INFRARED SPECTROSCOPY OF MOLECULES IN CIRCUMSTELLAR MATERIAL

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ABSTRACT

High resolution spectra of red giants and long period variables exhibit lines of infrared CO vibration-rotation bands arising in circumstellar material. In the few such stars so far observed at very high resolution ($\lesssim$ 1 km/s) the circumstellar material appears localized in 3 distinct regimes with temperatures of 800K, 200K and 75K and expansion velocities of 0, 10 and 16 km/s rather than being uniformly distributed.

Many red giants, supergiants and long period variables are known from high resolution observations of atomic resonance lines to be losing mass at a substantial rate and to have enveloped themselves in clouds of circumstellar material. The elucidation of such processes is critical to the understanding of both stellar and galactic evolution, for such stars probably shed enough material to change their evolutionary tracks while at the same time substantially altering the composition of the interstellar medium by ejecting material which has been processed in the star's interior. Many of the circumstellar shells are prolific sources of both thermal and maser lines at millimeter wavelengths while infrared excesses indicate dust coexists with the circumstellar gas. However the mass loss mechanism, factors governing chemical equilibrium in the expanding material and even actual mass loss rates remain unspecified. The subject of mass loss has been reviewed by Goldberg (1979), Reimers (1977), Weymann (1977), Conti (1978) and Cassinelli (1979).

The importance of detecting molecular lines arising in circumstellar material seen in absorption against the central star is evident. One can, in principle, utilize the rotational level distribution both to obtain excitation temperatures and as a depth dependent probe. Attempts to detect molecules such as CN (Weymann, 1962) and

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TiO (Bernat, 1976; Lambert and Vanden Bout, 1978) at visible wavelengths have yielded negative results. Of all molecules, CO is a particularly attractive candidate for detection in circumstellar material because of both its high dissociation potential and the high cosmic abundances of carbon and oxygen. Although CO does not have any electronic bands accessible to ground based observers, it does have vibration rotation bands in convenient regions of the infrared, notably the fundamental around 4.6μm and the first overtone around 2.3μm. The strengths and particularly the frequencies of the lines of these bands have been precisely determined and, in principle, allow accurate determinations of radial velocities and rotational excitation temperatures. The rotational B value (1.93 cm^{-1}) is such that even at the lowest circumstellar temperatures a number of levels will be populated, thus permitting accurate determination of a rotational excitation temperature. In addition, the relatively large isotope shifts of vibration-rotation lines are favorable to the measurement of carbon and oxygen isotope ratios in the material being expelled. This is particularly important in distinguishing circumstellar material from interstellar clouds which happen to lie in the line of sight.

In the past year or two a number of instrumental techniques have reached the point where it is possible to observe infrared molecular transitions arising in circumstellar material at a resolution better than the 1 km/s necessary to resolve the line profiles. We have used a 1.4 m Fourier Transform Spectrometer at the coudé focus of the Mayall 4 m Telescope at Kitt Peak (Hall, et al. 1979) to observe CO vibration rotation lines arising in circumstellar material around late type supergiants, long period variables and obscured carbon stars. Observations in the CO fundamental at 4.6μm are hampered by strong CO absorption arising from the same transitions in the earth's atmosphere. However at a spectral resolution of 10 km/s or better, the doppler shift due to the earth's orbital motion is sufficient to move the lines of most stars out of the terrestrial absorption at the most favorable time of the year. Terrestrial CO absorption is not a problem in the first overtone bands at 2.3μm where the transitions are two orders of magnitude weaker. The Fourier Transform technique has the decided advantage of permitting simultaneous observation of an entire molecular band with very high spectrophotometric accuracy and an extremely well calibrated frequency scale.

At a spectral resolution of the order of 10 km/s, 4.6μm spectra of all M supergiants and long period variables we have observed to date exhibit sharp CO lines with expansion velocities in good agreement with the visible atomic resonance line values (which are generally of the order of 10 km/s). The intensity variation with rotational quantum number implies excitation temperatures of the order of 200K and, as distinct from atomic resonance lines, the radiative rates are low enough that CO is certainly in collisional equilibrium so this represents a true gas temperature. The CO results are thus in good agreement with previous observations; the derived gas temperature of

