DETECTION OF UNRESOLVED CIRCUMSTELLAR LINES IN STELLAR INFRARED SPECTRA AND DISCOVERY OF QUASI-STATIC MOLECULAR ENVELOPE AROUND RED GIANT STARS

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ABSTRACT. It is found that the low excitation lines of the first overtone band of CO in the infrared spectra of normal red giant and supergiant stars include excess absorption that cannot be explained by the photospheric absorption alone. The excess absorption is shown to be due to unresolved circumstellar absorption originating from hitherto unrecognized quasi-static molecular envelope around normal red giant and supergiant stars. As contrasted to the previously known expanding circumstellar envelope recognized by Doppler-shifted absorption lines, the newly found static envelope has the following characteristics: (1) excitation temperature determined from CO lines is between 500 and 1000K, indicating that the envelope may be located at a few stellar radii above the photosphere, (2) turbulent velocity may be as high as 5km/s, (3) CO column density increases from $10^{+19}/cm^2$ at early M giant to $10^{+20}/cm^2$ at the latest non-Mira M-giant, and (4) molecular envelope and stellar photosphere show slight relative motion in general. Some implications of such a quasi-static molecular envelope on circumstellar chemistry as well as on stellar mass-loss are discussed.

1. INTRODUCTION

Until the present, circumstellar lines, both of atomic and molecular origins, have been detected only when they are separated from photospheric lines by Doppler shift, mostly due to expansion of circumstellar envelope. Recently, during our analysis of high resolution infrared spectra of red giant and supergiant stars, we found that some circumstellar CO lines are just overlapping on the stronger photospheric lines. As these circumstellar lines are not resolved from photospheric lines by high resolution, they should be originating from circumstellar envelope that has little relative motion to stellar photosphere. We have succeeded in separating the circumstellar contribution by subtracting the photospheric component that can be predicted with reasonable accuracy on the basis of model atmospheres. Further, detailed analysis on line shapes and shifts finally convinced us the presence of quasi-static molecular envelope around normal red giant and supergiant stars.

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2. THE CASE OF α HERCULIS

The first hint on the presence of static molecular envelope came from inspection of the curve-of-growth of the first overtone band of CO in α Her(M5Ib-II), which showed unexpected upturn in the strong line part (see Fig.3 of Tsuji,1985). Such an upturn of the curve-of-growth could be explained by pressure broadening in general, but it is quite unusual for giant star such as α Her whose atmosphere is characterized by low density. It is also noticed that those lines that show peculiar upturn are all low excitation lines of 2-0 and 3-1 bands. Accordingly, we interpreted that the upturn is due to extra absorption of circumstellar origin. It is to be remembered that our analysis is based on a very high resolution IR spectrum observed by P. Connes but, as the circumstellar absorption is not resolved from photospheric lines even by resolution as high as $R\sim250{,}000$ or $\Delta v\sim1$Km/s(Connes & Michel,1974), it is not possible to measure the circumstellar contribution by the usual method. Accordingly, to separate the circumstellar contribution from the observed equivalent width, W_{obs} , we estimated the equivalent width of the photospheric lines, W_{ph} , based on the model-atmosphere with the abundance and the micro-turbulent velocity determined from higher excitation CO lines free from circumstellar contamination. Then, we obtain an approximate measure of the circumstellar absorption W^* by $W^* = W_{obs}-W_{ph}$.

In Fig.1, we plotted $\log(W^*/gf\omega)$ against lower excitation potential, and the slope of the plot gives excitation temperature of 800K if W^* 's are not saturated(but this is an upper estimate if W^* 's are saturated). In Fig.2, curves-of-growth for the circumstellar lines are shown for CO 2-0 band with T_{ex} =800 and 600K. These curves are then fitted to the theoretical curve-of-growth for the exponential absorption (van der Held, 1931): turbulent velocity is at least 5Km/s and CO column density is $\log N_{CO}$ =19.7 for T_{ex} =800K while turbulent velocity is about

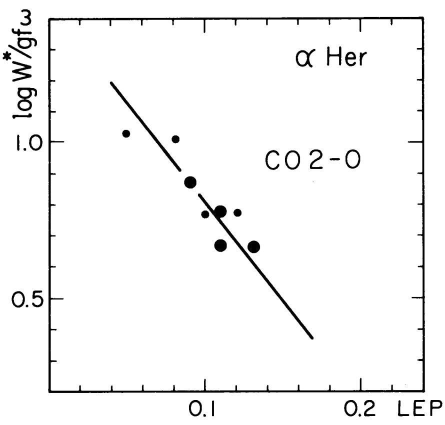

Figure 1. $\log(W^*/gf\ \omega)$ for CO lines of 2-0 band originating in molecular envelope of α Her plotted against lower excitation potentials(in eV). The slope gives T_{ex} =800K.

