PRESENTATION AND INTERPRETATION OF
HIGH RESOLUTION INFRARED SPECTRA
OF LATE-TYPE STARS

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Current interest in stellar evolution is concentrated on the life of a star after it has left the main sequence. Of particular interest are the red giant or supergiant periods during the hydrogen and helium shell burning phases. Convective mixing during these stages can mix nuclear processed material to the surface where it may be viewed by spectroscopic methods. It is imperative that this rare chance to view processed material be exploited fully to increase our knowledge of stellar evolution.

The observation and interpretation of cool star spectra has its own particular set of problems and advantages. A particular difficulty is the formation of molecules at the low temperatures which occur in the atmospheres of late stars. Not only must the particularly complex spectra of molecules be dealt with but the problem of chemical equilibrium in the atmosphere must be solved accurately before quantitative analysis may be performed. The formation of molecules, however, has one advantage in that it very dramatically separates those stars with carbon to oxygen ratios greater than one from those with ratios less than one. It is the very high dissociation energy of 11.1 eV for the CO molecule which performs this separation. If carbon is less abundant than oxygen all of the carbon is tied up in CO and only oxides are formed in the stellar atmosphere which produce typical M star spectra. If, however, carbon is more abundant than oxygen then carbon compounds such as C_2 are formed in place of the oxides and a carbon star spectrum is formed. One of the great advantages of infrared stellar spectra is that it is the only ground based technique for observing CO in stellar atmospheres.

Figure 1 shows a portion of the CO spectrum for four M giants and supergiants. These spectra have a resolution of 0.5 cm^{-1} or $\Delta\lambda/\lambda$ equal to 10^{-4} at a wavelength of two microns. A Michelson interferometer at the *Cassegrain* focus of the Steward Observatory 90″ telescope and the Baja Mexico 60″ telescope was used to obtain these spectra. Rapid scanning techniques with two liquid nitrogen cooled lead sulfide detectors were used to eliminate scintillation noise. Full sky subtraction was obtained by using both inputs and outputs of the interferometer and switching the source input after each scan. All of the spectra shown here were taken by the observing team of Dr Harold L. Johnson of the Universities of Arizona and Mexico, Fred F. Forbes, David L. Steinmetz and the author of the University of Arizona.

