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ENHANCED CARBON ABUNDANCES IN LONG-PERIOD VARIABLE CARBON STARS

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ABSTRACT

Infrared spectra of several long-period variable carbon stars with C/O ratios only slightly greater than unity display $\Delta V = 3$ CO bands which are not strongly contaminated by CN absorption. Spectral synthesis methods have been used to show that the strength of the CO bands is inconsistent with a CNO tri-cycle equilibrium abundance of H, C, N, and O in which C and O are reduced. The band strengths can, however, be duplicated with models in which the carbon has been enhanced in relation to the solar abundance of carbon as may occur if triple-α produced carbon is mixed to the surface.

Subject headings: infrared: spectra — stars: abundances — stars: carbon — stars: long-period variables

I. INTRODUCTION

Carbon stars have been a persistent theoretical and observational enigmatic riddle for as long as they have been known. It is difficult to quantitatively interpret their optical and infrared spectra because of the dense packing of blended and often saturated lines of carbon-containing molecules such as C_2, CO, C_3, CN, and SiC_2. Molecular equilibrium calculations demonstrate that the presence of the carbon molecules mentioned above requires the carbon-to-oxygen ratio by number to be greater than 1 as opposed to a ratio of 0.6 in the Sun. High abundances of *s*-process elements, the presence of short-lived elements such as technetium, and low $^{12}C/^{13}C$ ratios in some of these stars indicate that carbon stars display the results of interior nuclear processing in their atmospheres and that this anomalous C/O ratio is due to evolution rather than initial conditions.

The low $^{12}C/^{13}C$ ratios determined for many carbon stars led early investigators to consider the CNO cycle reactions during the hydrogen shell-burning stage to be a source of the anomalous C/O ratio. A C/O ratio greater than unity can only be achieved when the CNO cycle is operating very near, or at, equilibrium. Near equilibrium, although the carbon has been reduced via CN cycling to about 2–10% of its initial value, the slower NO cycle has burned oxygen below carbon to produce a C/O ratio greater than 1. At burning temperatures below $30T_6$ K the NO cycle proceeds so slowly that the CN cycle depletes all of the hydrogen before equilibrium can be reached. The net result of CNO equilibrium is a reduction of carbon and oxygen to form nitrogen. The carbon is reduced by a factor of 10 to 50 and the oxygen is depleted below that. In normal evolution only the inner 20% of a star by mass can reach equilibrium; thus mixing of the processed material has relatively little effect on the C/O ratio (Thompson 1972*a*) unless the star loses on the order of 80% of its mass. Current theories which involve CNO equilibrium abundances have been put forth by Scalo, Despain, and Ulrich (1975) and Ulrich and Scalo (1973). These ideas involve deep convective envelopes which mix all of the material above the hydrogen burning shell into the burning region and thus process the material to CNO equilibrium. These mechanisms have difficulties which have led the authors themselves to alternative processes.

The main alternative at this time is identified with the helium shell-burning phase in which additional carbon is produced via the triple-α process. Schwarzschild and Härm (1967) demonstrated that the helium burning shell was unstable with regard to thermal pulsation. This led several investigators to attempt to link the periodic helium shell flashes with the transport of newly formed carbon to the surface. Ulrich and Scalo (1972), Scalo and Ulrich (1973), Sackmann, Smith, and Despain (1974), and Iben (1975) have all considered the problem. Difficulties lie in the transport of the fresh carbon across the still active hydrogen-burning region without severe depletion via CN cycling, and in the quantitative handling of the convective transport of the material, as well as the exact method of contact between the triple-α carbon and the hydrogen-burning shell. The work of Iben (1975) has been to date the most quantitative treatment of this problem. A net result of all of the triple-α mechanisms, however, is to enhance the carbon abundance by factors of 2 to 4 in order to produce a C/O ratio greater than 1.

Observational attempts to discriminate between the carbon-enhanced triple-α theories and the carbon-depleted CNO theories have met with only limited, if any, success. A prime offender in this area has been the current author (Thompson, Schnopper, and Rose 1971) in whose paper inadequate model atmospheres and spectrum-synthesis techniques, coupled with the best available but inaccurate oscillator strengths for the C_2 Ballik-Ramsay band, led to the conclusion that carbon was indeed depleted. In light of the present work this conclusion seems erroneous. Work by

Kilston (1974) and Scalo (1973) has concluded from CN/C_2 ratios that the carbon abundance has been enhanced.