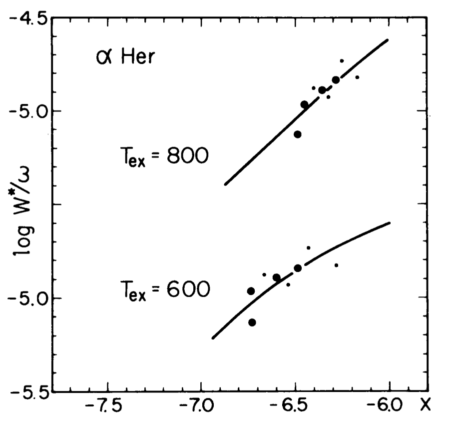

Figure 2. Curves-of-growth for CO 2-0 band in Figure 1 for T_{ex} =800 and 600K(X=log gf $-\chi\theta$,where χ is the lower excitation potential in eV and θ =5040/ T_{ex}).

3Km/s and log N_{CO} =19.8 for T_{ex} =600K. Note that the scatter of the plot is somewhat smaller for T_{ex} =800 than for T_{ex} =600K. This fact that the excitation temperature is as high as 800K implies that the molecular envelope is located at 5-10 stellar radii above the stellar photosphere.

In α Her, Bernat(1981) has previously found multiple CO envelopes with expansion velocities of 13 and 25Km/s. In these expanding envelopes, excitation temperatures are lower and CO column densities are smaller than those in static CO envelope just found. Thus, it is now clear that the molecular envelope around α Her consists of static component at a few stellar radii and multiple expanding components at further distances.

3. EXTENDED ANALYSIS ON A LARGER SAMPLE OF RED GIANT STARS

The peculiar behaviour of the low excitation lines of the CO first overtone band has also been noticed in infrared spectra of some 20 M-giant stars observed by KPNO FTS(Tsuji,1986), and the circumstellar CO absorptions in these stars are separated by the same method as for α Her. The resulting mean equivalent widths for circumstellar lines of CO 2-0 band with J'' =18 ~ 24 are plotted against spectral types in Fig.3. It is to be noted that the equivalent widths of the circumstellar CO lines increase towards later M-types(filled circles). Also, one supergiant star α Ori (open circle) shows much larger absorption as compared with giant of the same spectral type. Excitation temperatures for these circumstellar CO lines are also found to be between 500 and 1000K. CO column densities are about $10^{+19}/cm^2$ at early M-giants and $10^{+20}/cm^2$ at late M-giants.

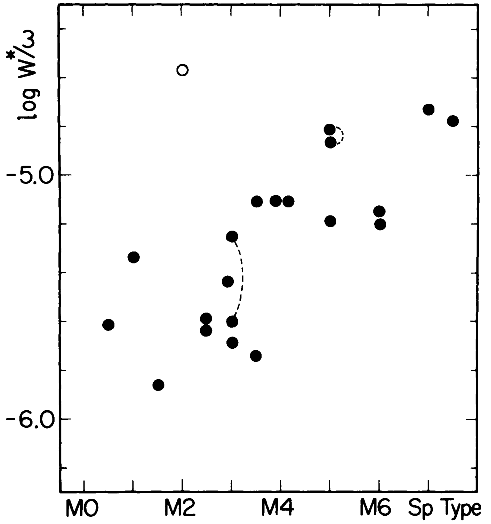

Figure 3. Mean equivalent width of CO lines(2-0, J''=18~24) originating in stationary molecular envelope is plotted against spectral type of M-giant star(o:α Ori).