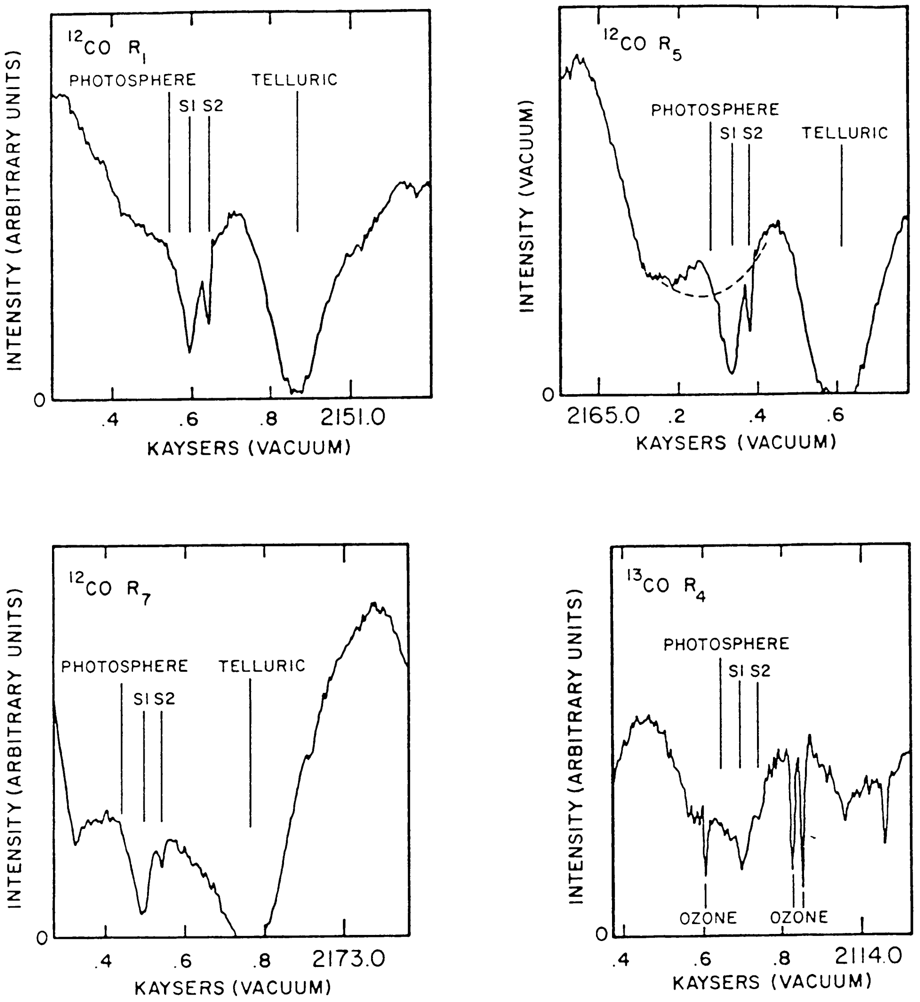

Figure 1: Selected CO 1-0 lines from a 0.6 km/s resolution spectrum of α Orionis. Components due to the stellar photosphere, the two circumstellar shells and telluric absorption are indicated.

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200K is reasonable, implying the material is of an average distance of the order of 100 stellar radii.

The situation is, however, considerably more complex in one supergiant, α Orionis, and one long period variable, o Ceti, which we have observed at substantially higher spectral resolution at 4.6μm. At a resolution of 0.6 km/s the circumstellar lines in α Orionis (Bernat et al. 1979) are clearly resolved into two components (Figure 1). The redward component, designated S1, is characterized by a rotational temperature of the order of 200K, an expansion velocity of 11 km/s relative to the center of mass and a column density of the order of 5×10^{17} cm^{-2}; it corresponds to the classical, expanding, circumstellar shell. At this resolution and signal-to-noise ratio a second component, designated S2, is clearly resolved. The extremely narrow (but still fully resolved) S2 lines exhibit an expansion velocity of 18 km/s, a column density of 1.2×10^{16} cm^{-2} and a temperature of 70 ± 10K. These lines might be due to some intervening interstellar cloud except that $^{13}C^{16}O$ features are detected in both components at a strength corresponding to a $^{12}C/^{13}C$ ratio of the order of 6, clearly establishing their stellar origin. Somewhat surprisingly, the curves of growth for each component can be characterized by a single distinct temperature; there is no evidence of material at intervening velocities. Equation of the gas temperatures of the two components to Tsuji's (1979) α Ori dust model temperatures implies that the S1 shell lies at a radius of 150 stellar radii and the S2 shell at the order of 2000 stellar radii. If we assume these shell radii represent the mean distance of the shell, the carbon abundance is solar and all C is tied up in CO, then we infer mass loss rates of 5×10^{-6} and 3.2×10^{-6} $M_\odot$/yr for S1 and S2 respectively. These values for the two shells agree to within model and observational uncertainties and suggest that they are two regimes within a continuous outflow. The initial accelerating force for the gas in the S1 component is likely provided by radiation pressure on dust grains which drag the gas along (Gilman, 1972). Then the abrupt acceleration at large radii from the star might be due to either a change in grain absorption properties or in the gas to dust ratio. It is tantalizing that the observed temperature of the S2 component is in the range where gases such as CO may begin to precipitate as mantles on grains at high enough densities.