In carbon star atmospheres all of the oxygen is tied up in the form of CO; therefore, a measurement of the CO abundance is a direct measure of the oxygen abundance as well as a lower limit on the carbon abundance. If, as in the case of the stars studied in this paper, the C/O ratio is only slightly greater than unity, then the CO abundance is also a fairly direct measure of the carbon abundance. The first overtone CO bands at 2.3 μm are too saturated to provide accurate abundance measurements, but the second overtone bands at 1.5 μm are relatively unsaturated and are sensitive to changes in the C and O abundances. In N-type carbon stars with higher C/O ratios it is very difficult to use these bands for analysis because of the high density of CN lines which can reduce the observed continuum by a factor of 10 or more. If the C/O ratio is only slightly greater than unity, then very little carbon is left after CO formation to form significant CN. The second overtone CO bands of these stars are not contaminated to an excessive degree with CN lines, as can be seen both by the weak observed CN features and by their low CN index (Baumert 1972), and thus analysis becomes tractable. The second overtone CO bands of two carbon long-period variable stars, RS Cyg and RR Her, are analyzed in this paper in terms of carbon enhancement versus carbon depletion.

II. OBSERVATIONS

Infrared spectra of two carbon long-period variable stars, RS Cyg and RR Her, and of the irregular variable carbon star Y CVn, were taken on the night of 1976 May 12. In preliminary spectra of these stars taken in 1975 April, strong CO second overtone bands were noticed in RS Cyg and RR Her. The 1975 spectra were taken with the Fourier transform spectrometer (FTS) developed by Harold Larson and Uwe Fink of the Lunar and Planetary Laboratory of the University of Arizona (Larson and Fink 1975). The spectra presented in this paper were taken with the Steward Observatory FTS (Thompson and Reed 1975) at the Cassegrain focus of the Steward 2.3 m telescope. A resolution of 1.9 cm^{-1} ($\Delta\lambda/\lambda = 3.2 \times 10^{-4}$) was used for these spectra. The detailed resolution function is given in a later section.

Figure 1 shows the region of the CO second overtone ($\Delta V = 3$) bands in Y CVn, RR Her, and RS Cyg. It is clear that in the strong CN star Y CVn the CO bands have been strongly masked by CN absorption. The CO bands in RR Her and RS Cyg, on the other hand, are deep in a strong continuum. Yamashita (1967) has classified these stars as: Y CVn (C5, 4), RR Her (C7, 1), and RS Cyg (C8, 2). It is evident from the weak Ballik-Ramsay C_2 band for RR Her and RS Cyg as well as the absence of strong CN absorption that the C/O ratio for those two stars is very close to unity.

III. ANALYSIS

The method of spectrum synthesis via model atmospheres is used to interpret the second overtone CO bands observed in RS Cyg and RR Her. A grid of model atmospheres for carbon stars has been published by Hollis Johnson (1974). These atmospheres are used as the basis for the calculation of the synthetic spectrum. The usual assumptions of LTE, plane-parallel transfer, and hydrostatic equilibrium have been made in the calculation of the atmospheres. Continuous opacity from H and H^- free-free and bound-free transitions, H_2^- free-free transitions, H and H_2 Rayleigh scattering, and Mg I and Si I bound-free transitions is included in the program. Straight mean opacities over 100 wavenumber intervals of H_2O, CN, and CO are also included as continuous opacity.

