Solar twins in M67: Evolutionary status and lithium abundance

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ABSTRACT

Aims. We determine the age and mass of the three best solar twin candidates in open cluster M67 through lithium evolutionary models.

Methods. We computed a grid of evolutionary models with non-standard mixing at metallicity \([Fe/H] = 0.01\) with the Toulouse-Geneva evolution code for a range of stellar masses. We estimated the mass and age of 10 solar analogs belonging to the open cluster M67. We made a detailed study of the three solar twins of the sample, YPB637, YPB1194, and YPB1787.

Results. We obtained a very accurate estimation of the mass of our solar analogs in M67 by interpolating in the grid of evolutionary models. The three solar twins allowed us to estimate the age of the open cluster, which is \(3.87^{+0.05}_{-0.06}\) Gyr, which is better constrained than former estimates. Conclusions. Our results show that the 3 solar twin candidates have one solar mass within the errors and that M67 has a solar age within the errors, validating its use as a solar proxy. M67 is an important cluster when searching for solar twins.

Key words. Stars: fundamental parameters – Stars: abundances – Stars: evolution – Stars: interiors – Stars: solar-type

1. Introduction

Lithium depletion of each star depends on the evolution of its rotational history and the changes in the convective envelope due to internal mixing. In main-sequence solar-like stars, lithium is easily destroyed by nuclear burning in stellar interiors at temperatures above \(2.4 \times 10^6\) K, and its surface abundance indicates the depth of mixing below their photospheres. The Sun has long been thought to be highly Li-poor by a factor of 10 compared to the other field G stars (Lambert & Reddy 2004). However, two of the best solar twins found by Meléndez & Ramírez (2007) (namely, HIP 56948 and HIP 73815) are Li-poor. The amount of Li depletion in solar twins is sensitive to microscopic diffusion, and an extra-mixing process is required to explain the low Li abundances observed, indicating that they also share a similar mixing history with the Sun.

M67 is one of the most studied open clusters. Its chemical composition, metallicity and age are similar to those of the Sun. Various chemical analyses (Tautvaisiene et al. 2000, Randich et al. 2006, Pace et al. 2008) show that not only abundances of Fe, but also element abundances of O, Na, Mg, Al, Si, Ca, Ti, Cr, and Ni, are very similar to their solar counterparts, as close as allowed by the precision of the measurements. The ages determined are similar to those of the Sun, between 3.5 and 4.8 Gyr (Yadav et al. 2008). Another interesting aspect of open cluster M67 is its Li-depleted G stars. Lithium abundance study is a crucial point for understanding the physics involved in stellar interiors. Pasquini et al. (1997) show there is a large spread in Li abundances among solar-type stars in M67. Almost 40% of their sample shows Li depletion comparable to that of the Sun. In this context, M67 is a perfect target to search for solar analogs and solar twins. Indeed, many stars are similar to the Sun in terms of effective temperature and chemical composition, but their Li abundance is much higher than in our star. Furthermore, among the 90 MS stars studied by Pasquini et al. (2003) in M67, 10 had similar effective temperature and Li content as low as that of the Sun, making them excellent solar twin candidates.

In do Nascimento et al. (2009), we showed that it is possible to precisely determine the mass of solar twins using evolutionary models. We determined the mass and the age of 5 solar twins taken from two sources: Meléndez & Ramírez (2007) and Takeda et al. (2007). We began to compute a solar model, helioseismically calibrated, to reproduce not only solar luminosity and radius, but also Li depletion. To that end, we introduced mixing due to meridional circulation with a feedback effect from the \(\mu\)-currents (Zahn 1992, Vauclair & Théado 2003, Théado & Vauclair 2003). This calibration was used to compute models of different masses whose tracks in a \(T_{\text{eff}} - \log N(\text{Li})\) diagram passed through the observational point. In the range of effective temperatures studied (typically 5400-6000 K), Li...
destruction is very sensitive to mass, and we were able to precisely determine the mass of each solar twin and its age. In the present work, we computed helioseismically calibrated, evolutionary, solar-like models with microscopic diffusion and rotation-induced mixing in the radiative interior, as in do Nascimento et al. (2009). We estimate the masses of the 10 solar analogs in M67 found by Pasquini et al. (2008). We estimate the age of the three most probable solar twins of the sample. The working sample is described in Sect. 2. Improved Li abundances, using spectral synthesis instead of calibration based on equivalent width (EW, hereafter), are presented in Sect. 3. In Sect. 4, we describe the grid of evolutionary models with the non-standard physics that we computed. In Sect. 5, we present our results and compare our estimation of the age of M67 with earlier estimate. In this section we also show that the constitutive physics of the models influence and alter the isochrones constructed. We present the M67 color-magnitude diagram constrained by main sequence solar twins. Finally, our conclusions are outlined in Sect. 6.

2. Sample of solar analogs in M67

Pasquini et al. (2008) observed 90 targets belonging to cluster M67 with the multi-object FLAMES/GIRAFFE spectrograph (see Sect. 3). They computed the effective stellar temperatures of these stars using two spectroscopic methods: the line-depth ratios (LDR) and the Hα wings. They derived Li abundances from measured EW using the calibration of Soderblom et al. (1993). The authors highlight 10 stars in their sample, for which both $T_{\text{eff, LDR}}$ and $T_{\text{eff, Hα}}$ are within 100 K of the solar values and which have a strong Li depletion. These stars are good solar twin candidates. However, as observed by the authors, given the limited resolution (R~17000) and S/N (80-110/pixel in average), the errors in Li abundance determination are high and the stars with upper limits may have a Li abundance comparable to the solar value, or even higher.

