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Low-resolution spectral indices to derive M-dwarf abundances using wide binary systems

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Abstract

M-type dwarf stars play an important role in contemporary stellar astrophysics, influencing diverse areas such as the Galactic chemical evolution and the characterisation of exoplanetary systems. Despite their significance, the determination of the chemical composition of these stars remains challenging due to the complex nature of their spectra, rich in prominent molecular features compared to solar-type stars. Our research aims to investigate the metallicity and elemental abundances of M dwarfs using 192 wide physical multiple systems composed of an F-, G-, or K primary star paired with an M-dwarf companion. We characterised the FGK primaries using HERMES high-resolution spectra, deriving abundances for 15 chemical elements. Assuming a common chemical composition within the components of the binary systems, we developed a novel methodology to infer calibrations for estimating the abundances of M dwarfs from CAFOS low-resolution spectral indices. By employing projection predictive feature selection and Bayesian inference, these calibrations demonstrate robust predictive performance, yielding abundance estimates with a scatter ranging from 0.09 to 0.15 dex. Finally, we applied these calibrations to derive abundances for more than 770 M dwarfs observed with CAFOS, producing reliable results consistent with photometric estimations of metallicity and observational Galactic trends.

1 Introduction

M-type dwarf stars, which are cool and low-mass, dominate the Milky Way's stellar population and are ideal for exoplanet searches. However, accurately modeling their spectra is challenging due to their complexity and strong molecular features. A common solution is to study physical binary systems where the primary star is of F, G, or K type, and the companion is an M dwarf [4, 5, 9, 11, among others]. Since these binaries are thought to form from the same molecular cloud simultaneously, both stars share the same age and chemical composition.

The low brightness of M dwarfs makes it difficult to obtain high-resolution spectra with good signal-to-noise ratios, requiring large telescopes and long integration times. However, low-resolution spectra can be obtained more efficiently using various spectrographs, like the Calar Alto Faint Object Spectrograph (CAFOS[1]), which provides a wavelength coverage between 4200 and 8300 Å with a resolution of ~1500.

[5] compiled a sample of 192 wide physically-bound systems and determined stellar atmospheric parameters ($T_{\rm eff}$, $\log g$, ξ, and chemical abundances for 13 elements) for the primaries using the equivalent width method [10, StePar code] and high-resolution HERMES spectra [8] from the 1.2m Mercator Telescope at the Observatorio del Roque de los Muchachos (La Palma, Spain). [3] extended the analysis, deriving C and O abundances and updating Sc, V, Mn, and Co abundances, accounting for hyperfine structure and non-LTE effects. The present work aims to calibrate the abundances of these 15 elements for the M-dwarf companions using spectral indices from CAFOS low-resolution spectra.

2 Methodology

[1] compiled 31 low-resolution spectral indices from the literature for M-dwarf spectral classification. We also added seven metal-sensitive features identified by [6] within the CAFOS spectral range. Our goal is to predict the abundances of the M-dwarf secondaries using these spectral indices and features.

We developed a novel methodology to infer calibrations for estimating the 15 abundances (C, O, Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni) of M dwarfs based on the approach proposed by [7] to find a minimal subset of predictors (spectral indices) that reproduce the given abundances. To do this, we used a Gaussian linear regression model with sparsifying priors on the regression coefficients.

Since the spectral indices and features also depend on the star's effective temperature (or mass), some may be more useful for certain spectral types. Therefore, we divided the sample into two groups: an early-type subsample, down to M2.0, and a late-type subsample, including M2.5 and cooler stars, as in [6].

