Solar analogues in open clusters: The case of M67

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Abstract. Solar analogues are fundamental targets for a better understanding of our Sun and our Solar System. Usually, this research is limited to field stars, which offer several advantages and limitations. In this work, we present the results of a research of solar twins performed for the first time in a open cluster, namely M67. Our analysis allowed us to find five solar twins and also to derive a solar colour of (B − V)⊙ = 0.649 ± 0.016 and a cluster distance modulus of 9.63 ± 0.08. This study encourages us to apply the same method to other open clusters, and to do further investigations for planet search in the solar twins we find.

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INTRODUCTION

The search for solar analogues and for exo-planets has been mostly focused 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. However, any astrophysical parameters cannot be constrained a priori in field stars. This was the fundamental reason leading us to begin for the first time in a open cluster the research for solar analogues. In fact, they show homogeneous age and chemical composition, common birth and early dynamical environment ([8]), providing us an excellent laboratory for investigating the physics of planetary system formation. The old open cluster M67 is to this purpose a perfect target, having many solar-type stars and showing an age encompassing that of the Sun (3.5 − 4.8 Gyrs; [11]), a solar metallicity ([Fe/H]=0.03 ± 0.02, [9]) and lithium depleted G stars ([6]).

The present paper is the culmination of a work involving the chemical determination of M67 ([9]), photometry and astrometry ([11]) 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 for deriving accurate effective temperatures with respect to the Sun (ΔΤLDR and ΔΤHα; [7]).
SAMPLE SELECTION AND OBSERVATIONS

We acquired spectra of 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, catching the Hα and the lithium lines in one shot. With this configuration, the resolution of 17 000 gives us the possibility to obtain for almost 100 stars good radial velocities and to determine effective temperature and lithium abundance. We have chosen from the catalogue of [11] bright stars ($V = 13.0 − 15.0$ mag) with $(B − V)$ close to that of the Sun (0.60 − 0.75) and showing the best combination of proper motions measurements ($\mu_\alpha \cos \delta$, $\mu_\delta$) and proper-motion membership probability ($P_\mu$) allowed us to observe at a time almost 100 stars ([7]).

RESULTS

Radial Velocity

From the radial velocity variations of our stars observed during our run, we find that 59 of them are probable single cluster members with an average radial velocity $< V_{rad} > = 32.9 \pm 0.73$ km s$^{-1}$ (Fig. 1; [7]).

![Figure 1](image1.png)

**FIGURE 1.** M67 colour-magnitude diagram ([11]). In blue the 59 retained single member candidates, while in red the stars discarded are shown.

Effective Temperature

*Line-depth ratios*

In the spectral range covered by FLAMES/GIRAFFE, we have selected six line pairs sensitive to effective temperature and applied a method based on line-depth ratios...
Thus, we have developed appropriate LDR–$T_{\text{eff}}$ calibrations on synthetic spectra computed in the $T_{\text{eff}}$ range 5400–6300 K and derived the effective temperature of our probable single members.

**H$\alpha$ wings**

Since the wings of the H$\alpha$ line profile are very sensitive to temperature, we have also studied the behavior of this diagnostics. According to [4], the effective temperature of a star can be derived from the strength of its H$\alpha$ wings measured between 3 and 5 Å from the H$\alpha$ line-center, as compared to synthetic spectra H$\alpha$ line-wings in the same wavelength interval. In Fig. 2 we compare the results we obtain with the LDR and H$\alpha$-wing methods.

![FIGURE 2. $\Delta T_{\text{LDR}}$ versus $\Delta T_{\text{H}\alpha}$ for the probable single members. In blue the ten solar analogues are displayed.](image)

**Lithium Abundance**

Lithium is an element easily destroyed in the stellar interiors. It is important for understanding the complex interactions taking place in the past between the stellar external layers and the hotter interior. We have derived its abundance finding that many main sequence stars share the same lithium abundance of the Sun, indicating a similar mixing history. Furthermore, for the first time, we see the Li extra-depletion appears in stars cooler than 6000 K ([7]).
SOLAR ANALOGUES

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

$B - V$ solar colour

Taking into account a reddening towards M67 of $E(B - V) = 0.041 \pm 0.004$ ([10]), we have obtained a solar $(B - V)$ of 0.649 ± 0.016, which is in the middle between the old determinations (around 0.66–0.67) and the recent estimations (around 0.62–0.64).

Cluster distance modulus

At the same way we computed the solar $(B - V)$, we have derived the cluster distance. A value of $9.63 \pm 0.08$ was found, in excellent agreement with the most recent determinations ([7]).

CONCLUSIONS

By using spectroscopic observations performed with FLAMES/GIRAFFE, we have found the best solar twins in M67, solar colour, and cluster distance modulus. Thanks to our promising results, we plan from one side to observe our single candidates at very high resolution for exo-planet research and from the other side to apply our method to other open clusters younger and older than the Sun in order to study the “Sun in time”.

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