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HYDROGEN-DEFICIENT ATMOSPHERES FOR COOL CARBON STARS

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ABSTRACT

Motivated by recent work which hints at a possible deficiency of hydrogen in non-Mira N-type carbon stars and to further explore the parameter space of chemical composition, we have computed a series of hydrogen-deficient models for carbon stars. For these models $T_{\rm eff} = 3000$ K, and log $g = 0.0$. Solar abundances are used for all elements except for carbon (which is enhanced to give C/O = 1.05), hydrogen, and helium. As the fractional abundance of hydrogen is decreased, being replaced by helium, the temperature–optical depth relation is affected only slightly, but the temperature-pressure relation is changed. The most striking change in the emergent flux is the decrease of the H^- peak at 1.65 μm compared with the blackbody peak at 1.00 μm.

Subject headings: stars: atmospheres — stars: carbon — stars: hydrogen deficient

I. INTRODUCTION

In model atmospheres for carbon stars, the hydrogen abundance has always been assumed to be solar. While this is a natural starting assumption, its validity has never been rigorously established. For this reason, and to explore further the parameter space of chemical composition, we undertake this investigation of hydrogen-depleted carbon star models.

Hydrogen deficiencies for "normal" carbon stars have, in fact, been suggested by several investigators (Vardya 1966; Utsumi 1970; Johnson *et al.* 1983; Goebel and Johnson 1984), but other workers (Warner 1967; Eriksson *et al.* 1984) find solar hydrogen abundance. The evidence is presently inconclusive, because direct observations of hydrogen are not easy, and no intensive efforts have been made. Yet the hydrogen abundance is a matter of major concern, because the association and dissociation of H and H_2 largely control the thermodynamics of the atmosphere.

This study has been motivated in part by two recent observations. First, while the quadrupole 1–0 $S(1)$ line of H_2 at 4712.9 cm^{-1} is observed to be fairly strong in the spectra of several Mira-type carbon stars (Johnson *et al.* 1983), it is absent in the spectra of cool, non-Mira carbon stars. This absence is in conflict with the predictions of model atmospheres based on diatomic molecular opacities (Querci, Querci, and Tsuji 1974; Johnson 1982), and several possible resolutions of the discrepancy have been suggested (Johnson *et al.* 1983), of which the inclusion of polyatomic molecular opacities has been most strongly advocated (Eriksson *et al.* 1984). Second, the wavelength distribution of the emergent fluxes from standard carbon star models (Johnson 1982) differs significantly from spectrophotometric observations of cool, non-Mira stars taken at NASA/Ames Research Center (Goebel *et al.* 1984) in the region of the H^- opacity minimum at 1.65 μm (Goebel and Johnson 1984). Again, a possible deficiency of hydrogen may be indicated.

II. MODEL ATMOSPHERES

To investigate the effects of possible hydrogen depletion in the atmospheres of cool carbon stars, we have constructed a sequence of model atmospheres using the ATLAS6 model atmosphere program (Kurucz 1970), modified at Indiana University to include molecular effects. The important diatomic absorbers CN, CH, C_2, CO, NH, and MgH are included through the opacity sampling method (Peytremann 1974; Sneden, Johnson, and Krupp 1976), with the molecular data given by Johnson, Bernat, and Krupp (1980) and Johnson (1982). Hydrostatic equilibrium, radiative plus convective equilibrium, and local thermodynamic equilibrium in a plane-parallel, horizontally homogeneous medium have been assumed in all models.

A series of models were computed with an effective temperature of 3000 K and a surface gravity of 1 dyne cm^{-2}. Standard solar abundances are used, with two exceptions: (1) carbon is enhanced so that the carbon-to-oxygen ratio is 1.05, and (2) hydrogen is depleted by various amounts and is replaced by helium. That is, holding the fractional metal abundance by number a constant, we reduce the fractional abundance of hydrogen relative to the total, and the fractional abundance of helium is consequently increased.

The structure of the models is affected in interesting ways by the hydrogen depletion, as can be seen in Figures 1 and 2. Perhaps surprisingly, the thermal structure [$T(\tau)$, where τ is the Rosseland optical depth] shows little change, although the more hydrogen-deficient models are slightly cooler throughout the outer photosphere (by ~100 K) and slightly warmer in the boundary layers. By contrast, the temperature-pressure relation is strongly affected as the changing opacity (primarily replacing H^- with He^- and replacing Rayleigh scattering from H and H_2 with Rayleigh scattering from He) affects the pressure corresponding to each optical depth. (The change is very reminiscent of that produced by increments in surface gravity.) Since helium is a less efficient absorber than hydrogen, hydrogen-depleted atmospheres have lower opacities and therefore higher pressures for a given temperature or optical depth.

