A grid of MARCS model atmospheres for S stars

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Abstract. S-type stars are late-type giants whose atmosphere is 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 ≤ T_eff(K) ≤ 4000 with 0.5 ≤ C/O ≤ 0.99. ZrO and TiO band strength indices as well as VJHKL photometry are needed to disentangle T_eff, C/O and [s/Fe]. A “best-model finding tool” was 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 on T_eff up to 400 K. We constrain the parameter space occupied by S stars of the vast sample of Henize stars in terms of T_eff, [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 physical parameters (T_eff, gravity, C/O, [s/Fe], [Fe/H]) (Keenan 1954; Keenan & McNeil 1976; Ake 1979; Keenan & Boeshaar 1980) only lead to imprecise results, because low-resolution diagnostics are strongly entangled in terms of T_eff, 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 the s-process elements overabundance. His investigation was however mostly limited to qualitative statements, due to obvious technical limitations. Most subsequent analysis of S stars 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, superseeding the one presented in [Plez et al., 2003], covering most of the parameter space of S-type stars, and 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 S stars has been calculated: $2700 \leq T_{\text{eff}} (\text{K}) \leq 4000$ (step of 100K); C/O = 0.5, 0.750, 0.899, 0.925, 0.951, 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 $[\alpha/\text{Fe}] = -0.4 \times [\text{Fe/H}]$. Opacities as complete and accurate as possible were included, including polyatomic molecules and a specific ZrO linelist (described in Plez et al., in preparation). Models were computed through opacity sampling with more than $10^5$ wavelength points, local thermodynamic equilibrium, mixing-length theory of convection and spherical symmetry for log(g) $\leq 2$.

A total of 3522 converged model atmospheres was obtained. The model structure for $T_{\text{eff}} = 3000$ K and [s/Fe]=+2 dex models is shown in Fig. 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$_{\text{gas}}$ - $\tau_{500}$ relation (fixed mostly by log g) stays basically unchanged, whereas the T - $\tau_{\text{Ross}}$ 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 a large decrease of the partial pressures of H$_2$O and TiO, two major opacity contributors. Fig. 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 spectral 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 that purpose, since (i) it collects S stars with no bias against high galactic latitudes (Van Eck & Jorissen 2000b), and (ii) a large 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 (Fig. 3). Similarly, a set of TiO and ZrO band-strength indices have been computed from the low-resolution spectra, and displayed on Fig. 3. Their comparison with the model values make it possible to estimate $T_{\text{eff}}, C/O$ and $[\text{s/Fe}]$ since: (i) the $(V-K)_0, (J-K)_0$ color-color diagram disentangles $T_{\text{eff}}$ and $C/O$; (ii) the (TiO, ZrO) diagram disentangles $T_{\text{eff}}$ and $[\text{s/Fe}]$. In both cases, there is a good segregation between M and S stars with, however, some degeneracy between C/O and $[\text{s/Fe}]$, 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.
4. The atmospheric parameters of S stars

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

Fig. 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 TPAGB) S stars is clearly visible. Among Tc-rich stars,
Figure 4. Comparison of the $T_{\text{eff}}$ distribution of Tc-rich (shaded histogram) and extrinsic (unshaded histogram). The 7 top panels separate the stars according to the C/O ratio despite the small number statistics, the expected gradual increase of the C/O ratio as the star cools down and ascends the TPAGB is also visible.

This new grid of model atmospheres is an unavoidable prerequisite to reliable spectroscopic chemical analyses of these 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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