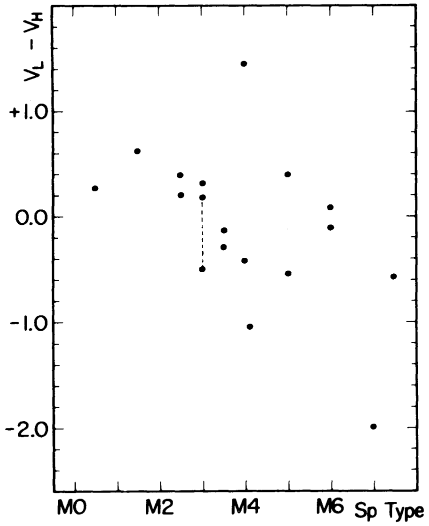

Figure 4. Mean radial velocity of low excitation CO lines, V_L ,relative to that of high excitation CO lines, V_H , is plotted against spectral type(V's in Km/s).

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In Fig.4, the differences of the mean radial velocity of low excitation lines showing excess absorption by molecular envelope, V_L , and that of high excitation lines free from circumstellar contamination, V_H , are plotted against spectral types. To clarify the meaning of such differential velocity shifts among different stars, we compare a portion of the observed spectra of CO 2-0 band shown by solid line and predicted spectra(based on model atmospheres with physical parameters determined from photospheric lines; see Tsuji,1986) shown by dotted line in Fig.5: The left panel shows the case of SW Vir that has the largest negative V_L-V_H in Fig.4. Note that observed and predicted spectra show almost perfect agreements in position, intensity, and line-shape for high excitation lines(R79,80) but observed profiles, as contrasted to the predicted ones, show excess absorption on the high frequency side in low excitation lines(R21,22). Thus, the molecular envelope around SW Vir may have a slight outflow motion if the photosphere is not moving(this should be confirmed yet). Such a blue-shifted core has also been noted in low excitation CO lines of δ^2Lyr by Ridgway and Friel(1982) from their analysis of line asymmetry. The right panel of Fig.5 shows the case of ρ Per that has the largest positive V_L-V_H in Fig.4. Again, observed high excitation lines can reasonably be understood on the basis of the model prediction, but observed low excitation lines show excess absorption on the low frequency side of the predicted line profiles. This fact does not necessarily imply that the molecular envelope of ρ Per is infalling, since photosphere of red giant stars may be moving in general, as will be discussed elsewhere. Neverthless, the meaning of Fig.4 is now clear: observed radial velocities of low excitation lines relative to high excitation lines reflect the relative motions of the molecular envelope and the photosphere. This fact presents a definite evidence that the anomalous strength of low excitation CO lines is due to excess absorption in molecular envelope well separated from stellar photosphere and not due to problem of line formation in the photosphere.

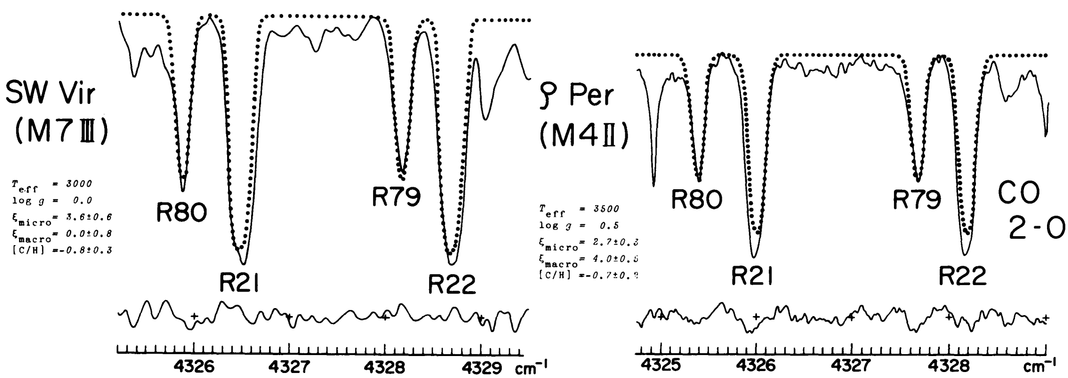

Figure 5. A portion of observed spectrum(solid line) plotted against wavenumber(cm^{-1}) is compared with predicted one based on model atmosphere(dotted line). Observed high excitation lines(R79,80) of CO 2-0 band are well explained by predicted photospheric lines, but low excitation lines(R21,22) show blue-shifted excess absorption in SW Vir(left panel) or red-shifted excess absorption in ρ Per(right panel).