A recently obtained, comparably high resolution spectrum of the archetypal long period variable o Ceti exhibits three clearly resolved circumstellar velocity components. The reddest, at a heliocentric velocity of 62.7 km/s (52.9 km/s LSR), probably corresponds to the center of mass velocity. The two other components are then expanding at velocities of 7.5 and 12.2 km/s and preliminary analysis indicates rotational temperatures of 200K and 70K respectively. The velocity of the 200K component is in excellent agreement with those of the OH, H_2O and SiO masers in o Ceti (Dickinson, Kollberg and Yngvesson, 1975; Snyder and Buhl, 1975).

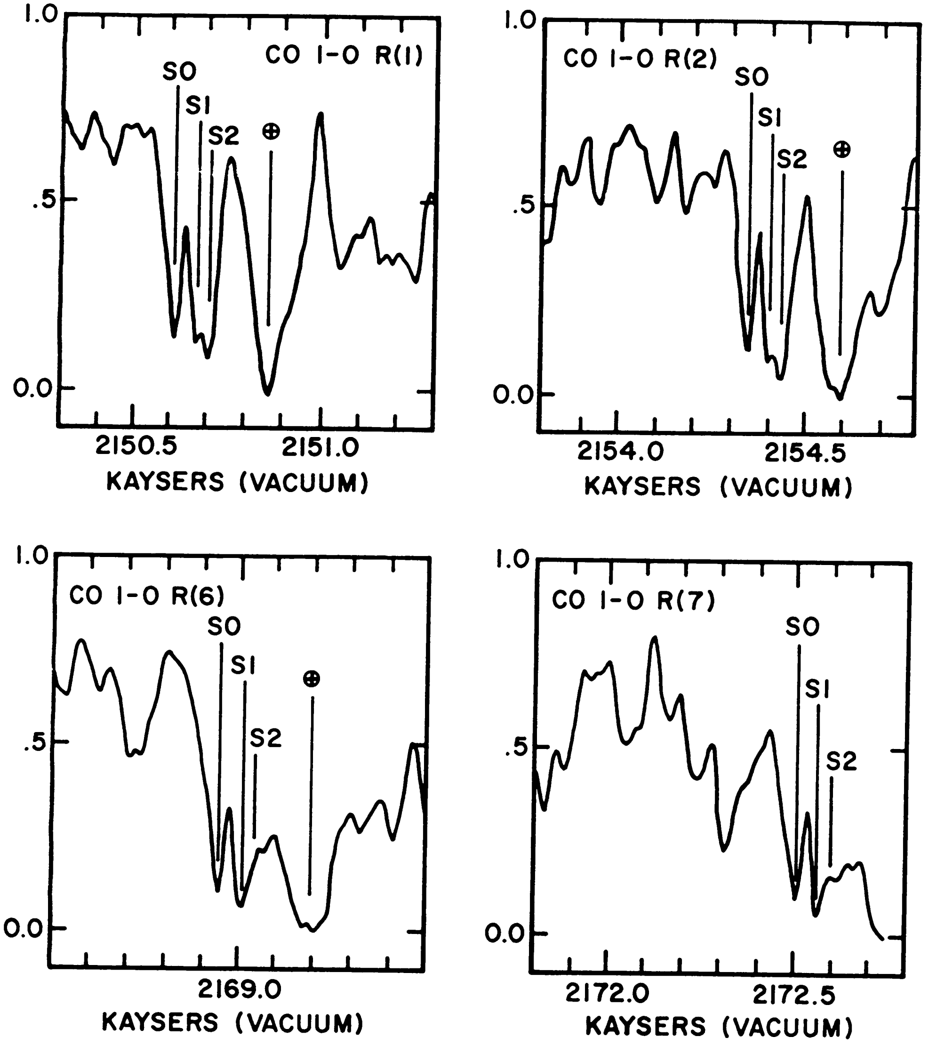

Figure 2: Selected CO 1-0 lines from a 0.6 km/s resolution spectrum of o Ceti. Components due to the three circumstellar shells and telluric absorption are indicated.