We use this sequence of hydrogen-deficient models particularly to study the emergent flux near the flux peak. Values of the flux are computed at 9136 wavenumbers and then averaged over 200 cm^{-1}. Figure 3 shows that the most significant change in the emergent fluxes as hydrogen is depleted is the disappearance of the H^- peak at 1.65 μm. This can easily be

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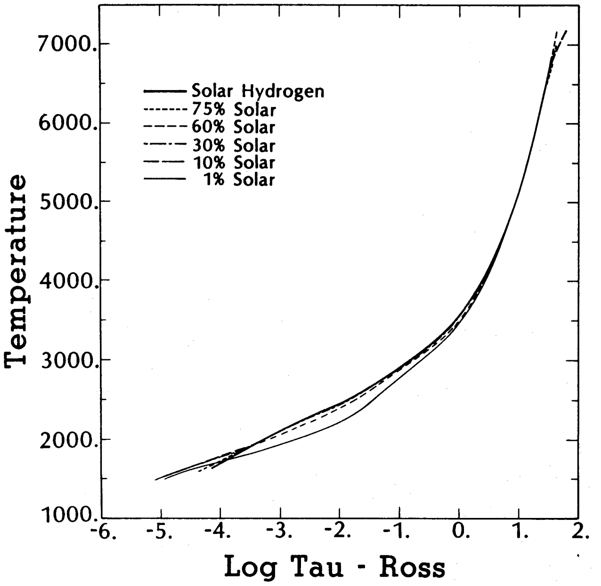

FIG. 1.—The temperature–Rosseland optical depth relation for six models in the hydrogen-deficient sequence. Each model is identified by the fractional abundance of hydrogen relative to the Sun.

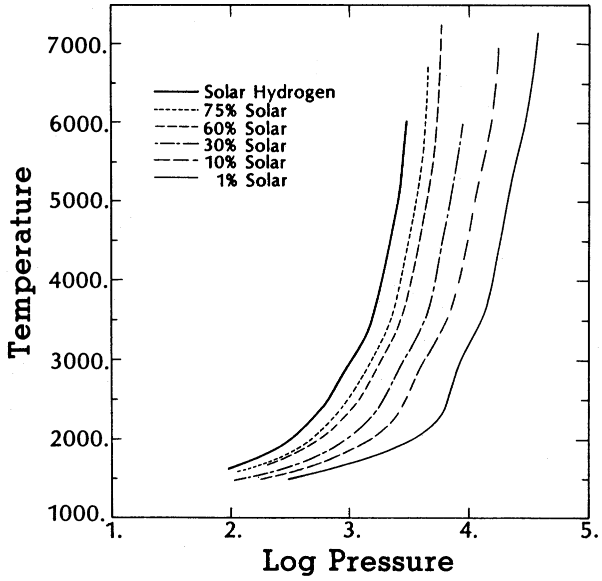

FIG. 2.—The temperature-pressure relation for the same models shown in Fig. 1. The differences between the models are due to the changing opacity as hydrogen is depleted from (and replaced by helium in) the atmosphere.

seen by comparing the height of the H^- peak at 1.65 μm to the blackbody peak at 1.0 μm. As is apparent, models with normal hydrogen abundance predict an H^- peak stronger than the blackbody peak. As hydrogen is reduced, the H^- peak is weakened, becoming less prominent than the blackbody peak for hydrogen abundances less than 30% of the solar abundance. A similar result is apparent in the hydrogen-deficient spherical model atmospheres of Wehrse (1981) for M supergiants, which were computed with straight-mean opacities.

III. DISCUSSION AND CONCLUSIONS

How do the predictions of these models compare with real carbon stars? Assembling a complete energy flux curve for a cool carbon star is not easy, even if one ignores the variability of the star and combines observations taken at different epochs. We have collected the available data on the well-observed star TX Psc (HD 223075; N0; C6, 2), for which an angular diameter has been measured and an effective temperature of 3000–3100 K has been deduced (Walker, Wild, and Byrne 1979; Ridgway, Joyce, and Wells 1980; Tsuji 1981). We use the following: (1) infrared spectrophotometry from 1.25 to 5.4 μm by a team including one of the authors (J. H. G.) at NASA/Ames; (2) spectral scans from 0.4 to 1.1 μm (Faÿ and Honeycutt 1972); (3) complete broad-band photometry (Mendoza and Johnson 1965; Walker 1980); and (4) narrow-band photometry on the Wing system (Wing 1967). The internal absolute calibration of each system has been retained; no adjustments have been made, and no account has been taken of differences in phase or brightness. The final curve is displayed in Figure 4. While the curve is generally complete, a vital region from 1.0 to 1.2 μm is missing, and the sections are therefore imperfectly tied together. Spectrophotometry of several non-Mira N-type carbon stars in the important spectral region 0.8–2.0 μm should be given very high priority.

A comparison of the models in Figure 3 with the observations of TX Psc in Figure 4 indicates that hydrogen depletion to a value $\leq 30\%$ of the solar abundance is required to obtain a good match. The agreement between the model with 10% solar hydrogen abundance and the observations is excellent. The column density of H_2 in the model with 10% solar hydrogen abundance is reduced from that in a model with standard hydrogen abundance by a factor of 20.

