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True solar analogues in the open cluster M67

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Abstract. The solar analogues are fundamental targets for a better understanding of our Sun and Solar System. Notwithstanding the efforts, this research is usually limited to field stars. The open cluster M67 offers a unique opportunity to search for solar analogues because its chemical composition and age are very similar to those of our star. In this work, we analyze FLAMES@VLT spectra of about one hundred of M67 main sequence stars with the aim to identify solar analogues. We first determine cluster members which are likely not binaries, by combining both proper motions and radial velocity measurements. Then, we concentrate our analysis on the determination of stellar effective temperature, using the analyzes of line-depth ratios and Hα wings. Finally, we also compute lithium abundance for all the stars. Thanks to our analysis, we find ten solar analogues, which allow us to derive a solar color $(B-V) = 0.649 \pm 0.016$ and a cluster distance modulus of 9.63 ± 0.08, very close to values found by previous authors. Among them, five are the best solar twins with temperature determinations within 60 K from the solar values. Our results lead us to do further spectroscopic investigations because the solar analogues candidates are suitable for planet search.

Key words. Stars: fundamental parameters – Open clusters and associations: individual: M67 – Stars: late-type

1. Introduction

The search for exo-planets has been mostly developed around field stars. Such stars present several advantages, for instance a wide range of stellar characteristics (mass, age, effective temperature, chemical composition, etc.), which allows us to study the dependence of planet formation on stellar parameters.

Another line of research is the specificity of our Sun and the opportunity to find solar stars hosting exo-planets. This search is best performed in open clusters, which, showing homogeneous age and chemical composition, common birth and early dynamical environment (Randich et al. 2005), provide us an excellent laboratory for investigating the physics of planetary system formation. The old open cluster M67 is to this purpose a perfect target,

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having many solar-type stars and showing an age encompassing that of the Sun (3.5 − 4.8 Gyrs; Yadav et al. 2008), a solar metallicity ([Fe/H]=0.03 ± 0.02, Randich et al. 2006) and lithium depleted G stars (Pasquini et al. 1997).

The present paper is the culmination of a work, which involved the chemical determination of this cluster (Randich et al. 2006), photometry and astrometry (Yadav et al. 2008) to obtain membership, and FLAMES/GIRAFFE high resolution spectroscopy to clean this sample from binaries, and to look for the best solar analogues using the line-depth ratios method and the wings of the Hα line to determine accurate temperatures with respect to the Sun (Pasquini et al. 2008).

2. Observations

We observed M67 for 2.5 hours during three nights in February 2007 with the multi-object FLAMES/GIRAFFE spectrograph at the UT2/Kueyen ESO-VLT in Paranal (Chile). We chose the HR15N MEDUSA mode, which allows us to cover the spectral range 6470-6790 Å and, consequently, to cover the Hα and the lithium lines. With this configuration, the resolution of 17 000 gives us the possibility to obtain for almost 100 stars good radial velocities and to perform effective temperature and lithium abundance measurements.

We have chosen from the catalogue of Yadav et al. (2008) bright stars ($13^{\rm m}_{.}0 < V < 15^{\rm m}_{.}0$) with $(B-V)$ in the solar neighbor (0.60 − 0.75) which shown the best combination of proper motions measurements ($\mu_\alpha \cos\delta$, μ_δ) and proper-motion membership probability (P_μ) allowing us to observe at a time almost 100 stars to be observed with FLAMES/GIRAFFE (Pasquini et al. 2008).

3. Results

3.1. Radial velocity

From the radial velocity variations of the 90 stars observed in three nights with FLAMES/GIRAFFE, we find that 59 of them are probable single cluster members with an average radial velocity $< V_{\rm rad} >= 32.9$ km s^{-1} and a σ=0.73 km s^{-1} (Pasquini et al. 2008).

3.2. Lithium abundance

Since the lithium element is likely a 'thermometer' of the complex interaction taking place in the past between the stellar external layers and the hotter interior, we have computed the equivalent width of the lithium line at λ=6707.8 Å. One of the important points characterizing M67 is that we find many main sequence stars sharing the same lithium abundance of the Sun, indicating a similar mixing history. Moreover, for the first time, we see the Li extra-depletion appears in stars cooler than 6000 K (Pasquini et al. 2008).

3.3. Effective temperature

Thanks to synthetic spectra computed in the temperature range between 5400 − 6300 K, we have analyzed, in the spectral region covered by FLAMES/GIRAFFE, which lines were sensitive to temperature. At the end, we have selected six couples of them and applied a method based on line-depth ratios (LDRs) to derive the effective temperature of the probable members (Gray & Johanson 1991; Catalano et al. 2002; Biazzo et al. 2007a,b). Thus, we have developed appropriate LDR−$T_{\rm eff}$ calibrations on synthetic spectra and derived the effective temperature of the probable members. Fig. 1 shows the temperature difference $\Delta T^{\rm LDR}$ between the FLAMES/GIRAFFE targets and the Sun obtained from LDR method as a function of the de-reddened $(B-V)$ color.

Since the wings of the Hα line profile are very sensitive to temperature, we have also studied the behavior of this diagnostics. According to Cayrel et al. (1985), the effective temperature of a star can be derived from the strength of its Hα wings measured between 3 and 5 Å from the Hα line-center, as compared to synthetic spectra Hα line-wings in the same wavelength interval. Figure 1 shows the relationship between the temperature difference $\Delta T^{\rm H\alpha}$ of the FLAMES/GIRAFFE targets and the Sun as obtained from the Hα wings, and the de-reddened $(B-V)$ color.