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Clearly both further observations and more careful modelling of the outflow are required to distinguish between continuous outflow and discrete events. Comparable resolution observations of a number of high mass loss supergiants and long period variables are undoubtedly critical. The occurrence of multiple components with similar velocities and temperatures in many stars would argue strongly for the same physical processes in a continuous outflow. Similarly it is important to see, on a detailed level, whether a continuous outflow model, such as that proposed by Goldreich and Scoville (1976), is compatible with the apparently discrete nature of the components observed in α Orionis and o Ceti.

I would like to turn now to evidence for yet another circumstellar shell revealed by the violence of photospheric motions in the long period variables. From a time series of 1.5 to 2.5μm spectra covering several periods of the long period variable Chi Cygni, Hall, Hinkle and Ridgway (1979) have shown that the stellar photosphere undergoes violent motions which are well correlated at the optical variability. Just before maximum light an outwardly propagating wave, presumably driven by a general stellar oscillation, emerges into the photosphere and over the following month propagates through it. The velocity difference between the gas in front of and behind this wave exceeds the sound speed before the wave emerges from the photosphere. As a result the wave appears as a shock separating regions of differing velocity and temperature. The compressional wave accelerates the stellar surface material to at least 15 km/s, and more probably 20 km/s, outward relative to the center of mass. By phase 0.1 the shock is propagated out into the more tenuous material surrounding the star. The stellar surface layers then appear to decelerate at a constant rate until around phase 0.85 the now infalling material begins to interact with the precursor of the next wave and ceases to accelerate inwards. During a cycle the photospheric CO excitation temperature falls linearly from 3500K to 2400K.

At phases when the photospheric features are shifted away from the center of mass velocity, it is possible to distinguish broad, resolved CO 2-0 lines which are at the center of mass velocity and which exhibit excitation temperatures of approximately 800K. We are unable to detect any significant variations in either the excitation temperature or the radial velocity throughout our entire period of monitoring although the lines are very badly blended with the photospheric features around minimum light. The low excitation temperature of this material implies that it must be circumstellar and simple calculations indicate that it is probably at a distance of 4 to 8 stellar radii from the photosphere. It is presumably some turbulent layer of material which has been ejected from the star and may now be supported by the residual energy of the outwardly propagating shocks. Given the existence this relatively dense material at a temperature highly condusive to the formation of dust grains, and at a distance at which gravitational acceleration is markedly reduced, it seems highly plausible that this material provides the reservoir from which the classical mass loss is accelerated by radiation pressure acting on condensing dust. It is attractive to identify this relatively narrow region of acceleration with the SiO microwave maser. These masers cannot originate near the true stellar photosphere for, if radial, they would mimic the photospheric velocities and, if tangential, their intensities should correlate with the photospheric motions.

One may speculate whether this 800K, circumstellar material is unique to the long period variables, supported by dissipation of the energy associated with the outwardly propagating shock waves, or is instead a common characteristic of all the late type stars exhibiting high mass loss. In the late type supergiants photospheric motions are far too small to separate such circumstellar features from their photospheric counterparts and so it is impossible to obtain the same unambiguous evidence provided in the case of the long period variables. If, however, the variation of line strength with rotational quantum number is plotted for the CO 2-1 lines in the spectra of these stars, the line depth often peaks at a J value of the order of 10, corresponding to a temperature of $\lesssim$ 1000K. Similar plots for the vibrationally excited bands (3-1 etc.) show no such peaking, instead exhibiting a broad plateau characteristic of photospheric temperatures. It thus appears highly plausible that such 1000K circumstellar shells are characteristic of all late type stars exhibiting high mass loss and probably provide a reservoir from which mass loss is driven by radiation pressure on precipitating dust. The mechanism by which material is injected into these circumstellar shells and supported there remains obscure.

It seems likely that continuing CO observations will greatly improve our knowledge of conditions within circumstellar material around late type stars over the next few years. The availability of a high resolution Fourier Spectrometer on the Kuiper Airborne Observatory offers the possibility extending such measurements several molecules obscured to ground based observers. Particularly important here are the vibration rotation bands of OH and H_2O. Similarly, improvements in 10μm spectroscopic techniques may well open up the possibility of observing circumstellar lines of SiO fundamental vibration rotation bands in the spectra of these stars.

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DISCUSSION FOLLOWING HALL

Dickinson: Observations of thermal and maser SiO in o Ceti (Mira) suggest an expansion velocity of $\sim$5 km s^{-1}, and maser velocities close to the stellar velocity. Can you reconcile these with your model?