The procedure for the creation of a synthetic spectrum is as follows. An appropriate atmosphere is chosen in which the temperature, pressure, electron density, and depth at each depth point are used. The elemental abundances of H, He, C, N, and O are taken from the model, and solar values are used for all other elements. A chemical equilibrium program (Thompson 1972*b*) is then used to calculate the atomic, positive and negative ion, and molecular abundances at each point. These abundances, along with the temperature, pressure, and depth, are used in a program which integrates the equations of radiative transfer through the atmosphere. In the integration all of the continuum opacity sources in the Johnson atmosphere are used except CN, CO, Mg I, and Si I. A general atomic line blanket code is used instead of just Mg I and Si I. CO is treated as a line opacity source rather than as a continuum source. CN is not used since the C/O ratio is near unity, and it was attempted to try to produce the strongest possible CO bands. The wavenumbers are calculated via the same code as used by Kunde (1967), and the oscillator strengths are calculated from Chackerian's (1970) polynomial expression for the line strengths. It is assumed that the line strengths for ^{12}CO and ^{13}CO are the same. A terrestrial value of $^{12}C/^{13}C$ is assumed, although this is too high for these stars. The line profiles are described by the Voigt function in which a microturbulent velocity of 4 $km\ s^{-1}$ is used, and the collisional damping is calculated from the expressions given in Thompson (1973). The frequency points are spread every 0.02 cm^{-1}. LTE is assumed throughout the atmosphere; therefore, the source function is set equal to the Planck function at the temperature of the depth point being integrated. The result of this calculation is the emergent flux at frequency intervals of 0.02 cm^{-1}. This synthetic spectrum is then convolved with the apodized resolution function of the interferometer to produce the spectrum to be compared with the observed spectrum. In this work the resolution function is represented by

$$\frac{\sin^2[\pi(1.929050)k]}{[\pi(1.929050)k]^2},$$

where k is in cm^{-1}.