3 Results

By employing our methodology, we obtained calibrations that demonstrate robust predictive performance, yielding abundance estimates with scatters ranging from 0.09 to 0.15 dex, as can be seen in Fig. 1. The accuracy of these estimates varies depending on the specific chemical element, with some abundances not being well-reproduced by our set of spectral indices. Additionally, we observed a general overestimation of abundances for metal-poor stars, likely

[1] `http://www.caha.es/es/telescope-2-2m-2/cafos`

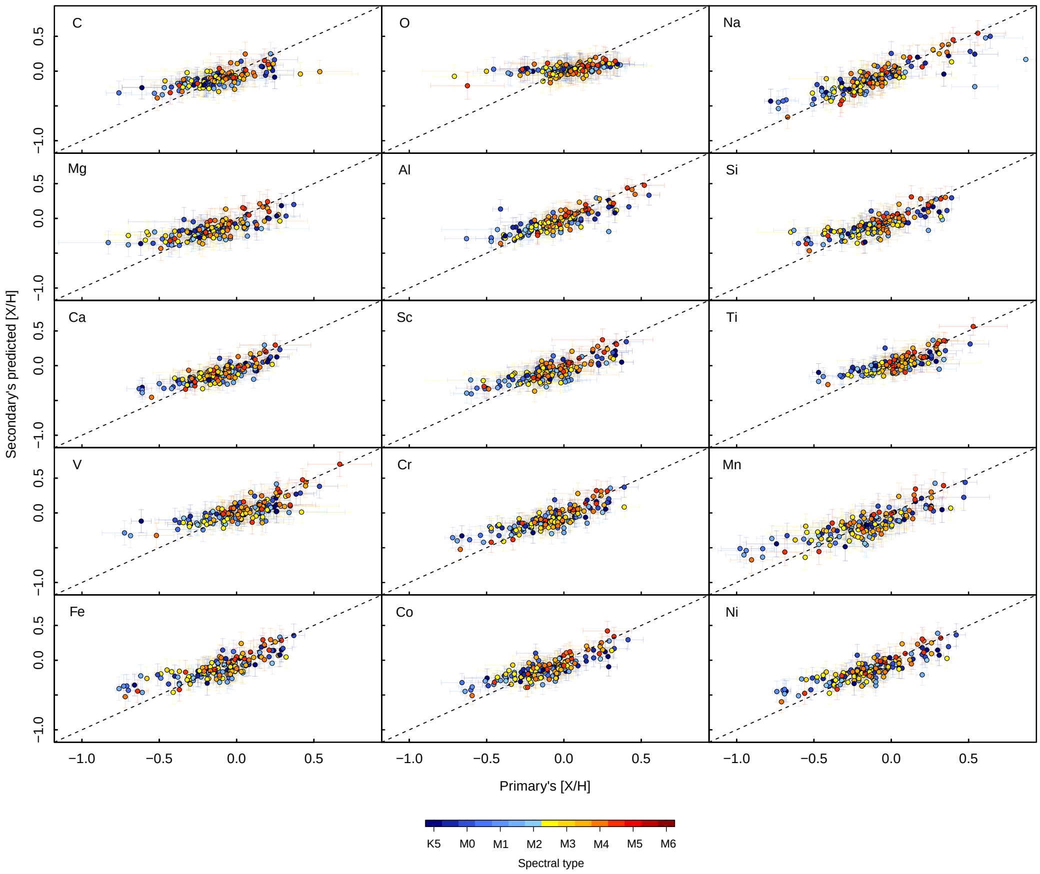

Figure 1: Predicted abundances for the M-dwarf companions versus the primaries' abundances. The stars are color-coded by spectral type.

due to the limited number of datapoints in the low-metallicity regime, which constrains the reliability of our calibrations in this range.

We applied these calibrations to derive abundances for more than 770 M dwarfs observed with CAFOS. The results are consistent with photometric estimations of the metallicity down to the 0.13 dex level (see Fig. 2) and reproduce the Galactic trends observed for FGK stars (see Fig. 3).

4 Conclusions

This study reaffirms the value of binary systems with FGK primary stars and M-dwarf companions as crucial benchmarks for improving our understanding of M dwarfs. Given that both stars in these systems share the same age and chemical composition, they provide a unique opportunity to calibrate M-dwarf properties more accurately. Our analysis further highlights the reliability of using these systems to refine atmospheric models for cool, low-mass stars.