All of the CO bands in Figure 1 are due to the first overtone vibration-rotation transitions in which the vibrational quantum number changes by 2 units. Individual lines may be observed in the right most (2, 0) band although the line shapes are not
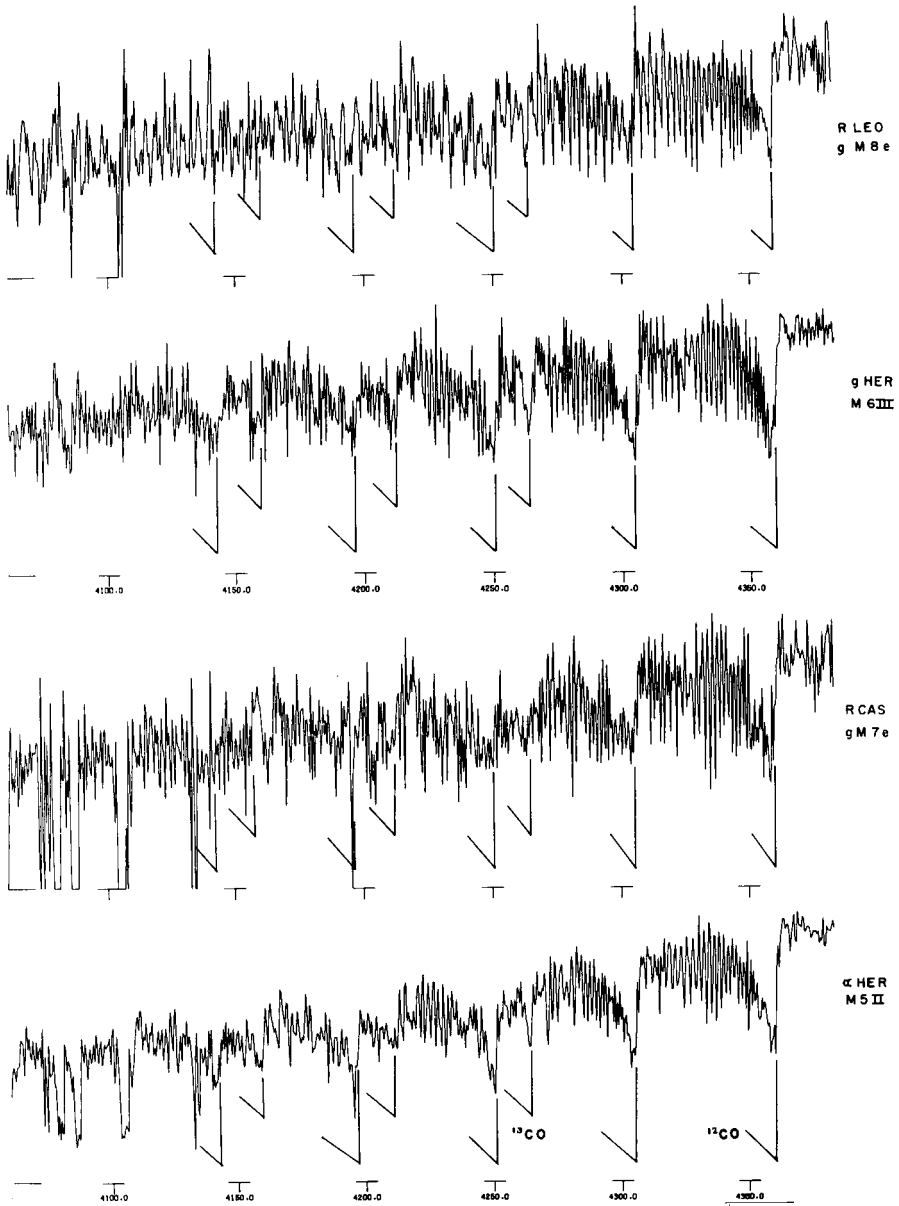
Fig. 1.   Spectrum of four M stars with ^{12}CO and ^{13}CO positions marked. The lowermost markings are for ^{12}CO and the uppermost ^{13}CO. The first band head to the right is the (2, O) head for each isotope. The bottom scale is in wave number cm^{-1}.
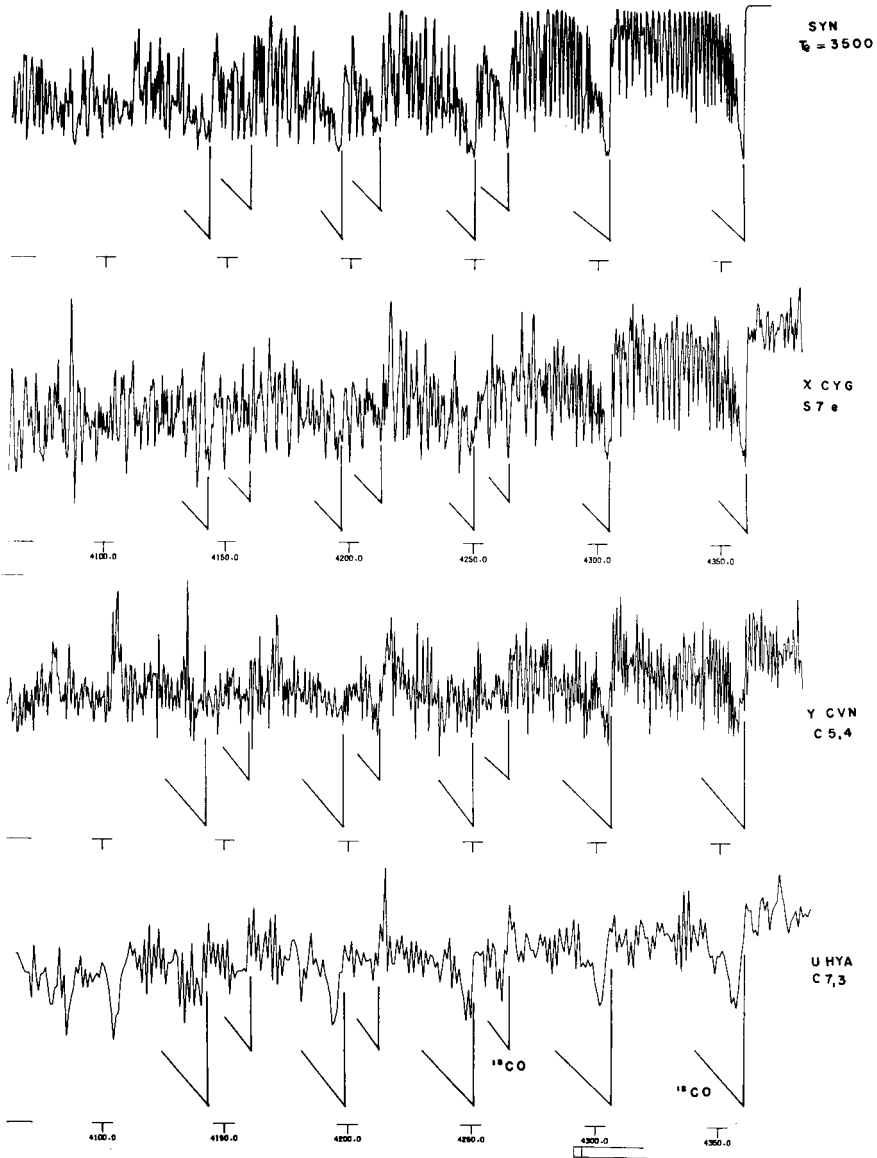
Fig. 2. The same region as Figure 1 for χ Cyg and two carbon stars. The top spectrum is a synthetic spectrum of CO described in the text. The spectrum of U Hya is 1.0 cm⁻¹ as opposed to 0.5 cm⁻¹ for all others.

resolved at this resolution. Since all of the bands are red shaded it becomes more difficult to determine individual lines for the higher order bands $(3, 1)$, $(4, 2)$, etc. where considerable overlap occurs. Individual band heads of ^{12}CO and ^{13}CO are marked on the figure. It should be noted that the ^{13}CO $(2, 0)$ and $(3, 1)$ band heads appear in all of the spectra. The significance of this is discussed below.

Figure 2 shows the same spectral region for the S star χ Cyg and the two carbon stars Y CVn and U Hya. χ Cyg shows a very strong and clean spectrum of CO whereas the two carbon stars show evidence of blanketing by other opacity sources such as CN and C_2 in this spectral region. Above the spectrum of χ Cyg is presented a synthetic spectrum of CO for comparison purposes. This spectrum was produced by integrating the flux equation

$$F_\nu = 2 \int_0^\infty S_\nu(\tau_\nu) E_2(\tau_\nu) \, d\tau_\nu$$

through a computed model atmosphere with $T_e = 3500\,K$, $\log g = 0$, solar abundance, turbulent velocity $= 4\ \mathrm{km\ s^{-1}}$ and a $^{12}C/^{13}C$ ratio of 27. The usual continuum opacity sources and H_2O along with CO as a line opacity source were used to form τ_ν. Local thermodynamic equilibrium was assumed so that the source function $S_\nu(\tau)$ became the Planck function at the local temperature. The calculated spectrum was then convolved with the $0.5\ \mathrm{cm^{-1}}$ instrumental profile to give the spectrum shown in Figure 2.

As can be seen by a comparison of the synthetic spectrum with that of χ Cyg below, most of the spectral features can be accounted for by CO alone except in the case of the carbon stars. A local minimum in the $(2, 0)$ band can be observed at about $J = 30$ for both the observed and synthetic spectra. This minimum is produced at the point where the low J lines coincide with the high J returning lines of the band. Since the lines are unresolved and highly saturated the coincidence greatly reduces the observed equivalent width.