Hall: The single sharp maser-feature seen in SiO, CO, OH, and H_2O in o Ceti has an LSR velocity of about +46 km/s, in good agreement with our 200 K shell at 45.5 km/s. I choose to associate the 53 km/s component in our spectra with the stellar velocity, as I am not aware of any mm detections of thermal SiO or CO. This assumption implies that the center of mass velocity of the SiO and CO pedestal features is not the stellar velocity of o Ceti.

Snyder: When we observed o Cet last winter we found that part of the SiO maser (v=1, J=1-0) pedestal was missing. Do you see any evidence in the infrared for destruction of SiO maser coherence lengths?

Hall: We have only one spectrum of the 4 μm SiO first overtone bands on o Ceti, and have not observed the SiO fundamental region. These data are inadequate to provide any indication of the SiO maser coherence lengths.

Goldreich: I have some criticisms of your model. First, I think that connecting the dust temperature to the gas temperature in these circumstellar envelopes is almost certainly incorrect. The dust temperature is set by radiative interaction with the star, and there is no reason why the gas temperature should come to equilibrium with the dust temperature at any appreciable distance from the star. In fact, the dust is being driven supersonically through the gas, and the heating effect of the dust is more through the supersonic drag than through the thermal temperature of the dust. Also I think it is very unlikely that the SiO masers are as far from the stars as you propose they are. There are a couple of VLBI experiments which indicate that the SiO masers are essentially in the atmospheres of the stars. Furthermore simple theoretical considerations on keeping a significant population in these excited vibrational levels of SiO indicate that the masers have to operate right at the surfaces of the stars. My final objection is to the idea that there is an appreciable second stage of acceleration at hundreds or even thousands of stellar radii. There would need to be an enormous increase in the opacity per gram of the material in order to have an appreciable acceleration occurring at a hundred or a thousand stellar radii. Perhaps it would have to go up by factors of thousands. So I think that it is much more likely that this evidence for variation or change in velocity either has something to do with the evolutionary state of the star or with a much closer-in region where acceleration is more likely to occur.

Hall: I agree there are real questions about the closeness of the gas and dust temperatures. However, if one assumes that radiative transfer determines the gas temperature, calculations give radii that are within a factor of two or so of those derived from adopting the dust temperature for the gas. So while there is certainly a doubt whether the gas and the dust are in close thermal equilibrium, I do not think we are wrong by an order of magnitude in our estimates of where these shells are. In particular it is very difficult to understand material at 7K being at distances much closer to the star than those we are talking about.

Goldreich: I am not arguing that this material at 7K is very close to the star, I am just arguing that it is fairly evident that there is no good thermal contact between the dust and gas, and that there is no point in using an argument which is incorrect.

Anonymous: We now have a very long time-series of observations of a number of long period variables that have SiO masers associated with them. There is direct evidence now that material is moved many stellar radii during the general oscillation, yet one sees no evidence of these velocity changes in the SiO maser velocities.

Interruption: We see velocity changes all over in the SiO maser. What do you mean by that?

Anonymous: There were no velocity changes that were in any way correlated with the photospheric motions.

Goldreich: There is again no reason to think the principal gain direction of the SiO masers is radial. In fact, if the maser operates in the region where there is a very strong outward radial acceleration of material, the best gain paths will be tangential, so you will see the maser at the limbs of the star, and there will be no velocity change at all, certainly nothing that correlates with the radial velocities that you observe in the photosphere.

Ramsay: Okay, you have a lot to write up there now. Who's going to be next?

Zuckerman: The water masers also indicate sizes smaller than your scale of 10 stellar radii, and material does seem to be moving out at a few kilometers per second or more from both the radio and other observations. Somehow you have gas flowing out and stopping. I do not understand what physical mechanism would cause this deceleration at the shell at 10 stellar radii.

Hall: The problem is that we see no evidence for gas outflow until outside the material at 10 stellar radii.

Zuckerman: Models based on visible and infrared observations also indicate that within this distance of 10 stellar radii there are substantial outflow velocities, not as great as the terminal velocity, but nonetheless substantial.

Hall: I am not aware of any visible observations that show that.

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Allamandola: Do you see any absorption in the region of the zero line of CO between the P and R branches? An absorption there would indicate that CO has condensed onto the dust grains, and may be the evidence you are looking for.

Hall: There is no such absorption evident in α Orionis, although the region is complex because of photospheric CO features. In 5 μm spectra of early-type stars embedded in molecular clouds, the continuum is much cleaner, but there is still no indication of such an absorption feature.