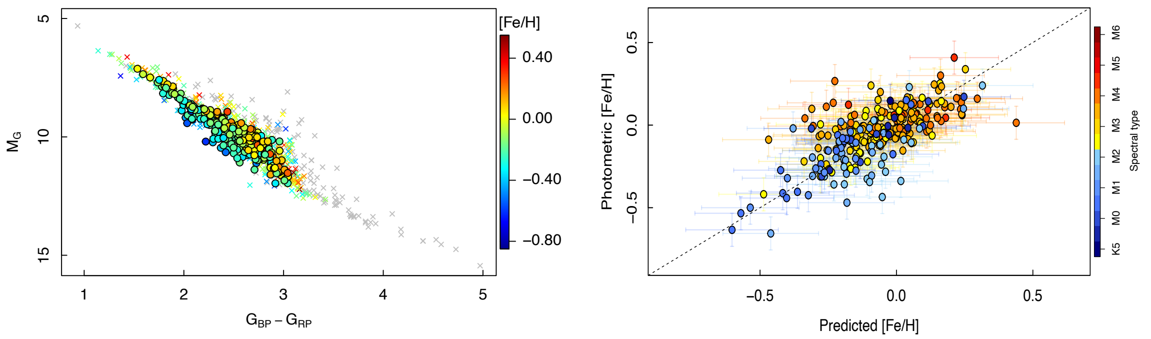

Figure 2: Left panel: Color-magnitude diagram of the CAFOS sample, color-coded by the predicted [Fe/H] using the low-resolution indices. Stars outside the range of application are represented in gray. Right panel: Comparison between our predicted [Fe/H] using the CAFOS low-resolution indices and the photometric [Fe/H] using the relations by [2], color-coded by spectral types.

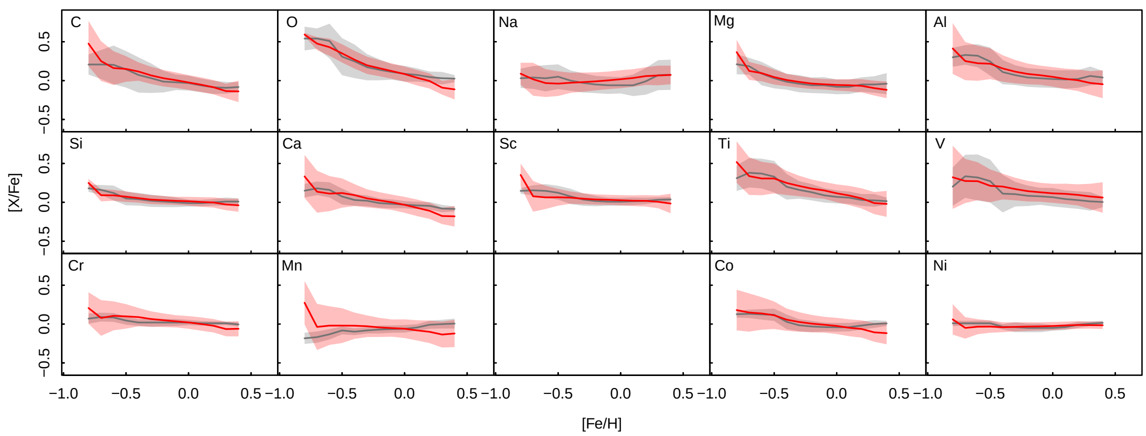

Figure 3: Mean and standard deviation of the [X/Fe] versus [Fe/H] trends for the FGK (grey) and M dwarfs (red).

We demonstrated that low-resolution spectra, when carefully analyzed, can yield valuable insights into the chemical abundances of M dwarfs. Despite the inherent challenges posed by the complex molecular features in M-dwarf spectra, the spectral indices and metal-sensitive features analyzed in this study show that low-resolution data can still be used effectively for abundance determination. This opens the door for more extensive and efficient surveys of M-dwarf populations.

Additionally, this work also underscores the necessity of exploring advanced, data-driven methodologies to fully exploit the available data. Machine learning and other statistical approaches could help address the limitations of current methods and improve the precision of abundance estimates. By combining these innovative techniques with our existing framework, we can enhance the analysis of M dwarfs and push the boundaries of stellar characterization.

Acknowledgments

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