Of particular interest is the good agreement between the observed and synthetic spectrum for the ^{13}CO $(2, 0)$ and $(3. 1)$ band heads. A $^{12}C/^{13}C$ ratio of 27 was used in the synthetic spectrum as it is the number predicted by convective mixing during the hydrogen shell burning red giant stage. Equally good agreement, however, can be obtained with $^{12}C/^{13}C$ ratios in the range from 89 to 5 due to the highly saturated nature of the lines. Figure 3 shows the (high resolution unconvolved) result of (synthetic spectrum) calculations for the ^{13}CO $(2, 0)$ band head with $^{12}C/^{13}C$ ratios of 89, 27, and 5. When more than one line is visible the top is for a ratio of 89, the middle 27 and the lower 5. It is easily seen that there is very little difference in the spectrum produced by the three ratios. The differences in the convolved spectra are less than the error in current spectra of this region. Previous determinations of low $^{12}C/^{13}C$ ratios in M stars form the CO first harmonic bands are most likely in error and are by no means definitive measures of the ratio.

An alternative to the first harmonic CO bands for $^{12}C/^{13}C$ ratio determination are the second overtone bands which begin near $6400\ \mathrm{cm^{-1}}$. These bands have oscillator

strengths approximately 10^2 less than the first overtone bands and therefore are much less saturated. Figure 4 shows a region dominated by CO second overtone absorption for the four M stars. The ^{12}CO band heads are clearly visible although the ^{13}CO band heads are either very weak or not present. Preliminary analysis shows that a ^{12}C/^{13}C ratio on the order of 30 can account for the observed spectrum but a definite conclusion must await further work.

The two carbon stars and χ Cyg are shown in Figure 5 for the same spectral region. Again χ Cyg displays strong, clean CO features whereas the carbon stars show the presence of other molecules such as CN and C_2. It is difficult in the presence of strong C_2 and CN absorption to determine the ^{12}C/^{13}C ratio from the CO second overtone bands in this region. The spectra, however, do not seem inconsistent with the low ^{12}C/^{13}C ratios found by other means for many carbon stars.

A puzzling part of the CO spectrum in late stars is the $(3, 0)$ band head at 6417.77 cm^{-1}. In most stars this band head is either missing or greatly reduced from its expected strength. Figure 6 shows this spectral region for the four M stars. De-
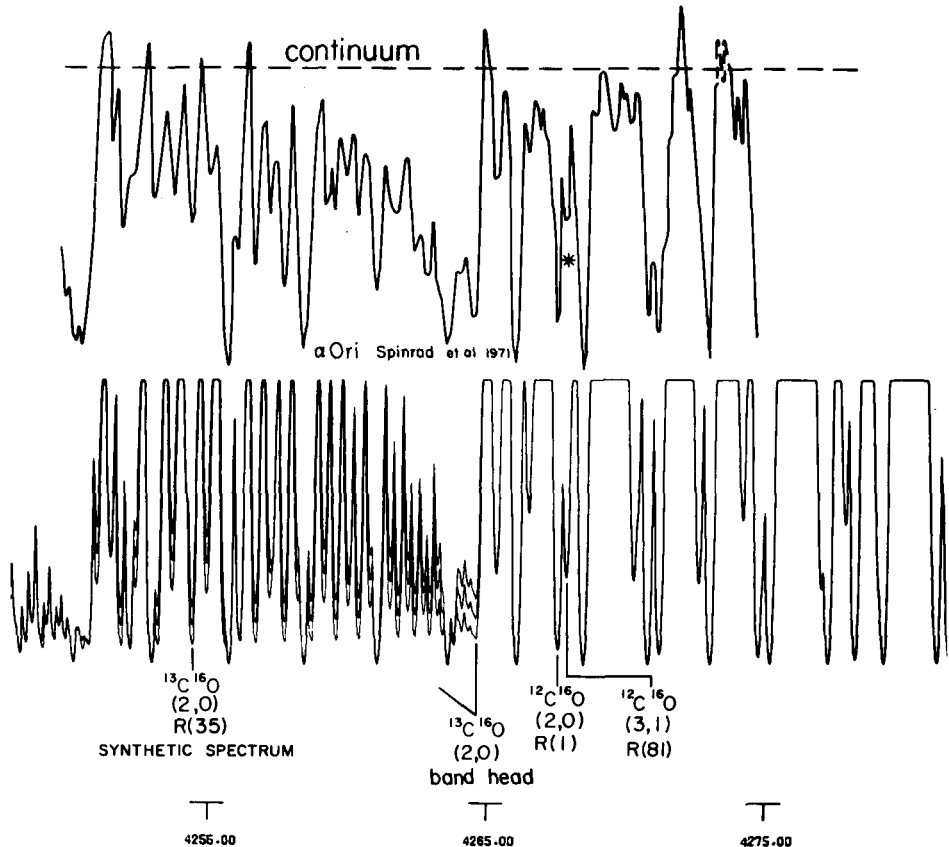

