OBSERVATIONS OF CIRCUMSTELLAR CLOUDS

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Observations have been made of J=2-1 CO in eleven circumstellar clouds including seven carbon stars and four oxygen-rich stars. Observations in four sources, including IRC+10216 have already been published (Wannier et al. 1979, henceforth Paper I) and the remaining observations are being prepared for publication (Knapp et al. 1980, henceforth Paper II). Several results are discussed below with special emphasis on the implications for two sources, namely IRC+10216 and Mira (o Ceti). The observations of IRC+10216 show CO emission over a diameter of 6 arcmin ($\sim$ 0.5pc), a result suggesting a very large mass-loss rate. Mira is unique among the objects studied in displaying a small CO opacity and a high CO excitation temperature. It is suggested that this heating results from the orbital velocity of Mira due to its close binary companion.

1. INTRODUCTION

There is, by now, a considerable list of late-type stars which exhibit measurable CO lines from extended envelopes of ejected material. The observations of thermal millimeter-wave emission lines hold the promise of providing an accurate picture of the entire mass-loss process. In turn, the history of the mass-loss rate $\dot{M}(t)$, the ejection velocity $V_e(t)$ and the composition of the ejecta, should provide additional information about the very uncertain post-main sequence stellar evolution. To date, most of the spatial information about stellar envelopes has been provided by comparing the lines of molecules which have very different excitation requirements. However, such information is indirect and the spatial information so derived is model dependent.

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The observations discussed below provide high spatial resolution ($\sim$25 arcsec) of a line (CO (J=2-1)) which traces out the most extended molecular gas. Spatial resolution of the stellar envelopes provides valuable new information, as evidenced especially by the results from IRC+10216.

2. DISCUSSION

Full details of the observational techniques are given in Paper II, and will not be repeated here. The important point is that the 10m antenna at the Owens Valley Radio Observatory provides a reasonably clean beam with a FWMH beamwidth of 25 arcsec at the observing frequency of 230 GHz. Calibrations of size and intensity were made using Saturn, Jupiter and Mars (Paper I).

In order to appreciate the significance of the maps, it is necessary to understand a few of the simple properties of constant mass outflow. When this is done, we see that the extended emission is far more significant in terms of total mass than is the brighter central source. Complete treatment of such outflow is given, for example, by Kwan and Hill (1977).

The observed outflow velocity far exceeds the escape velocity from the central object so that there can be no significant deceleration of the material. Thus, in the case that $\dot{M}$ and the initial velocity are constant, the space density is expected to fall as $1/r^2$. This gives rise to three effects significant for the observed CO brightness temperature: 1) the tangential column density falls as 1/r, 2) the collision rate falls as $1/r^2$ and 3) the free expansion gives rise to adiabatic cooling. So long as the CO rotational lines are heavily trapped ($r \lesssim 3 \times 10^{16}$ cm in the case of IRC+10216), the apparent brightness temperature remains quite high. However, beyond a radius of 10^{17} cm the column density falls, the kinetic temperature falls and the collision rate is so low as to yield a very subthermal excitation. For the J=2-1 line, subthermal excitation is especially significant. Thus, the 2-1 CO brightness temperature is expected to fall precipitously with increasing radius.

Another property of circumstellar clouds is that the computational models are likely to be quite accurate. The kinematics, the geometry and the age of the material are reasonably well known. This situation contrasts the case for giant interstellar clouds where clumping, turbulance and a total lack of symmetry can make the application of computational models difficult at best. Our observations are therefore profitably examined in light of the computational model of Kwan and Hill.

2.1 IRC+10216

This well-studied object is an isolated variable carbon star at a distance of 200-300 pc. It displays very intense infra-red emission symptomatic of a thick dust shell. The initial mass of the star is unknown, though it is probably greater than $3M_\odot$. A high mass-loss rate ($\sim 10^{-4.5}$ $M_\odot$/yr) has been indicated by millimeter-wave emission lines, and the IR observations are discussed by A.L. Betz and by D.N. Hall and S.T. Ridgeway in these proceedings. The ejected material is strongly affected by evolution in the parent star, as can be seen by its unusual nuclear composition (Wannier and Linke, 1977). However, until the indications in Paper I of a non-constant mass-loss rate, there had been no indications of physical evolution of the central object.

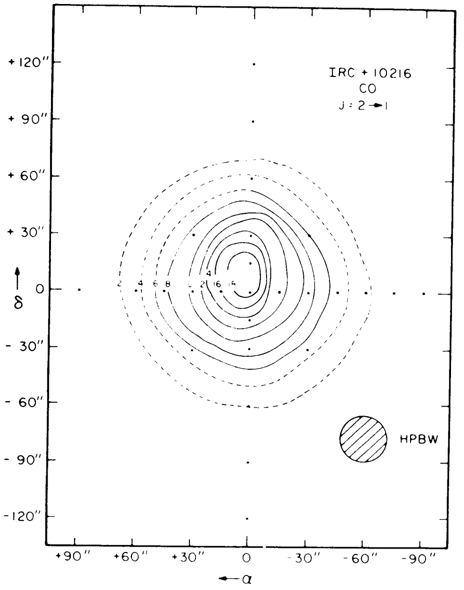

Figure 1. Map of the peak temperature T_A* for IRC+10216. Map points are indicated by dots and the telescope halfpower beamwidth is shown. A circular symmetry is apparent.

