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A grid of S stars MARCS model atmospheres

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Abstract.

S stars are cool stars of temperatures similar to those of M giants, but their 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. Despite numerous attempts to link phenomenological spectral classification criteria to physical parameters (T_{eff}, gravity, C/O, [s/Fe], [Fe/H]), the parameter space of S stars is poorly known and this has prevented accurate abundance analysis of S stars until now. Here we present a large grid of S-star model atmospheres. ZrO and TiO band strength indices as well as V J H K L photometry are needed to disentangle the effective temperature, C/O and [s/Fe]. The stellar parameters derived on the basis of low-resolution spectra and photometry are shown to be fairly accurate when compared to high-resolution data of the same stars. The C/O ratio of S stars is found to be between the solar value (0.5) and 0.99, and not 1 as often claimed in the literature. Consistently with stellar evolution expectations, the C/O ratio increases as the effective temperature decreases.

1. Introduction

S stars are giant stars with effective temperatures comparable to those of M giants, but with ZrO bands in addition to TiO bands characterizing M giant spectra. In the past, several attempts to link phenomenological spectral classification criteria to physical parameters (T_{eff}, gravity, C/O, [s/Fe], [Fe/H]) [1, 2, 3, 4] 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 [5]. Piccirillo 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] variations.

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2. S stars in the GAIA context

S stars are often believed to be transition objects with C/O = 1. This is not true, because to form their characteristic ZrO bands, enough free oxygen must be available and the C/O ratio has to be lower than unity. Anticipating results found in Sect. 7, the C/O ratio of S stars in fact spans the complete range 0.5 < \( \frac{C}{O} \) < 1. Some rough statistics can then be performed and indicates that S stars are not numerically negligible. Stellar evolution timescales extracted from the STAREVOL code (L. Siess, personal comm.), tagging as S stars all stars with 0.5 < \( \frac{C}{O} \) < 1, combined with the initial mass function of [6], show that the number ratio of carbon stars over S stars is around C/S \( \approx 2 \).

As an alternative estimate, different galactic catalogs have been examined (GCGCS [7], GCSS2 [8]). Imposing various cuts on the \( V \) magnitude in the interval [8..10] leads to the same proportion C/S \( \approx 2.2 \), independently of the adopted magnitude cut.

Given this non-negligible proportion, it is important to properly identify and characterize S stars, otherwise important stellar properties, like the third dredge-up luminosity, might be biased, since roughly 50% of S stars are extrinsic and, as such, do not populate the thermally-pulsing AGB.

3. Model atmosphere grid

A large grid of S-star model atmospheres, superseding the one presented in [9], has been computed. More than 3500 converged MARCS model atmospheres were calculated, covering the following parameter space: 2700 \( \leq T_{\text{eff}} \) (K) \( \leq 4000 \) (steps of 100 K); C/O = 0.5, 0.75, 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. A stellar mass of \( M = 1 \) M\(_{\odot} \) was adopted for all models. Consistently with [10], \( \alpha \)-elements were assumed to follow the relation \( \alpha/\text{Fe} = -0.4 \times [\text{Fe/H}] \). 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 \( g \) \( \leq 2 \).

The model structure has been described elsewhere [11, 12]. C/O has a major influence on the thermal structure, whereas the [s/Fe] ratio has less importance. In summary, the \( T - T_{\text{Ross}} \) 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, because the important \( \text{H}_2\text{O} \) and TiO opacities decrease, making the atmospheres much more transparent.

4. Comparison with observed photometry

The agreement between synthetic spectra and observational material collected on the large Henize sample of S stars [13] is now examined. From these data, the \((V-K)_0\), \((J-K)_0\) color-color diagram, dereddened according to [14], has been constructed (Fig. 1).

The \((V-K)_0\), \((J-K)_0\) color-color diagram reveals that, for a given \( V - K \), the range in effective temperature 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 the effective temperature of up to 400 K.

5. Comparison with low-resolution spectroscopic data

Similarly, a set of TiO and ZrO band-strength indices have been computed from the low-resolution spectra, and displayed on Fig. 2. Here again, the indices measured from observations are well reproduced by the indices computed on synthetic spectra.
Figure 1. Left-hand panel: Comparison between color indices of observed M (square symbols), S (triangle symbols) and C (cross symbols) stars, and color indices computed on synthetic spectra of S stars for log $g=0$, [s/Fe] = 0. Right-hand panel: Same for [s/Fe] = 2.

Figure 2. Left-hand panel: ZrO index versus TiO index for [s/Fe]=0. The grid corresponds to solar-metallicity, log $g=0$. models ranging from $T_{\text{eff}}=4000$ K, C/O=0.5 (around coordinates 0.05, 0.05) to $T_{\text{eff}}=2700$ K, 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. Right-hand panel: Same for [s/Fe] =1.

6. Comparison with high-resolution spectra
The comparison of photometric colors and spectroscopic indices with the model values makes it possible to estimate $T_{\text{eff}}$, C/O and [s/Fe] since: (i) the $(V-K)_0$, $(J-K)_0$ color-color diagram
Figure 3. Abundances derived from high-resolution HERMES spectra for 4 Henize S stars (bullet symbols) compared to the Fe and Zr abundances derived from low-resolution spectra (square symbols). The abundances connected by a straight line ‘bullet’ correspond to a standard s-process scaled to the star metallicity. For the sake of clarity, elements are labelled in the third panel.

Disentangles $T_{\text{eff}}$ and C/O; (ii) 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 assignment of a ‘best model atmosphere’ to each observed star is made on the basis of $\chi$-square minimization between the set of photometric and spectroscopic indices computed on the synthetic and observed data. This assignment has been checked on an individual basis to ensure that the derived parameters were meaningful, e.g., were leading to giants with plausible effective temperatures and surface gravities.

For four stars, high-resolution HERMES [15] spectra were available in addition to low-resolution data. The metallicity and zirconium abundance were derived from the HERMES spectra through spectrum synthesis using the best-fitting model atmosphere, and compared to low-resolution estimates. As shown on Fig. 3, the agreement is very satisfactory. The abundances of other s-process elements (e.g. Ba, La) have been also derived through spectral synthesis and are plotted together with their ‘scaled-solar’ estimates. An agreement is, however, not required since there is no reason for the s-process to be ‘scaled-solar’. In particular, the s-process is known to be very sensitive to metallicity: the overall overabundance level, as well as the ratio of heavy-s elements (Ba, La, Ce) to light-s elements (Sr, Y, Zr), are very metallicity-dependent.
7. The effective temperatures and C/O ratios of S stars

Temperature histograms, according to various C/O bins, are presented in Fig. 4. Not all Henize S stars have been analyzed yet, so the subsample of analyzed stars is certainly biased towards hotter and less photometrically variable stars, because the observations are more extensive for those. Hence an effective temperature of 3100 K cannot be considered as a lower temperature limit for S stars, whereas 3900 K probably represents a fair upper limit estimate.

The decrease of effective temperature with increasing C/O ratio, as expected from stellar evolution, is clearly observed. The temperature difference between Tc-poor (polluted binary) S stars and the cooler Tc-rich (genuine thermally-pulsing AGB) S stars is also clearly demonstrated.

This new grid of model atmospheres is an unavoidable prerequisite to reliable spectroscopic chemical analysis 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 [16].

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