Fig. 3. A synthetic spectrum of the ^{13}CO (2, 0) band head is shown for the ^{12}C/^{13}C ratios of 89, 27 and 5. The top line is for 89, the middle 27 and the lower 5.
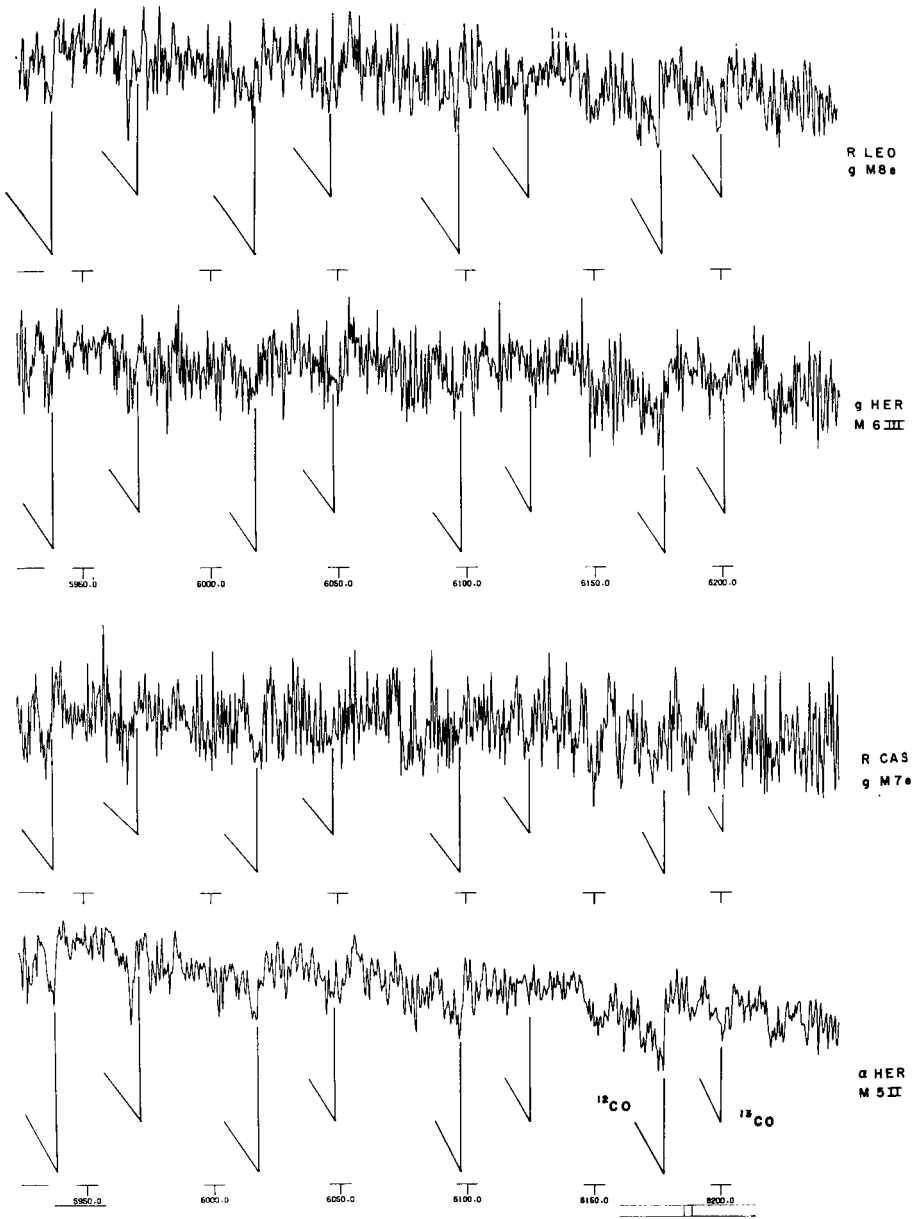
Fig. 4.   This spectral region is dominated by ^{12}CO and ^{13}CO second overtone bands. The upper markings are for ^{13}CO and the lower ^{12}CO.

population of the ground state cannot be the cause of the reduced strength because as is shown in Figures 1 and 2 the (2, 0) band is present in all of these stars with its normal strength. A most likely explanation is that an unidentified source of opacity exists in this region which masks the CO absorption. The spectra of the carbon stars and χ Cyg shown in Figure 7 add more intriguing aspects to the puzzle. It is easily seen that the peculiar S star χ Cyg shows very strong (3, 0) ^{12}CO absorption. In Y CVn no (3, 0) absorption is observed but in U Hya a strong feature is observed at the position of the (3, 0) band head. If the same source of opacity exists in both Y CVn and the M stars it would then have to contain neither carbon nor oxygen. This opacity source is clearly not present in χ Cyg and may not be in U Hya. Higher resolution spectra may eventually solve this problem.

High resolution infrared spectroscopy is not limited to problems in molecular spectroscopy. A particularly clean region of the spectrum for M stars is shown in Figure 8 in which several high excitation atomic lines are present. A few of these lines are indicated on the figures. No systematic attempts has been made at this time to analyze
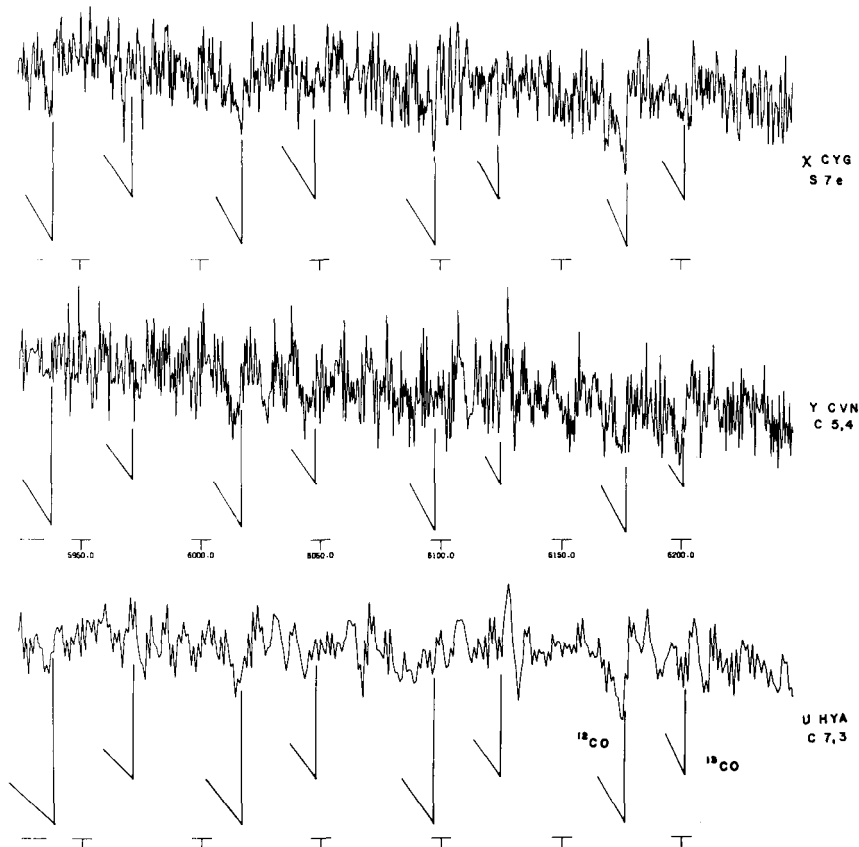