4. QUASI-STATIC MOLECULAR ENVELOPE AND STELLAR MASS-LOSS

The analysis outlined above demonstrated that the presence of the static molecular envelope around normal red giant and supergiant stars is a quite general phenomenon. Previously, such a stationary molecular envelope has been known only in Mira variable star, in which CO lines originating from stationary envelope have been separated clearly from photospheric lines by Doppler-shifts due to pulsation of photosphere (Hinkle et al, 1982). The physical parameters of the stationary envelope of χ Cyg found by these authors(T_{ex} =800K, ξ_{tur} =1.4km/s, and log N_{CO} =20.0) are remarkably similar to those of α Her found by us. This fact that the presence of the stationary envelope is not limited to Mira variable stars implies that its origin does not necessarily be related to stellar pulsation but rather it should be a more fundamental property of red giant(including Mira variables) and supergiant stars.

The total mass of the molecular envelope can be estimated from the CO column density if we assume that the envelope is a symmetry shell at $r \sim 5R_*$: $M \sim 10^{-7} M_\odot$ for early M-giant and $M \sim 10^{-4} M_\odot$ for the latest M-giant. These are comparable to the known mass-loss rates in these stars and this fact implies that the lifetime of the static molecular envelopes is of the order of years. This fact implies that the molecular envelope should be in quasi-static. At present, the mechanism how to produce such a quasi-static molecular envelope is unknown. However, once such a quasi-static envelope is formed at a few stellar radii above the photosphere, the subsequent process of mass-outflow may be relatively easy (e.g., by radiation pressure on dust formed in the outer part of the molecular envelope). Thus, to clarify how matters are supplied to the quasi-static envelope should be essential in our understanding on the mechanism of mass-loss in red giant and supergiant stars. In this connection, one interesting problem is how to understand the relationship of such a quasi-static molecular envelope with the upper chromosphere where outflow of material already starts as shown by Goldberg (1979). On the other hand, there is an evidence of an infalling material in chromosphere of α Ori as shown by the red-shifted FeII emission lines(Boesgarrd and Magnan, 1975). Clearly, velocity field in the inner part of stellar envelope is far more complicated than that of a simple accelerated flow. Anyhow, we now have a possibility to probe directly the process that may lead to stellar mass-loss in the quasi-static molecular envelope, while we only see the result of mass-loss by observing expanding circumstellar envelope.

5.CHEMISTRY IN QUASI-STATIC MOLECULAR ENVELOPE

As the presence of molecular envelopes at moderate temperature is confirmed, we examine first what are the major constituent in the envelope at thermal equilibrium by extending our previous study(Tsuji,1973) to lower temperatures. The resulting equilibrium features for H,C,N,O,Si,P, and S in oxygen-rich and carbon-rich cases are shown in Fig.6. It is interesting to notice that the equilibrium features show rather drastic change at low temperatures near 500K: for example, H_2O decreases because of the formation of hydroxyl compounds such as MgOH, $Mg(OH)_2$, and $Fe(OH)_2$ in oxygen-rich case, while CH_4 is so stable in carbon-rich case that some oxygens are released from CO and, consequently, SiO is as abundant as in oxygen-rich case. Thus, difference between oxygen-rich and carbon-rich cases is somewhat tempered at very low temperatures near 500K.

It is true that CO is the most abundant molecule next to H_2 (not shown in Fig.6), but it must be remembered that what we have been discussing in this paper is the first overtone band which is by far the weaker than the fundamental band. Thus there is a possibility that some stronger transitions of molecules less abundant than CO in Fig.6 and are masked by stronger photospheric lines could still be detected on high resolution spectra. Of course, the assumption of the thermal equilibrium is not always warranted for circumstellar envelope, but a theoretical modeling by Scalo and Slavsky(1980) suggests that neutral-neutral reactions will dominate in the inner envelope of oxygen-rich star and it seems that the thermal equilibrium can still be applied if effect of chromospheric UV radiation is not important. It is to be emphasized, however, that we have now a new possibility to prove directly if the assumption of the thermal equilibrium is valid(and consequently if the effect of chromospheric UV radiation is important) by observing molecules in the inner envelope on high resolution infrared spectra. In this regard, one interesting possibility is if a peculiar curve-of-growth of OH found in α Ori by Lambert et al(1982) could also be interpreted in the same way as for CO and if high abundance of OH in the circumstellar envelope is due to photoionization of H_2O by chromospheric UV radiation(also, see DISCUSSION after Lambert's review in this volume).