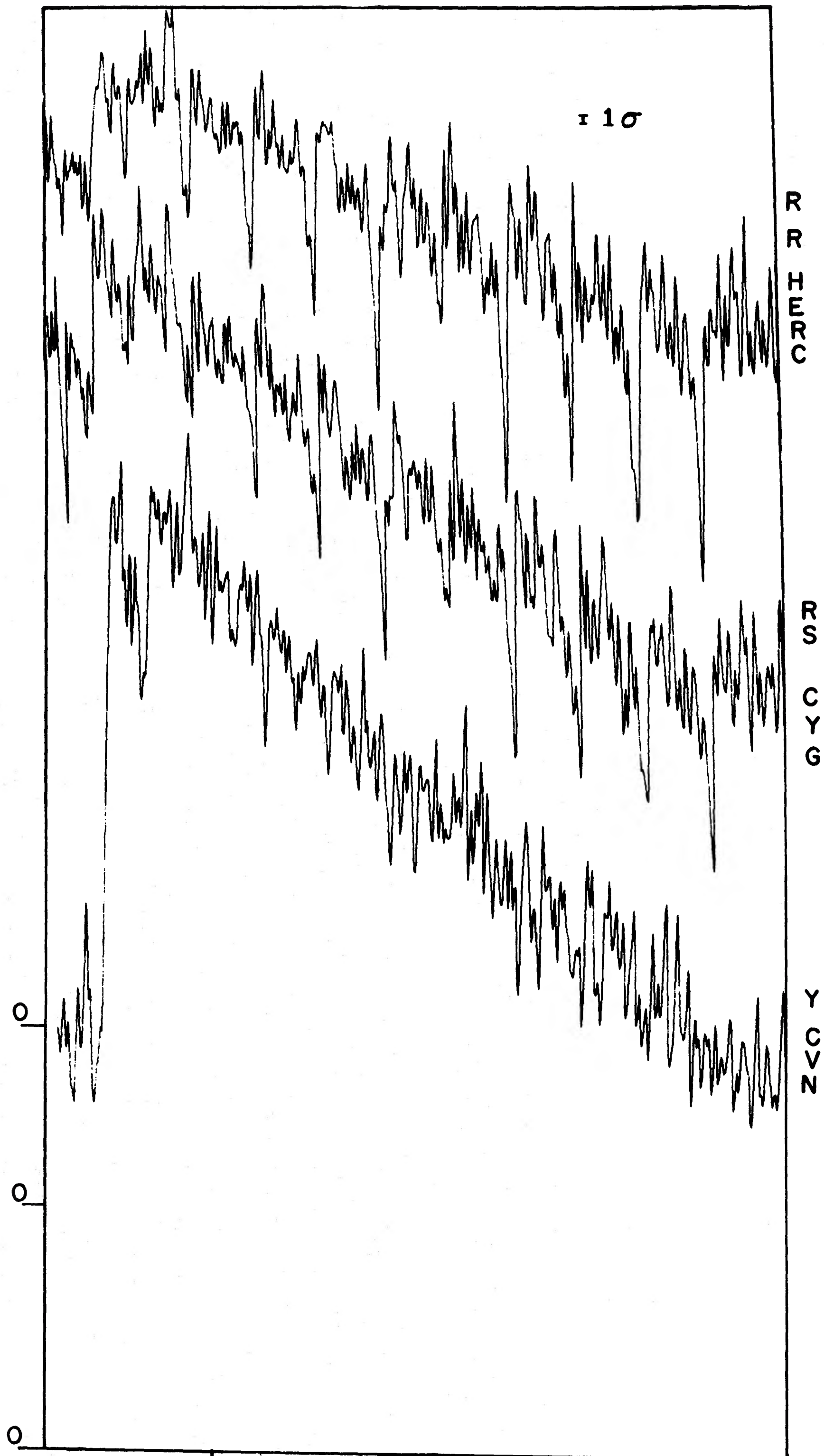

FIG. 1.—Spectra of RR Her, RS Cyg, and Y CVn from 5600 cm^{-1} to 6500 cm^{-1}. The spectra are normalized to the highest continuum point but have offset zeros indicated in the figure for clarity. The strong absorption at 5656 cm^{-1} is the C_2 Ballik-Ramsay band. The vertical scale is linear in relative flux per wavenumber.

For this study two different atmospheres were used from the tables of Johnson (1974). The first atmosphere used is J17, which represents a star in which the carbon has been depleted by a factor of 10 and the C/O ratio is equal to unity. The effective temperature of this model is 3000 K and $\log g = 0.0$. The abundances are represented by $C/H = 3.55 \times 10^{-5}$, $N/H = 9.57 \times 10^{-4}$, $O/H = 3.55 \times 10^{-5}$, and $He/H = 0.1$. This atmosphere represents the minimum depletion of carbon allowed in CNO equilibrium abundance ratios.

The second atmosphere is L1, with carbon enhanced by a factor of 2 and a C/O ratio of 1.2. The effective temperature is 3000 K and $\log g = 0.0$. Abundances for this model are $C/H = 7.10 \times 10^{-4}$, $N/H = 8.51 \times 10^{-5}$, $O/H = 5.89 \times 10^{-4}$, and $He/H = 0.1$. This atmosphere represents a carbon-enhanced atmosphere, as might be expected from the mixing of triple-α produced carbon to the surface.

IV. RESULTS

Figure 2 shows the synthetic spectra produced from these two models in the region between 6425 and 6245 cm^{-1}, which includes the (3, 0), (4, 1), and (5, 2) bands of $^{12}C^{16}O$ as well as the (3, 0)-band of $^{13}C^{16}O$.

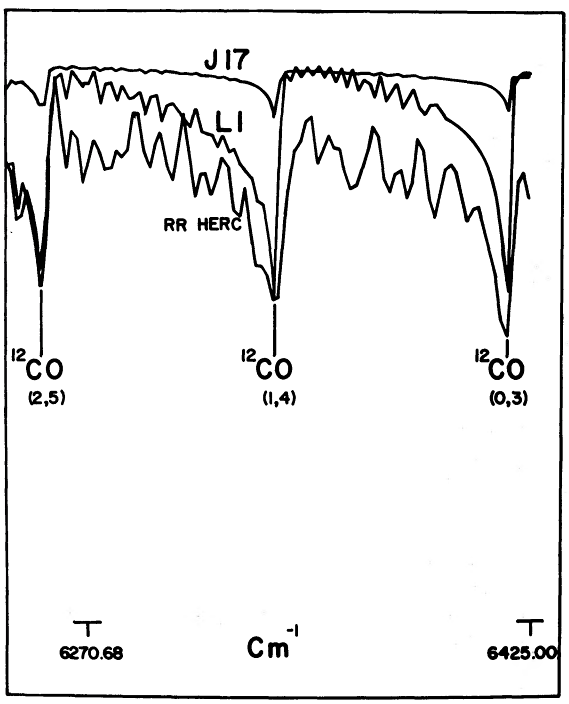

FIG. 2.—These spectra are calculated from a CNO equilibrium abundance model (J17) and a carbon-enhanced model (L1). The spectra are normalized to the highest continuum point. The spectrum of RR Her is compared with the calculated spectra. The spectrum of RR Her shows some CN absorptions which add extra features and enhance the continuum slope. The vertical scale is linear in flux per unit wavenumber. The horizontal lines of the wavenumber tick marks indicate zero flux for all three spectra.