Fig. 5.   The same region as Figure 4 for χ Cyg and the two carbon stars. The carbon stars show evidence of C_2 and CN absorption.
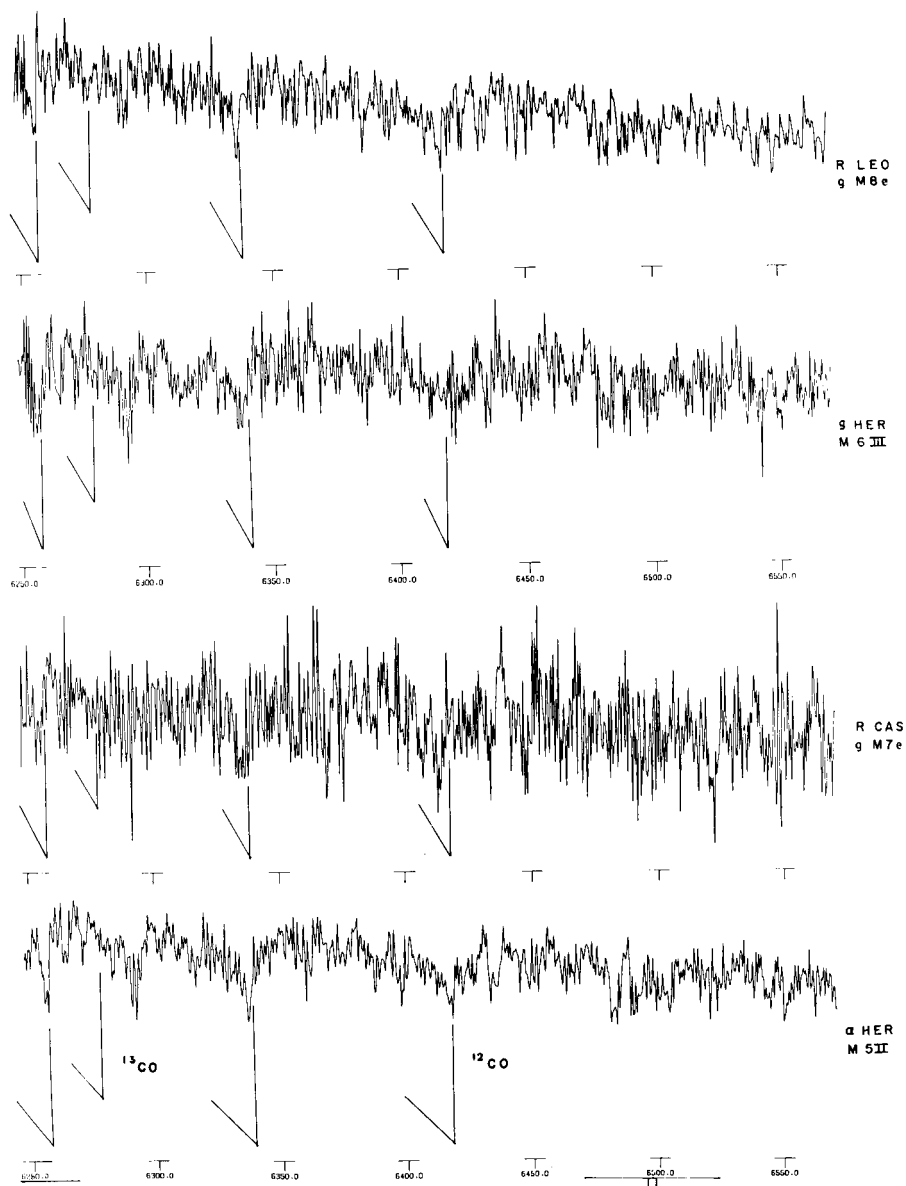
Fig. 6.   This region contains the (3, 0) ^{12}CO band head which is greatly reduced in these M stars. It is the right most feature marked.

these lines in terms of abundance or variation with period of the star. The same region is shown in Figure 9 for χ Cyg and the carbon stars. χ Cyg shows the same general spectrum as that of the M stars but Y CVn and U Hya show strong absorption due to CN and C_2. Positions for some CN band heads are indicated but the complicated nature of the CN spectrum tends to wash out band head features. An analysis of U Hya by Duane Carbon, Steven Ridgway and the author based on a $0.5\ \text{cm}^{-1}$ spectrum obtained by Ridgway indicates that a good fit can be obtained with CN alone. The more complicated spectrum of Y CVn however suggests that significant C_2 as well as CN absorption is present.

The spectra in Figure 10 confirm that significantly more C_2 is present in Y CVn than in U Hya. A strong absorption feature is present in both stars at the position of the $(0, 0)$ C_2 Ballik-Ramsay band head but the feature is much stronger in Y CVn. The strength of this feature is due both to a very close packing of lines of $^{12}C^{12}C$, $^{12}C^{13}C$
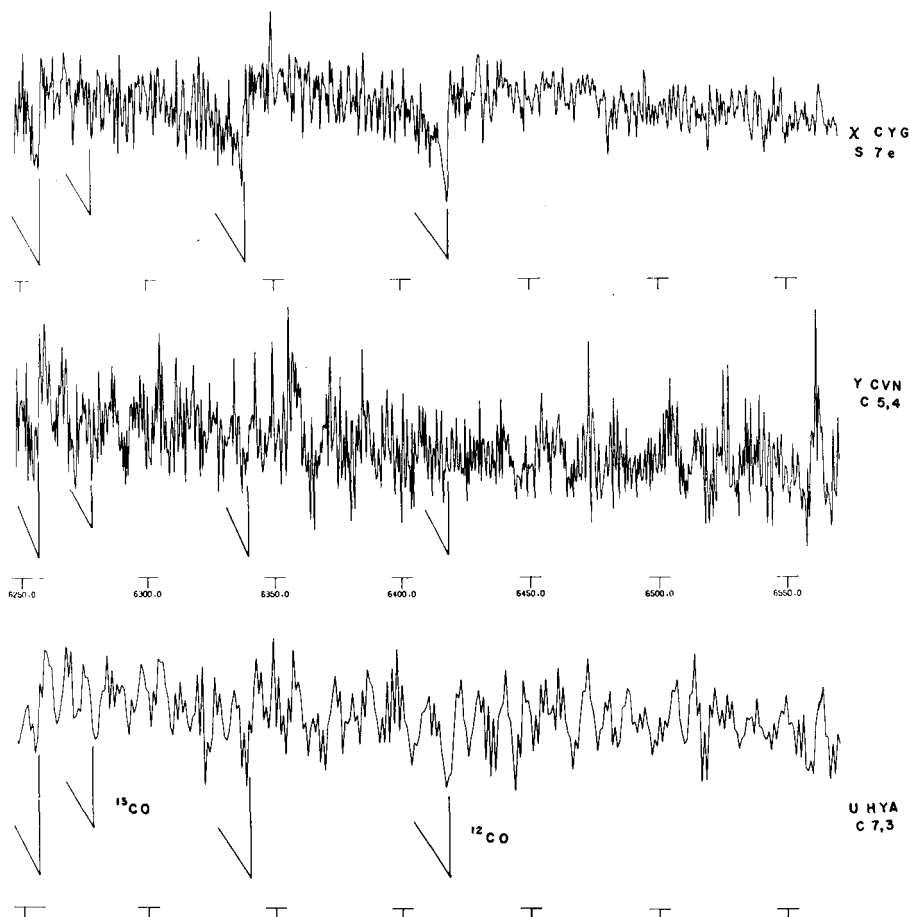