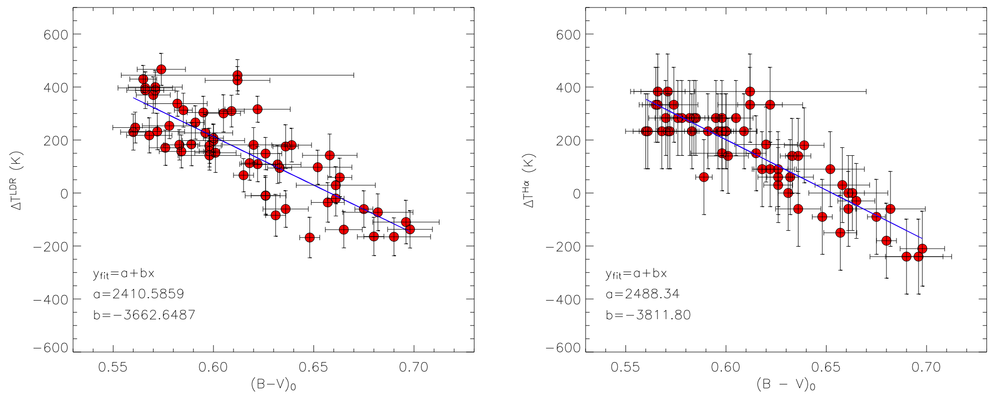

Fig. 1. *Left panel:* Results of the analysis of six line pairs and the three observing runs. *Right panel:* Results of the analysis of Hα wings on the summed GIRAFFE spectra. The two graphs represent the difference in temperature between the stars and the Sun, as a function of the de-reddened $(B-V)$.

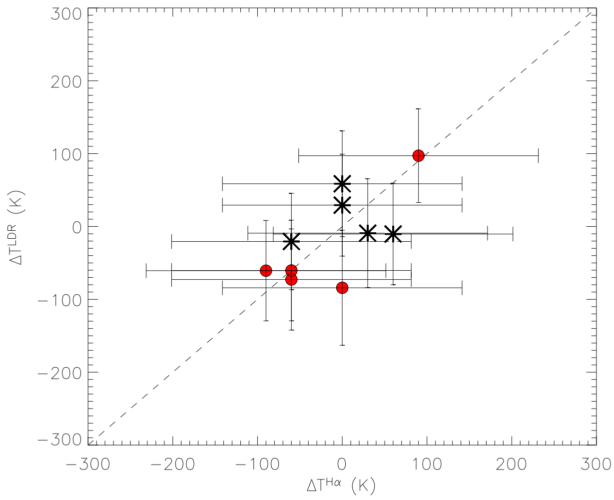

Fig. 2. Difference in temperature between the 10 best solar analogues and the Sun. The ordinate is referred to the temperature derived thanks to the LDR technique, while the abscissa is referred to the temperature derived thanks to the method based on the Hα wings. The asterisks represent the positions of the five best solar twins (Pasquini et al. 2008).

4. Solar analogues

Comparing the $\Delta T^{\rm LDR}$ and the $\Delta T^{\rm H\alpha}$ and taking into account our lithium abundance determination, we find ten solar analogues. In particular, five stars are the closest to the Sun, with effective temperature derived with both methods within 60 K from the solar one (Fig. 2).

Figure 3 shows a zoom of the M67 color-magnitude diagram centered on the all sample observed. The 59 single members and the 5 best solar twins are marked with different colors (Pasquini et al. 2008).

Moreover, through a inversion technique, our solar analogues allowed us to obtain a pre-

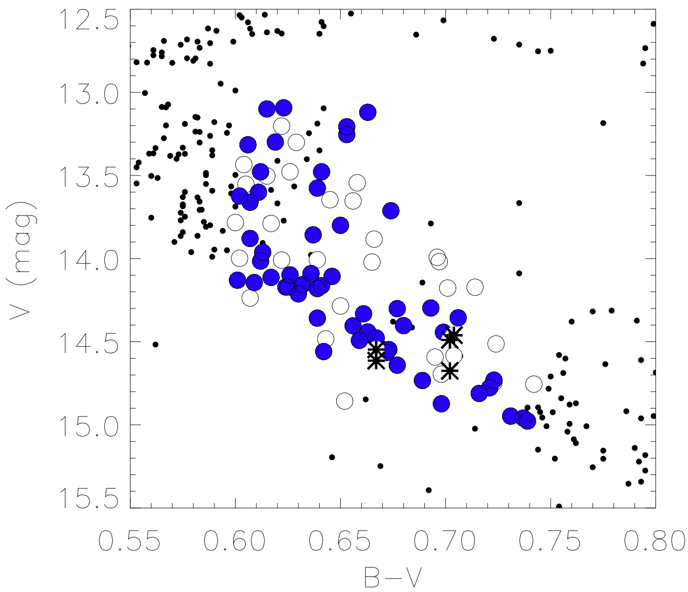

Fig. 3. Zoom of the M67 color-magnitude diagram, centered on the 90 targets observed. With empty circles the 59 retained single member candidates, while with filled circles the stars discarded are shown (figure taken from Pasquini et al. (2008). The 5 best solar twins are marked with asterisks.

cise estimate of the solar $(B - V)$ and accurate cluster distance modulus. Our final results are $(B - V)_{\odot} = 0.649 \pm 0.016$ and $V - M_{\rm V} = 9.63 \pm 0.08$, which are in excellent agreement with the most recent determinations.

Our method has proved to be suitable for the determination of both the solar color and the cluster distance modulus. It could therefore be applied for the same purpose to other open clusters.

5. Conclusions

By using spectroscopic observations performed with FLAMES/GIRAFFE at the VLT, we have found the best solar twins in M67 thanks to accurate determinations of radial velocity, lithium abundance, and effective temperature.

Thanks to our promising results, we plan to apply our method to other open clusters younger and older than the Sun in order to get informations about "progenitors" and "descendants" of our unique star.

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