A Grid of MARCS Model Atmospheres for S Stars

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Abstract. S-type stars are late-type giants whose atmospheres are enriched in carbon and s-process elements because of either extrinsic pollution by a binary companion or intrinsic nucleosynthesis and dredge-up on the thermally-pulsing AGB. A large grid of S-star model atmospheres has been computed covering the range 2700 ≤ Teff(K) ≤ 4000 with 0.5 ≤ C/O ≤ 0.99. ZrO and TiO band strength indices as well as VJHKL photometry are needed to disentangle Teff, C/O and [s/Fe]. A “best-model finding tool” has been developed using a set of well-chosen indices and checked against photometry as well as low- and high-resolution spectroscopy. It is found that applying M-star model atmospheres (i.e., with a solar C/O ratio) to S stars can lead to errors in Teff up to 400 K. We constrain the parameter space occupied by the S stars of the vast Henize sample in terms of Teff, [C/O] and [s/Fe].

1. Introduction

The S class was originally defined by Merrill (1922) to designate a group of curious red stars which did not fit well into either class M (TiO stars) or classes R and N (carbon stars). Keenan (1954) clarified the situation by accepting as S stars only those exhibiting ZrO bands. The numerous attempts to link phenomenological spectral classification criteria to the physical parameters Teff, gravity, C/O, [s/Fe], and [Fe/H] (Keenan 1954; Keenan & McNeil 1976; Ake 1979; Keenan & Boeshaar 1980) only led to imprecise results, because low-resolution diagnostics are strongly entangled in terms of Teff, C/O and [s/Fe] variations. The only in-depth discussion of the thermal structure dates back to the pioneering paper of Piccirillo (1980). He already insisted on the strong influence of the C/O ratio on the atmospheric structure and spectra of S stars, in addition to effects due to s-process element overabundance. His investigation was, however, mostly limited to qualitative statements, due to obvious technical limitations. Most subsequent analysis of S stars has relied on models designed for M-type stars, not allowing for
C/O or [s/Fe] ratio changes. In the present paper we present a new grid of model atmospheres, superseding the one presented in Plez et al. (2003), covering most of the parameter space of S-type stars, and we attempt to provide a calibration of photometric indices in terms of $T_{\text{eff}}$, C/O and [s/Fe].

2. Model Atmospheres and Spectra

Since models for S star atmospheres are virtually non-existent, a grid of MARCS model atmospheres (see Gustafsson et al. 2008, for details on the models computation) for S stars has been calculated: $2700 \leq T_{\text{eff}}$ (K) $\leq 4000$ (steps of 100 K); C/O = 0.5, 0.750, 0.899, 0.925, 0.951, 0.971, 0.991; [s/Fe] = 0, +1, +2 dex; [Fe/H] = −0.5 and 0 dex; log $g$ = 0, 1, 2, 3, 4, 5.

All models were computed for $M = 1\ M_\odot$ and with $[\alpha/\text{Fe}] = −0.4 \times [\text{Fe}/\text{H}]$. Opacities as complete and accurate as possible were included, including polyatomic molecules and a specific ZrO line list (described in Plez et al., in preparation). Models were computed through opacity sampling with more than $10^5$ wavelength points, local thermodynamic equilibrium, the mixing-length theory of convection, and spherical symmetry for log $g$ $\leq$ 2.

A total of 3522 converged model atmospheres were obtained. The model structure for $T_{\text{eff}}$=3000 K and [s/Fe] = +2 dex models is shown in Figure 1, where the major influence of C/O on the thermal structure is readily apparent (whereas the [s/Fe] ratio has less importance). The $P_{\text{gas}}$ $\sim \tau_{500}$ relation (fixed mostly by log $g$) stays basically unchanged, whereas the $T$ $\sim \tau_{\text{Ross}}$ relation (governed by the energy balance requirement) reaches higher temperatures at the surface for higher C/O. When C/O increases, $P_{\text{gas}}$ at a given $T$ increases. The latter effects are due to the large decrease of the partial pressures of H$_2$O and TiO, two major opacity contributors. Figure 2 illustrates how
the depth of TiO and ZrO bands decreases with increasing C/O, for different models of $T_{\text{eff}} = 3000$ K, and the influence on the spectra of the level of s-process enhancement.

3. Confronting the Models with Observed Color and Molecular Band Indices

Synthetic spectra are now compared to observations. The Henize sample of S stars (205 stars with $R \leq 10.5$ and $\delta \leq -25^\circ$; Henize 1960) is of particular interest for this purpose, since (1) it collects S stars with no bias against high galactic latitudes (Van Eck & Jorissen 2000b), and (2) a large amount of observational material has been collected for this sample (Van Eck et al. 2000). From these data, the $(V-K)_0$, $(J-K)_0$ color-color diagram, dereddened according to Drimmel et al. (2003), has been constructed (Figure 3). Similarly, a set of TiO and ZrO band-strength indices has been computed from the low-resolution spectra, and is displayed in Fig. 3. Their comparison with model values makes it possible to estimate $T_{\text{eff}}$, C/O and [s/Fe] since: (1) the $(V-K)_0$, $(J-K)_0$ color-color diagram disentangles $T_{\text{eff}}$ and C/O; (2) the (TiO, ZrO) diagram disentangles $T_{\text{eff}}$ and [s/Fe]. In both cases, there is a good segregation between M and S stars with, however, some degeneracy between C/O and [s/Fe], especially for low $T_{\text{eff}}$.