Fig. 7. The strong (3, 0) ^{12}CO feature is obvious for χ Cyg with the spectra of the two carbon stars shown below.

and $^{13}C^{13}C$ as well as a minimum in continuous opacity in this spectral region. This feature has great significance in the theory of carbon star evolution.

At present the two dominant theories of carbon star evolution are: (a) carbon star abundances represent CNO bi-cycle processed material in which case the carbon is depleted from its solar value or (b) carbon stars are the result of the mixing of triple-alpha produced carbon into a hydrogen shell during the Schwarzschild-Harm instability phase of helium shell burning. In case (b), the subsequent mixing of the carbon to the surface would enhance the carbon abundance over the solar abundance. Since the C_2 abundance varies essentially as the square of the C/O value it can serve as a sensitive monitor of the carbon abundance and thus an indicator of the correct theory.

A preliminary analysis of the C_2 bands by spectral synthesis techniques is shown in Figure 11. Along with the sources of continuous opacity mentioned earlier, CO, CN and both the Phillips and Ballik-Ramsay system of C_2 are included as line opacity sour-
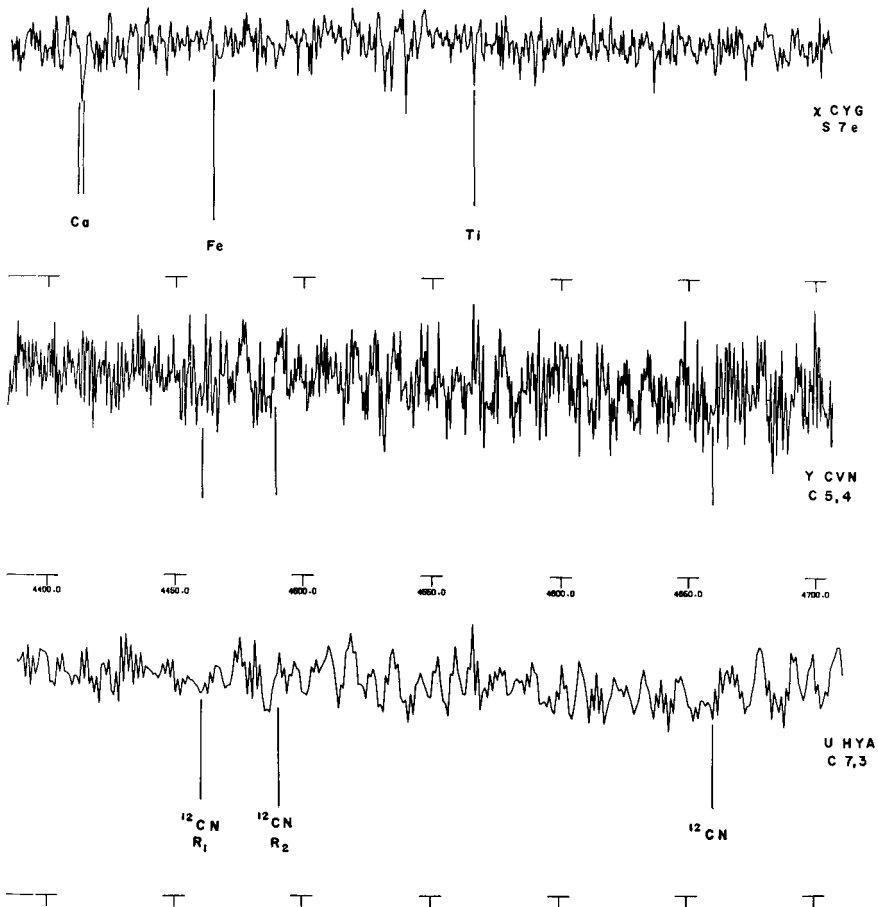

Fig. 8.   This region is relatively clean of molecular lines and some atomic features are marked.

ces. All isotopic combinations of ^{12}C and ^{13}C are included for all of the molecules. The top spectrum represents a model with enhanced carbon which is indicative of triple-alpha mixed carbon. The number ratios of H:C:N:O are $1.0: 8.4 \times 10^{-4}:$ $1.7 \times 10^{-4}: 5.9 \times 10^{-4}$. An effective temperature of 3250 K and a log g value of 0 is used in the model. A turbulent velocity of 4 km s^{-1} and a $^{12}C/^{13}C$ ratio of 4 is used in the synthetic spectrum production. As can be seen in the figure the computed spectrum matches the observed spectrum for Y CVn directly below it quite well. The depressed region to the right of the main band head is due to several satellite bands, notably the R_{21} band.