The central depths of the bands in the carbon-enhanced model are 5–6 times greater than those of the CNO model because of the increased CO abundance in the carbon-enhanced model. The depths of the CO band heads in the observed and computed carbon-enhanced spectra match to within 10%. This comparison indicates that the surface abundances in RS Cyg and RR Her cannot arise from mixing of CNO-cycle equilibrium abundances, but are consistent with the carbon-enhanced case.

In establishing the degree of validity of this result, several areas need to be examined which concern the accuracy of observed and computed spectra. In Figure 1, 1 σ error bars are shown except for Y CVn, which has error bars of the order of the line width. The errors are extremely small relative to the strengths of the bands and have no effect on the results. Due to the small random error, the continuum has been established at the level of the peaks of the highest features. At the present resolution of ~ 2 cm^{-1} this is probably an underestimate of the continuum level, which in turn underestimates the strengths of the bands. The sense of the error is therefore to strengthen the conclusion of enhanced carbon abundance.

The computed spectrum is of course subject to the errors in the previously mentioned assumption of model atmospheres which are plane-parallel, hydrostatic, and in LTE. The effect that errors in these assumptions might produce in the computed spectra of late stars has not been fully explored and therefore the errors must be left as possible uncertainties in the result. The question of CO LTE has been explored (Thompson 1973), and the existence of CO LTE in the atmosphere is a safe assumption.

The effective temperature of the models used in the calculation of the synthetic spectra is 3000 K. This is the lowest temperature for which a consistent set of models could be obtained from the work of Johnson (1974). Synthetic spectra computed from higher temperature 3500 K models show CO second overtone bands of diminished strength in both the enhanced carbon and CNO models, although the CNO model still produces bands which are significantly weaker than the carbon-enhanced mode. A continuum (H^-) optical depth of unity is reached in the 3500 K model at a depth above a significant fraction of the CO abundance. The total CO band strength is therefore less than if all of the CO could contribute to the line opacity. A 3500 K model cannot match the observed spectrum without an extreme overabundance of both carbon and oxygen.

It is quite possible that the correct effective temperature for the long-period variables used in this study is below 3000 K. Lowering the effective temperature would decrease the continuum opacity due to H^-, but would probably increase the opacity due to polyatomic molecules. Since CO is fully associated in the region of interest, a decrease in temperature would not increase the CO abundance. Without exact models it would be difficult to accurately estimate the behavior of the band strength with decreased temperature, but it would be very hard to increase the CNO cycle model band strength to that observed in RR Her and RS Cyg. It should be noted that most of the CO in the 3000 K models lies above the depth at which the continuum optical depth at the frequency of the CO second overtone bands reaches a value of 1; therefore, a decreased continuum opacity would not significantly enhance the CO strength.

Both models used in this study are for $\log g = 0$. Models with higher gravities produce weaker CO second overtone bands because of increased H^- opacity. It is therefore not possible to alter the conclusions by increasing the gravity. In the spectrum synthesis a microturbulent velocity of 4 km s^{-1} was used. Since the lines in the CNO cycle model are not saturated, it is not possible to significantly alter the equivalent width of the bands by changing the microturbulent velocity.

A supersonic microturbulent velocity of 7 km s^{-1} enhances some features of the convolved spectrum for the carbon-enhanced case by a maximum of 10%. The main enhancement is away from the band head, with a slight decrease of the maximum depth of band head. Convolved spectra of 1 km s^{-1} microturbulent velocity have a general narrowing of the band features, with a maximum reduction of 20%. The presence of CN in the observed spectra alters the band shapes by more than 10%; therefore, the correct microturbulent velocity cannot be determined. In no case can an altered microturbulent velocity significantly alter the conclusion that carbon is enhanced.

The effect of microturbulent velocities of up to 10 km s^{-1} has been considered. If the synthetic spectrum is first convolved with a Gaussian function of width 10 km s^{-1} and then reconvolved with the instrument function of approximately 100 km s^{-1}, less than a 10% change in any feature is found. This change, as explained above, is not significant. The spectra presented in Figure 2 have no microturbulent velocity included.