The $(V-K)_0$, $(J-K)_0$ color-color diagram reveals that, for a given $V-K$, the range in $T_{\text{eff}}$ covered by models of different C/O ratios can be as large as 400 K. Therefore, the application to S stars of the usual M-star temperature scale based on the $V-K$ index (as done in the past when specific S-star models were unavailable) leads to errors on $T_{\text{eff}}$ of up to 400 K.
Figure 3. Upper panels: Comparison between color indices of observed M (squares), S (triangles) and C (crosses) stars, and color indices computed from synthetic spectra of S stars for \([\text{[Fe/S]}] = 0\) (left) and \(+2\) (right). The models with the lowest temperature \((2700 \, \text{K})\) and highest C/O ratio \((0.991)\) are at the top of each “grid”. Lower panels: ZrO index versus TiO index for \([\text{[Fe/S]}] = 0\) (left) and \(+1\) (right). The grid corresponds to solar-metallicity, \(\log g = 0\) models ranging from \(T_{\text{eff}} = 4000 \, \text{K}, \, \text{C/O} = 0.5\) (around coordinates \(0.05, 0.05\) on the leftmost figure) to \(T_{\text{eff}} = 2700 \, \text{K}, \, \text{C/O} = 0.99\) (around \(0.3, 0.65\)). Stars clumping around (TiO,ZrO) = (0,0) are G and K giants. All S stars to the left of the region covered by the grid are SC stars.

4. The Atmospheric Parameters of S Stars

We have built a “best model finding tool”, based on an appropriate weighting of well-chosen photometric and narrow-band indices (de-reddened Geneva and VJHKL photometry, ZrO, TiO and NaD band strengths) and \(\chi^2\) minimization between observed and synthetic indices. The adequacy of the selected models has been checked on low-resolution spectra, de-reddened according to Cardelli et al. (1989); the agreement is very good in most cases (see Neyskens et al., this volume).

Figure 4 presents the distribution of Henize S giants in terms of temperature and C/O ratio. The temperature difference between Tc-poor (polluted binary) S stars and the cooler Tc-rich (genuine TP-AGB) S stars is clearly visible. Among Tc-rich stars, despite the small-number statistics, the expected gradual increase of the C/O ratio as the star cools down and ascends the TP-AGB is also visible.
Figure 4. Comparison of the $T_{\text{eff}}$ distributions of Tc-rich (shaded histograms) and extrinsic (unshaded histograms) S stars. The 7 top panels separate the stars according to the C/O ratio.

This new grid of model atmospheres is an essential prerequisite to reliable spectroscopic chemical analyses of objects enriched in s-process nucleosynthesis products. It will allow us to pursue on a more quantitative basis the comparison between extrinsic and intrinsic S stars initiated by Van Eck & Jorissen (2000a).

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References

Discussion

Ireland: You have a new ZrO line list. Does this one use any recent laboratory data from the last 10 to 20 years?

Van Eck: We use a ZrO line list assembled in the same way as the TiO line list of Plez (1998) using indeed data from 1973-1995. We consider the isotopes $^{90,91,92,94,96}$ZrO.

Marigo: TP-AGB evolutionary models with accurate molecular opacities predict an increase of the effective temperature as the C/O ratio increases from say $\sim 0.5$ to $\sim 1$. This is caused by a pronounced opacity minimum when C/O$\sim 1$. Is this trend consistent with your model atmospheres for S-stars?

Van Eck: Indeed the TiO and ZrO molecular bands disappear when approaching C/O=1. But we do not know the distances to the Henize stars to be able to see, at a given luminosity, a temperature shift for an increased C/O.

Srinivasan: Did you or do you plan to include the effects of dust in comparison to data?

Van Eck: We don’t yet include the effects of dust, but indeed we plan to estimate them. The problem is to know what exact species form when C/O is approaching 1.

Wing: From a classification point of view, it has always interested me that S stars show some of the same spectral characteristics as M dwarfs - the strong D-lines and CaI$\lambda 4226$, and enhanced metallic hydrides. Does your line list for synthetic spectra include CaH? I think that may be responsible for the strong sensitivity to C/O at around 6800Å.

Van Eck: Yes our line list includes CaH, which indeed has prominent bands around 6400Å and 6800Å, especially for high C/O ratios.

Zijlstra: The sample of S stars is defined spectroscopically. How well do the M and MS stars separate in your model? Is there a smooth transition or is it well defined?

Van Eck: Our grid of model atmospheres covers the range C/O=0.5-0.99. Hence M stars, with C/O=0.5 are modalized. The band depth indices computed on the synthetic spectra of M and MS stars are in very good agreement with those computed from observed M and MS star’s spectra. The agreement of photometric indices is also very good.