At the bottom of Figure 11 is a computed synthetic spectrum with a low value of carbon. The number ratios for H:C:N:O in this computation are $1.0: 1.8 \times 10^{-4}:$ $6.6 \times 10^{-3}: 5.9 \times 10^{-5}$. All other parameters are the same as for the high carbon spectrum. This abundance of carbon although low is not a CNO bi-cycle abundance which would be about a factor of five lower. At present the synthetic spectrum program does not contain He Rayleigh and He^{-} opacity terms which are needed for a
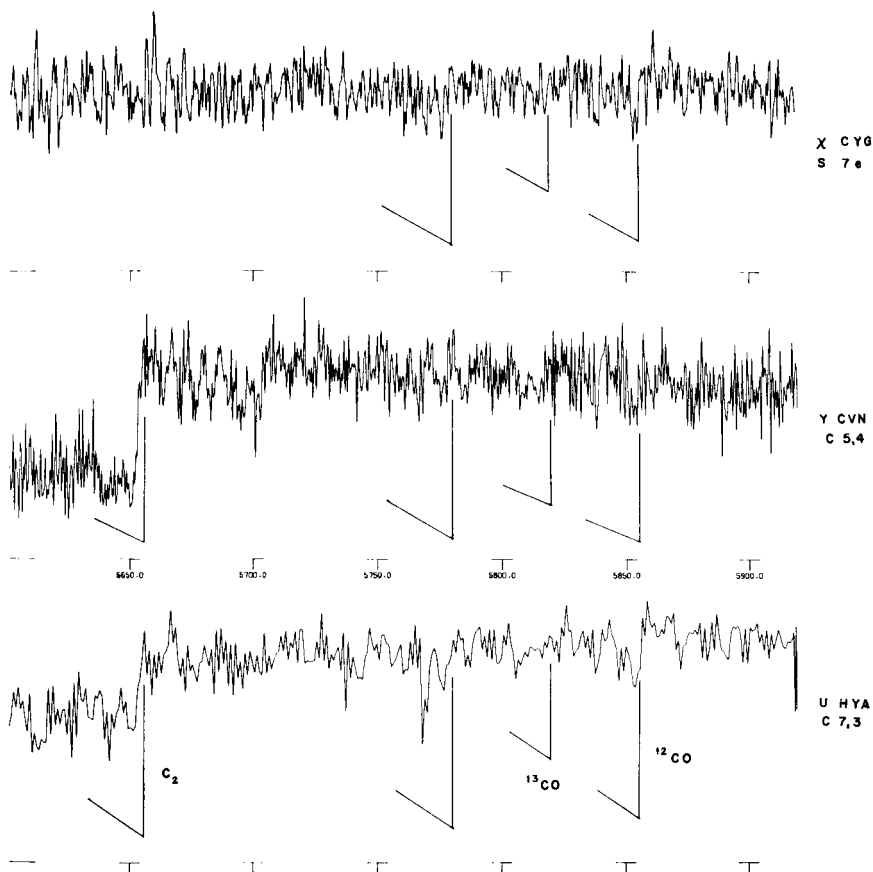

Fig. 9. Although this region is clean in χ Cyg the carbon stars show significant CN absorption.

true low H and high He CNO bi-cycle abundance. The computed low carbon spectrum is similar to that of U Hya in that no significant satellite band absorption is observed. Also if the synthetic spectrum resolution is reduced by a factor of two to match the resolution of U Hya, the main band intensities match well.

As it is the parameter C/O which determines the C_2 abundance the low C spectrum may be mimicked by an enhanced C spectrum in which C is just barely greater than O·
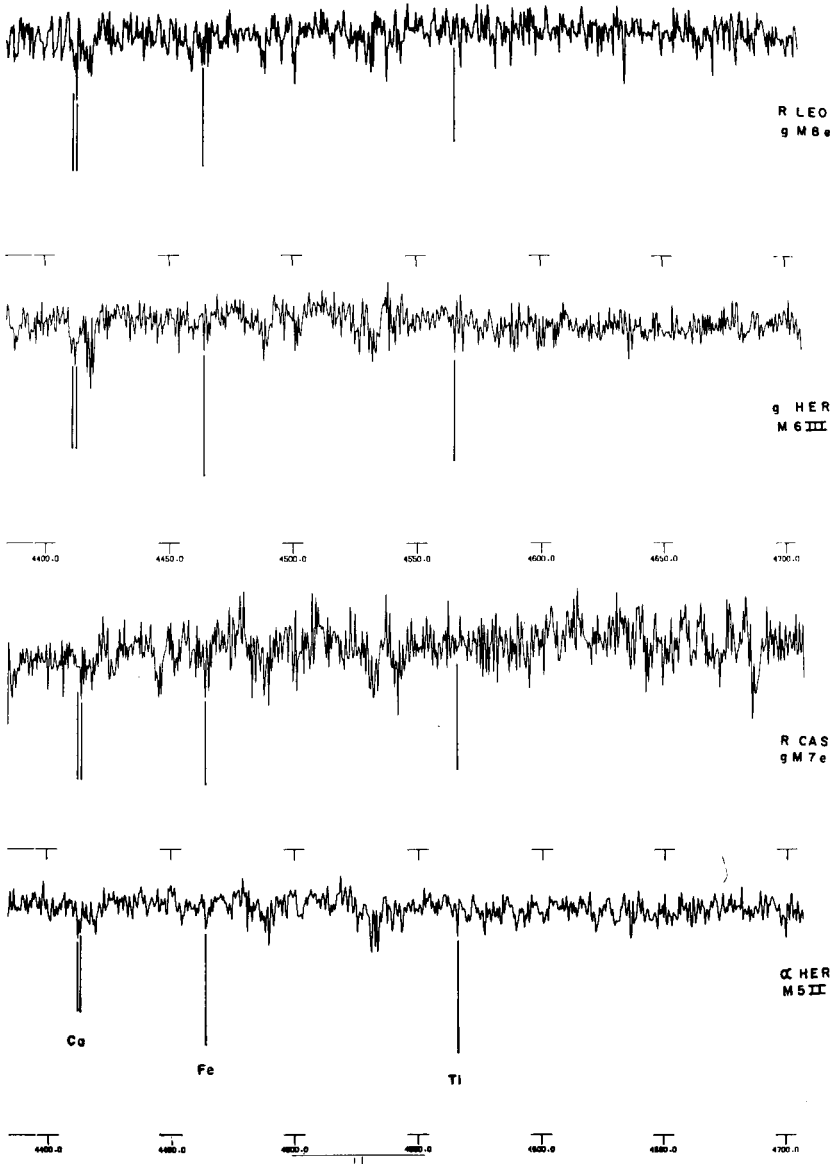

Fig. 10. This region shows the strong Ballik-Ramsay C_2 (0, 0) band in the carbon stars.