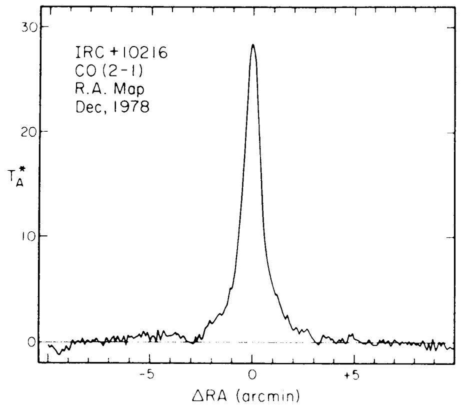

Figure 2. Map of CO (2-1) emission in IRC+10216 at V_{LSR} = -26 km/s.

In Figures 1 and 2, two different types of maps are shown for the 2-1 CO line. The first map, from Paper I, is of peak intensity made from individual 2-1 CO spectra. The second, from Paper II, is a strip map made by scanning the telescope past the source and is of the peak intensity at the central velocity using a total bandwidth of 1 MHz. The first map indicates that the circumstellar shell is spherically symmetric, at least out to a radius of 1.5 arcmin. Emission was detected even at the outermost points of the map. The second map shows that the 2-1 CO emission extends to a radius of at least 3 arcmin. Using an estimated distance of 290 pc (uncertain to at least ± 30%), this yields

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an apparent source diameter of 1.5×10^{18} cm which corresponds to an age of $\sim3\times10^4$ yrs for the material at the outer observed boundary of the cloud.

In light of our discussion about circumstellar clouds, the significance of the extended envelope is apparent. The extended wings, although less bright than the central source, are nontheless unexpectedly intense when compared to the model of Kwan and Hill(1977) by a factor of 3-6, depending on the radius (See Figure 3).

Using an assumed distance of 290 pc, a slightly better fit is obtained from the KH model by increasing the assumed mass-loss rate from 3×10^{-5} $M_\odot$/yr to 10^{-4} $M_\odot$/yr. This however, produces a 2-1 CO brightness which is at once too bright in the center and insufficiently bright in the extended envelope(Kwan, 1979). This extended emission is most naturally explained by assuming an increase in density above the $1/r^2$ relation which results from a constant value of $\dot{M}$ and V_e.

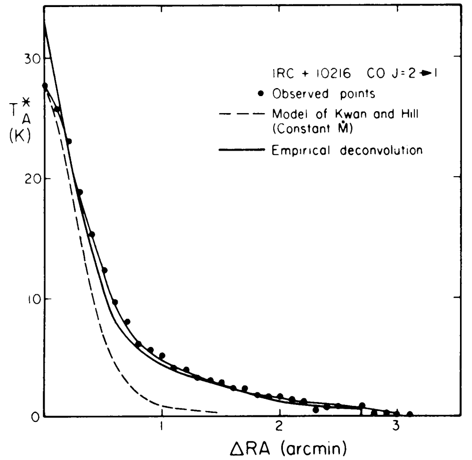

Figure 3. The observations of Fig. 2 are folded and displayed along with the model calculation for $\dot{M} = 2\times10^{-5}$ $M_\odot$/yr.

One property of the circumstellar envelope is that beyond a radius of $\sim3\times10^{17}$ cm (the antenna beam diameter), the space density is too low to allow for further evolution of the dust or of the chemical composition of the gas. Thus the fractional CO abundance and the efficiency of heating by radiation-driven dust must be considered to be constant. If the extended emission results from an unexpectedly large density of material, we must consider secular changes in either of the parameters $\dot{M}$ or V_e, a decrease in the former or an increase in the latter. However, a constant value of V_e is strongly indicated by the data of Kuiper et al. (1976) which show a dramatic high-velocity cut-off in the observed ^{13}CO (1-0) spectrum. We have recently confirmed the steep cut-off with improved (1-0) ^{13}CO observations. Therefore, a positive deviation from the $1/r^2$ density law must result from a larger past value of the mass-loss rate $\dot{M}(t)$.

2.2 Mira

In contrast to IRC+10216, Mira (o Ceti) is an oxygen-rich object exhibiting H_2O, OH and SiO maser emission. It has a much smaller mass-loss rate and is one component of a close binary system. The molecular envelope, whose size is large compared to the binary separation, exhibits a variable broad-velocity CO line (Lo and Bechis, 1977). The distance to Mira is known to be 77pc from measurements of trigonometric parallax.