Another consideration is the H/He ratio. Both models have solar H/He ratios which may not be appropriate for the two cases considered here. In the carbon-enhanced case, if the carbon comes from the triple-α process, then helium as well as carbon will be mixed to the surface. Even if a He/C ratio of 10 is assumed, however, the added He would not significantly affect the percentage of H in the atmosphere. A factor of 2 change in the percentage of H is needed to significantly affect the atmospheric structure of a star (Johnson 1976; Thompson 1972*b*).

The CNO cycle model has a higher likelihood of having an altered H/He ratio. Since the CNO cycle must be operating near equilibrium for a C/O ratio greater than 1 to be achieved, it is possible that a significant fraction of hydrogen has been burned into helium. It cannot conclusively be said that this is not the case for the two stars observed in this paper, although there is no evidence for hydrogen depletion as in an R Corona Borealis star.

In the spectral synthesis CN opacity has not been included, although the model atmospheres were constructed with CN used as a continuum opacity. CN was neglected as an opacity in order to observe the maximum CO band strength without regard to the CN blanketing. It is very strong evidence against the CNO model that it could not reproduce the observed band strength even with no CN opacity. CN of course does appear in the observed stars, although not to an extreme degree. The CO band strengths may then be even higher than those deduced from the spectrum.

The majority of the errors discussed err on the side of the CNO model. Even then the CNO cycle model fails by a factor of 5 to reproduce the observations. The outstanding uncertainties which remain are the basic assumptions of plane-parallel, hydrostatic atmospheres and the possibility of an altered H/He ratio in the CNO cycle model. In spite of these uncertainties, the evidence very strongly favors the carbon-enhanced model.

V. CONCLUSIONS

The results of the previous section are additional strong arguments against mechanisms for producing N-type carbon stars which rely on CNO cycle equilibrium abundances. Other evidence includes the presence of *s*-process elements and newly formed elements such as technetium in the atmospheres of many N stars. CNO cycle equilibrium also demands a $^{12}C/^{13}C$ ratio of 2.5, but the observed $^{12}C/^{13}C$ ratios in N stars vary widely, although the variance may be partially due to the difficulty of quantitatively determining this ratio from the complicated spectrum of most N stars.

At present the most likely stage of evolution for the production of N stars is the helium shell-burning epoch. At this epoch carbon is produced in the helium-burning shell via the triple-α process. The thermal instability of this shell leads to flashing or periods of high burning which initiate large-scale convection that extends into the previously quiescent helium buffer zone. The possibility of transporting the freshly created carbon to the surface of the star during this time has been investigated by several authors mentioned previously (Ulrich, Scalo, Iben, Sackmann, Smith, and Despain). A dominant problem in this mechanism is the transport of the carbon through the hydrogen-burning shell in a time short enough or at a temperature low enough to prevent most of the carbon from being burned into nitrogen via hydrogen burning.

To date the most quantitative investigation of the helium shell flash period has been that of Iben (1975). In Iben's calculations there is interplay between the convective shell and the convective envelope, and the extent of the convective shell stays constant in position with the mass flowing between them. After the tenth pulse the convective shell reaches a mass point that was previously inside the convective envelope. After the pulse the base of the convective envelope returns to its previous mass position and picks up the carbon-rich material left by the convective shell. This material then undergoes hydrogen burning at the base of the convective envelope on its way to the surface.

Iben mentions that the difficulty of the depletion of carbon during transit of the hydrogen burning shell may be alleviated either by mass loss, which reduces the diluting volume of the envelope, or by a reduction of the mixing length to pressure scale-height ratio from 1.0 to 0.7. The reduction of mixing length to scale-height ratio reduces the temperature at the base of the hydrogen burning shell to a value that would allow significant amounts of carbon to transit the burning region. Later calculations by Iben (1976) in which the mixing length to scale-height ratio was reduced have demonstrated that carbon stars are produced.

Long-period variable carbon stars are known to suffer large-scale mass loss (Frogel and Hyland 1972) which would deplete the envelope mass. Whether this mass loss is a result of or the reason for the star's becoming a carbon star is not certain. It is tempting to postulate an evolutionary sequence which begins with an M-type long-period variable, progresses to an S type with $C/O \approx 1$, and upon further mixing becomes a CS star and finally an N-type long-period variable. Return toward the main sequence after helium shell burning may be preceded by a large mass-loss phase such as in IRC +10216 and the Egg Nebula.

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