The high C spectrum which matches Y CVn, however, can not be reproduced by the CNO bi-cycle and is good evidence that in this star at least, a high carbon abundance is correct.

It should be cautioned that the above results are preliminary in that a full grid of temperatures, compositions and gravities has not been produced. The Ballik-Ramsay
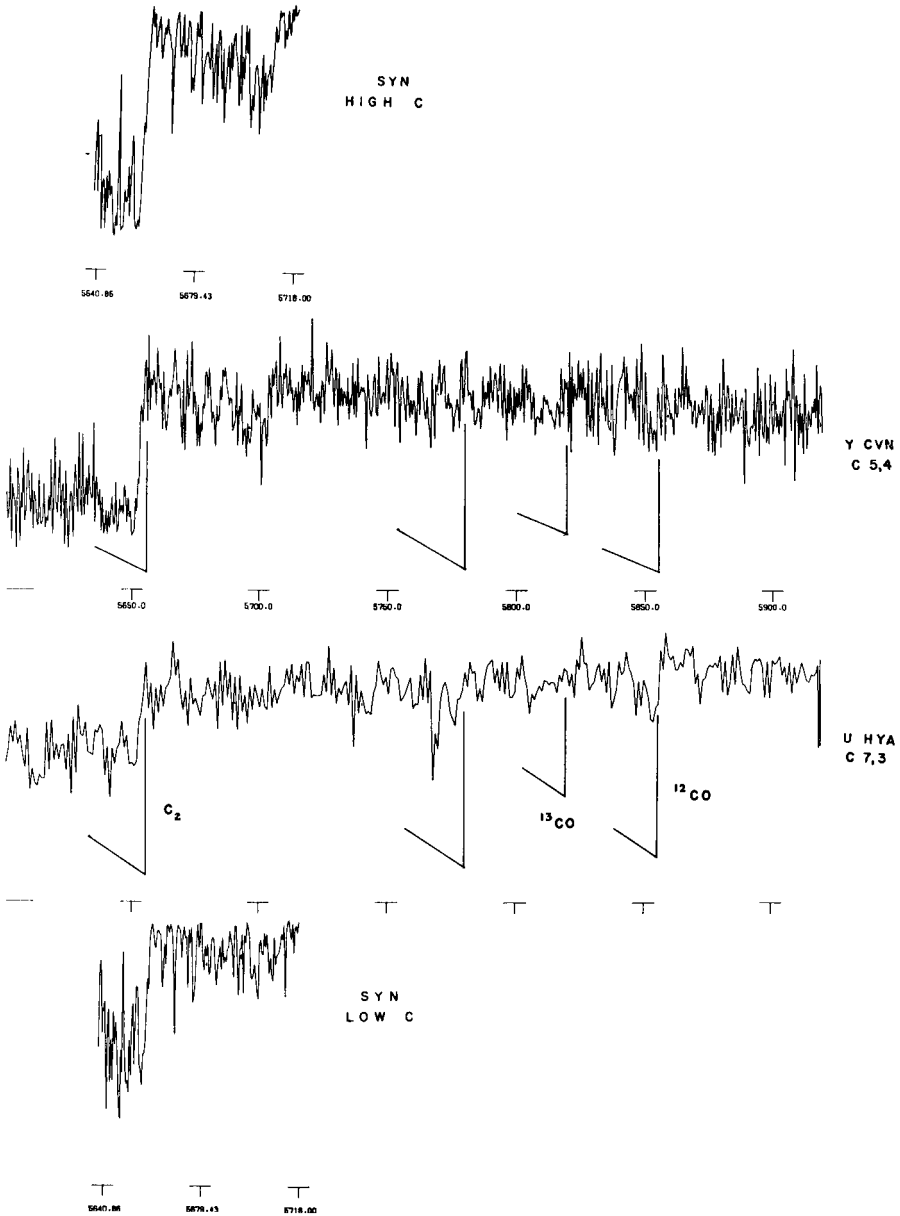

Fig. 11.   Synthetic spectra are compared with the carbon star spectra of Figure 10. A description of the synthetic spectra is given in the text.

oscillator strength has been obtained as an unpublished result of Cooper and may be subject to revision. At this time, however, the CNO bi-cycle theory of carbon star formation seems to be in deep trouble.

DISCUSSION

Bell: Could you tell me where you got the stellar temperature for these stars because I would think when you are discussing the C_2 Ballik-Ramsay bands that the strength of the band is extraordinarily sensitive to the temperature as well as the carbon oxygen difference.

Thompson: Well it is sensitive but not as sensitive to the temperature as you might think. We have not had a good determination of the temperature but we are looking to Dr Lockwood whose scanner spectra of carbon stars is just becoming available and we intend to match very carefully his scanner data to determine the temperature. Right now we have used a rather high temperature of 3200 deg. Of course if you drop the temperature you associate more C_2 but you also increase your opacities. We have tried two or three different temperatures. The point is that the differences between the CNO bi-cycle and the Ulrich model is so great; a factor of 50 different in carbon abundance which is almost 50 squared different in C_2 abundance. It is sort of an off/on phenomenon rather than trying to get just the exact amount of carbon. When we do try a CNO bi-cycle and keep the hydrogen up to approximate the opacity that the helium minus woud give us we just see no C_2 at all. It just completely goes away. We feel that though there are certainly temperature effects the abundance effects are so strong that it completely outweighs the temperature effect.