Our own observations indicate that the CO(2-1) brightness temperature is far in excess of the CO(1-0) temperature measured with a similar telescope. (See Figure 4). Indeed, whereas all other objects in our survey have a CO(2-1)/CO(1-0) brightness ratio of between one and eight, Mira has a ratio in excess of 16 for the non-variable narrow line. Such a large ratio is very difficult to produce. A factor of four enhancement is possible if the source is unresolved, because of the comparable sizes of the OVRO 10.5m antenna used for CO(2-1) and the NRAO 11m used for the CO(1-0). A second factor of four is possible from the ratio of optical depths, so long as both of the lines are optically thin. These two factors could just account for the ratio of 16. Two additional effects, if present, might tend to decrease the CO(2-1) intensity. First, if the hydrogen molecular density were $<4000\ cm^{-3}$, then the CO(2-1) line would become subthermally excited relative to the (1-0) line. Second, if the gas kinetic temperature were $\lesssim$ 20K, the line intensity ratio would be reduced because of the property of T_A*, the equivalent Rayleigh-Jeans brightness temperature (see the discussion in Paper I). This last effect is unlikely in view of the large brightness temperature of the 2-1 CO line. We therefore infer that 1) the source is largely unresolved at CO(2-1), 2) the source is optically thin and 3) the density is $\gtrsim 4000\ cm^{-3}$.

The uniquely large (2-1)/(1-0) CO intensity ratio does not seem to result from the rather unexceptional values for $\dot{M}$ and V_e ($2\times10^{-6}\ \dot{M}$/yr and 5.6 km/s respectively). However, a unique property of Mira is its membership in a close binary pair. The orbital parameters of the binary are not known, but reasonable assumptions for the masses and separation of the two stars ($\sim 1 M_\odot$ apiece and $\sim 7\times10^{14}$ cm) imply orbital motions of $\sim$3km/s, more than half of the envelope expansion velocity. From the discussion of Paper II, we see that this input of mechanical energy is easily enough to heat the gas to a temperature of 100K at the radius corresponding to our antenna beamwidth.

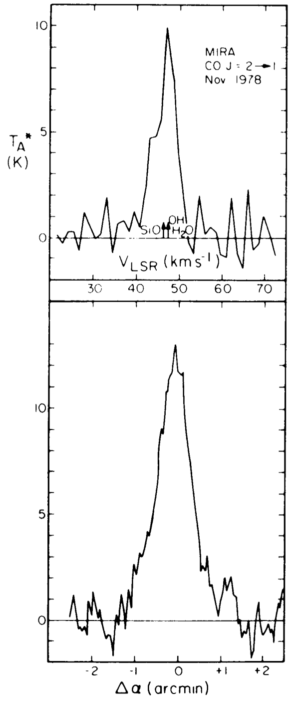

Figure 4. a) CO(2-1) spectrum of Mira showing velocities of the SiO, OH, H_2O masers. b) RA map at V_{LSR}=+47 km/s

3. CONCLUSIONS

We have observed unexpectedly

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intense CO(2-1) emission from a spatially extended envelope around IRC+10216. The implied mass-loss rate of $\sim 10^{-4} M_{\odot}$/yr is larger than that inferred from molecular line observations of the central source and may indicate a secular variation of $\dot{M}$ within the past 3×10^4 years.

In Mira we have observed a very large value of $\sim$16 for the CO(2-1)/CO(1-0) line intensity ratio. From this we infer that the CO(2-1) must be optically thin and that the source is largely unresolved by our 25 arcsec antenna beam. It is suggested that significant heating of the gas may result from the orbital motion of the central star.

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DISCUSSION FOLLOWING WANNIER

Black: The CO molecules in IRC+10216 are exposed to intense infrared radiation. How much does radiative excitation through vibrational transitions contribute to the formation of the rotational lines?

Wannier: The infrared radiation strongly affects the rotational excitation of molecules of high dipole moment such as HCN or CS. However, CO is relatively unaffected by IR radiation except in a very small region $<10^{16}$ cm which does not affect our measurement of even the central position. For comparison, our diffraction-limited beamwidth corresponds to $\sim 3 \times 10^{17}$ cm. I refer you to the work of Morris for a discussion of molecules other than CO.

Willner: If one attributes the excess CO emission to a decreasing mass-loss rate, by what factor and over what time scale has the rate decreased? Is the time scale not $r/v = \theta d/v \sim 10^4$ years? There are very few known objects with mass-loss rates exceeding that of +10216. Why do we not observe such objects?

Wannier: Your timescale is correct. The lifetime of a mass-loss

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object is inversely proportional to the mass-loss rate. Since the observed mass-loss rates vary over several orders of magnitude, the implied selection of observed objects is heavily weighted toward those with small rates. The observed list of circumstellar clouds, viewed this way, demonstrates a significant number of objects undergoing catastrophic mass loss.

Betz: In IRC+10216, infrared excitation of molecules such as HCN has been invoked to minimize the required H_2 density at radii <0'.5. Is there any direct evidence that the density within this radius is actually as low as the minimum required if infrared pumping is adopted? The mass-loss rate estimated from our NH_3 observations within the central ∿1" radius also is higher than that used in the Kwan and Hill model.

Wannier: The only evidence against a high central mass-loss rate comes from a comparison of our CO (2-1) map with the model of Kwan and Hill (see section 2.1). A constant mass-loss rate (and a constant fractional abundance of CO) gives a predicted CO intensity which is at once too large in the central regions and too small in the extended envelope.