow geometry prevents reabsorption at large distances from the star. Hence, little $P(3)$ fluorescent emission will be excited far from the star despite the large local line-center optical depths. We have made rough estimates of photon mean free paths and scattering optical depths in IRC +10216 which suggest that our measured size for the $P(3)$ line is reasonable.

An increase of a factor of 2 in spectral resolution will help significantly to distinguish differences among the sizes of line-emitting regions at different rotational levels. At a resolution high enough to resolve the lines, observation of different rotational levels should allow us to map the velocity as a function of distance from the star.

It is a pleasure to thank E. E. Becklin, D. Hall, R. Howell, M. Jura, J. Keady, and N. Scoville for helpful discussions. S. Ridgway kindly supplied data on the 4.8 μm continuum visibility, and D. Hall provided the high-resolution spectra of IRC +10216 for comparison with our own spectra. S. Beckwith was supported in part by NASA grant NSG 2412. B. Zuckerman was supported in part by NSF grant AST 80-23355 to the University of Maryland. The instrument was built with funds from the Research Corporation through a Cottrell Research Grant.

REFERENCES

Beckwith, S., Evan, N. J., II, Gatley, I., Gull, G., and Russell, R. W. 1983, *Ap. J.*, **264**, 152.
Dyck, H. M., and Howell, R. R. 1982, *A.J.*, **87**, 400.
Geballe, T. R., Wollman, E. R., and Rank, D. M. 1973, *Ap. J.*, **183**, 499.
Hall, D. N. B. 1982, private communication.
Howell, R. R. 1980, Ph.D. thesis, University of Arizona.
Keady, J. J. 1982, Ph.D. thesis, New Mexico State University.
Knapp, G. R., Phillips, T. G., Leighton, R. B., Lo, K. Y., Wannier, P. G., Wooten, H. A., and Huggins, P. J. 1982, *Ap. J.*, **252**, 616.
Kwan, J., and Linke, R. A. 1982, *Ap. J.*, **254**, 587.
Mariotti, J. M., Chelli, A., Foy, R., Lena, P., Sibille, F., and Tchountonov, G. 1983, preprint.
McCarthy, D. W., Howell, R. R., and Low, F. J. 1980, *Ap. J.* (*Letters*), **235**, L27.
Ridgway, S. T. 1982, private communication.
Ridgway, S. T., and Hall, D. N. B. 1980, in *Interstellar Molecules*, ed. B. H. Andrew (Dordrecht: Reidel), p. 509.
Werner, M. W., Beckwith, S., Gatley, I., Sellgren, K., Berriman, G., and Whiting, D. L. 1980, *Ap. J.*, **239**, 540.
Zuckerman, B. 1980, *Ann. Rev. Astr. Ap.*, **18**, 263.

S. BECKWITH: Department of Astronomy, Space Sciences Building, Cornell University, Ithaca, NY 14853

H. M. DYCK: Max-Planck-Institut für Astronomie, D-6900 Heidelberg, Konigstuhl, West Germany

B. ZUCKERMAN: Astronomy Department, University of California, Los Angeles, CA 90024