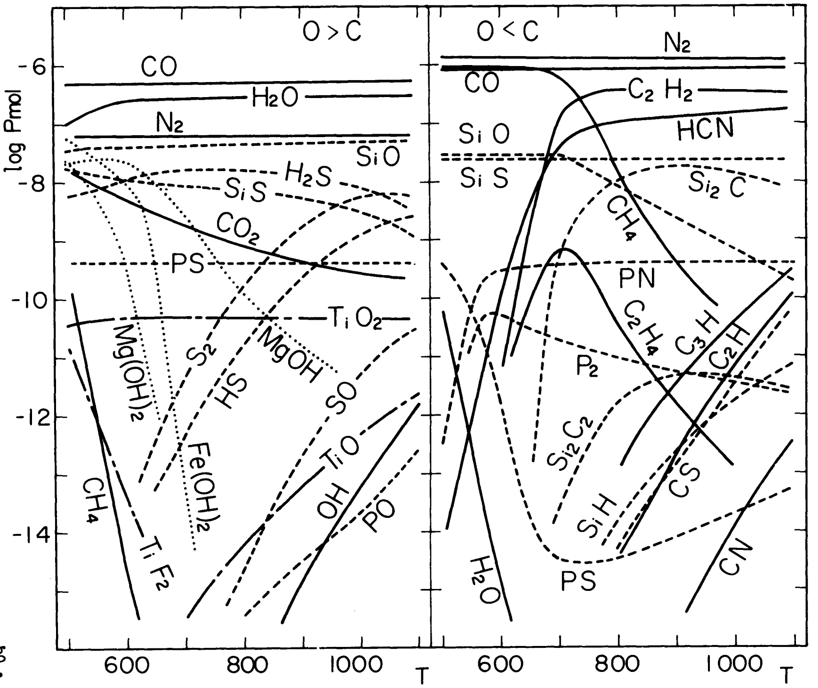

Figure 6. Gas phase chemical equilibria in O-rich(left panel) and C-rich(right panel) molecular envelope with chemical compositions of H/C/N/O/Si/P/S=12.0/ 8.55/ 7.93/8.77/ 7.55/ 5.43/ 7.21 and 12.0/ 9.07/ 9.25/ 8.77/7.55/ 5.43/ 7.21(logarithmic scale), respectively. Gas pressure is kept to be log P_g =-3.0 throughout.

6. CONCLUDING REMARKS

In circumstellar chemistry, much attentions have been directed to a small number of extreme objects such as IRC+10216 or VY CMa, in which large number of molecules have been found. However, as these objects have thick molecular envelopes, it has been difficult to probe the inner part directly. On the other hand, number of molecules found in circumstellar envelopes of normal red (super)giant stars has been surprisingly small, but we now found a new possibility to detect more molecules in circumstellar envelopes of these normal stars. Moreover,it is possible to see the inner envelope directly in these objects by the high resolution infrared spectra, and it is such an inner quasi-static envelope that may have a key to understand the mechanism of stellar mass-loss.

The reason why such a quasi-static molecular envelope around normal red (super)giant stars has not been recognized till now is simply because the circumstellar lines are masked by the stronger photospheric lines. To separate the circumstellar contribution from the photospheric absorption, it is necessary to have a good understanding on the photospheric spectra. For this purpose, basic theory on the atmospheres of cool stars has now matured enough, if not complete, to make such an analysis possible as review by Vardya(in this volume), and one of its important applications is to the chemical abundance analysis as reviewed by Lambert(in this volume). In this paper, we have shown another aspect of such an application; to use the photospheric spectrum as a boundary condition for circumstellar problem. Thus, although we have focused our attention to circumstellar problem in this paper, we should like to emphasize the importance of quantitative spectroscopy on high resolution stellar spectra and thorough understanding of stellar atmospheres, not only for stellar problems but also for circumstellar problems.

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DISCUSSION

HUEBNER: Your molecular abundance curves show no obvious evidence of any condensations down to a temperature of 500K. Was condensation ignored? If so, why?

TSUJI: These show gas phase equilibrium without solid phase, but condensation should be considered if necessary. There is no positive reason for this, except that this was done as a simple extension of my previous work for stellar atmospheres to lower temperatures. So far as red giants such as α Herculis are concerned, however, evidence of dust condensation is not known while evidence of rather thick molecular envelope at a temperature of several hundred degree has been found.

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