While the improved match with observation of the fluxes from the hydrogen-deficient atmospheres compared with atmospheres with normal hydrogen abundance is gratifying, one should be careful not to overinterpret these results. As already pointed out (Johnson *et al.* 1983), alternative explanations for the discrepancies in the H_2 observations may be available, and these have not been examined. Furthermore, a

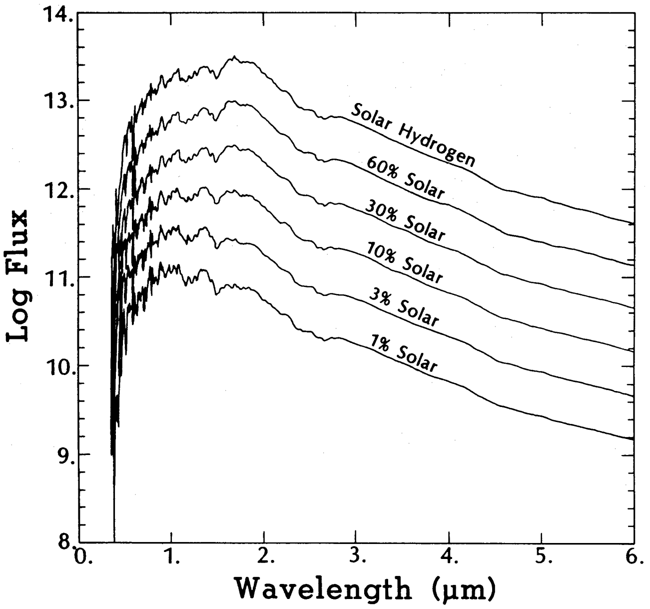

FIG. 3.—Relative predicted energy flux curves for five hydrogen-deficient models compared with a model with solar hydrogen abundance. The emergent flux is computed at 9136 values of wavenumber, and then averaged over intervals of 200 cm^{-1}.

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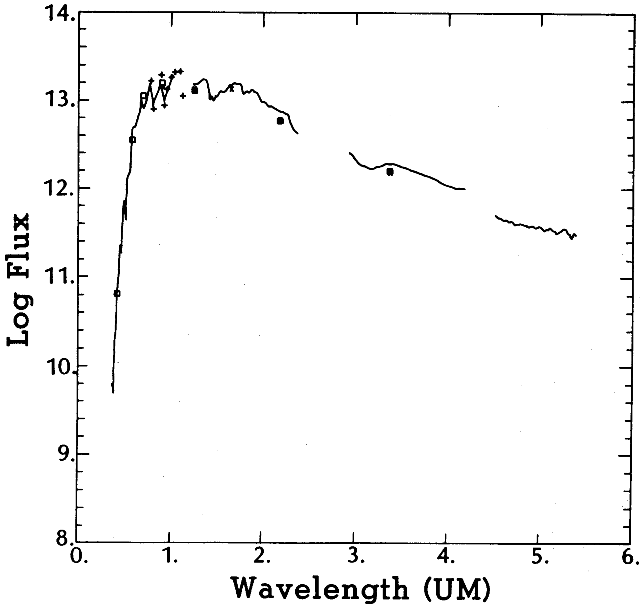

FIG. 4.—The observations of TX Psc, including infrared spectrophotometry (Goebel *et al.* 1984), scanner observations at shorter wavelengths (Faÿ and Honeycutt 1972), narrow-band photometry (Wing 1967 [*plus signs*]), and broad-band photometry (Mendoza and Johnson 1965 [*open squares*] and Walker 1980 [*crosses*]) to yield a complete relative flux curve.

hydrogen deficiency of this magnitude would appear to be in direct conflict with results from calculations of stellar interiors and evolution. In fact, present model atmospheres for cool carbon stars should properly be regarded as exploratory (see, e.g., Johnson 1984). Eriksson *et al.* (1984) and Tsuji (1984) point out that the polyatomic molecule HCN is an extremely important absorber in the atmospheres of cool carbon stars, especially for stars cooler than $T_{\mathrm{eff}} = 2900$ K, although these authors differ in their conclusions regarding its effect. Even though its most important absorption feature is at 2 μm, it may have a strong effect on the energy flux peak because the reemission of radiation absorbed at 3 μm occurs primarily shortward of 1.5 μm. This has the effect of strengthening the blackbody peak at 1.0 μm relative to the H^- peak at 1.6 μm. Whether this phenomenon could bring a 3000 K model of standard hydrogen abundance into agreement with the observations of TX Psc awaits further testing.

It would be most interesting to extend the comparison of hydrogen-deficient models to very cool, non-Mira M stars, for which speculations of hydrogen deficiencies have also been made (Auman 1972) and for which Tsuji (1983) found the strong 1–0 $S(1)$ H_2 line to be absent. Observations of spectral energy distributions for these stars are also urgently needed.

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