For our study, we used the effective temperature determined by the LDR method, which is believed to be more precise (Pasquini et al. 2008). For cluster M67 we adopted a metallicity of $[Fe/H] = 0.01 \pm 0.03$ (Randich et al. 2006) and an age of $4.0 \pm 0.5$ Gyr (Dinescu et al. 1995). Pasquini et al. (2008) give a distance modulus for the cluster of $(m - M)_0 = 9.63 \pm 0.06_{\text{stat}} \pm 0.05_{\text{sys}}$, which corresponds to a distance $d = 843^{+44}_{-41}$ pc. Intrinsic absolute magnitudes $M_V$ were derived from this distance, the $V$ magnitude given by Pasquini et al. (2008),...
and a visual extinction $A_V \sim 3.1 + E(B-V) = 0.127$ mag 
(Schultz & Wiemel 1975) with $E(B-V) = 41 \pm 4$ mmag, the 
reddening of M67 (Taylor 2007). We computed relative stellar 
luminosity compared to solar luminosity, using the bolometric 
corrections of Flower (1996) and the associated error from the 
uncertainty in distance.

The atmospheric parameters of all these stars are in excel-
herent agreement with those of the Sun. However, the Li deter-
mination given in Pasquini et al. (2008) could be improved by 
spectral synthesis (see Sect. 5.1). The parameters of the solar 
ance in M67 are summarized in Table 1.

3. Observations and lithium abundance

The spectra were acquired on three observation nights with the 
multi-object FLAMES/GIRAFFE spectrograph at the UT3 
Kueyen ESO-VLT (Pasquini et al. 2002) in MEDUSA model 
as part of a project searching for solar twins in M67 
(Pasquini et al. 2008). The setting used was HR15N, which si-
multaneously covers the H α resonance doublet at 670.8 
nm with a resolution of R=17 000. Three separate exposures 
were obtained to identify short and intermediate period bina-
ries by comparing the radial velocities at different epochs. On 
average, combined spectra had a typical S/N of 80-110/pixel. 
For an extended description of sample selection, observations, 
and data reduction, see Pasquini et al. (2008).

3.1. Lithium abundance

The Li abundance of all M67 twins was derived from the Li$ii$ 
resonance transition at $\lambda 6707$ Å synthetic spectrum fitted to 
the GIRAFFE spectrum for the fundamental atmospheric pa-
rameters. First, we used $T_{\text{eff}}$ spectroscopic determination and 
surface gravity log $g$ = 4.44 dex, metallicity [Fe/H] = 0.0, 
projected surface velocity $v \sin i$ = 2.0 km.s$^{-1}$, microturbu-
ateness velocity $\xi$ = 1.21 km.s$^{-1}$ from Pasquini et al. 
(2008). Atmospheric models were interpolated in the Kurucz grid 
(Kurucz 1993), and the synthetic spectra were computed with 
MOOG (Sneden 1973). The GIRAFFE instrumental broadening 
profile was set at 0.39 Å, which is the FWHM of the 
giraffe spectrum. From the fundamental parameters, we de-
erived log N(Li) = 1.5, log N(Li) < 1.3 and log N(Li) = 1.6 re-
spectively for YPB637, YPB1194, and YPB1787 (Fig. 2 
and Fig. 3), on the usual scale where log N(H) = 12.00.

Given the limited S/N and resolution of the YPB1194 
spectrum, only an upper limit for the Li abundance of this 
star can be determined. The consequences are discussed in 
Sect. 5. These values are higher than the determinations of 
Pasquini et al. (2008), log N(Li) = 1.4 and 1.0, and lower than 
0.6. Our Li abundance in the 10 solar twin candidates dif-
fered somewhat from the estimates obtained by Pasquini et al. 
(2008), because we used spectral synthesis instead of a calibra-
tion based on EWs, which may not be adequate for Li-depleted 
stars. For each star we determined log N(Li) from synthetic 
models on the range of effective temperatures uncertainties. 
The procedure gives us an error of about 0.05 dex for log N(Li) 
due to uncertainty in effective temperature. The errors arising 
from uncertainties surface gravity and microturbulent velocity 
are less than 0.01 dex, so can be ignored. The total error in 
log N(Li) obtained by summing the error in model-fitting pro-
dure (see Bonifacio et al. 2007) and effective temperature un-
certainties in quadrature is equal to 0.10 dex as represented in 
Figs. 2 and 5.

4. Stellar evolutionary models

For the purposes of this study, stellar evolutionary models 
were computed using the Toulouse-Geneva stellar evolu-
tion code TGE (Hui-Bon-Hoa 2003). Details on the physics 
of these models can be found in Richard et al. 
(1994, 2004), do Nascimento et al. (2000), and Hui-Bon-Hoa 
(2008). Standard input physics, non standard processes, 
diffusion, and rotation-induced mixing added in the models 
are described in do Nascimento et al. (2009). The method 
assumes the existence of an expected dependency between 
log N(Li) and the star’s mass and age for solar analogs stars 
e.g. Montalbán & Schatzman 2006, Charbonnel & Talon 
2008, Xiong & Deng 2009, do Nascimento et al. 2009, 
Baumann et al. 2010. This implies that stars with larger 
convective zones on the main sequence and a higher degree 
of differential rotation between the envelope and the radiative 
core present enhanced Li depletion, consequently we should 
know the angular momentum history of each studied star. 
Somehow, for solar twins stars belonging to the same cluster, 
their angular momentum average may be approximated well 
by a mean angular momentum evolution history. In this context, 
our analysis is limited to solar-like stars on the main sequence 
and with a similar angular momentum history.

4.1. Models and calibration

We computed a grid of hundreds of evolutionary models of 
masses in the 0.90 to 1.10 $M_\odot$ range with a step of 0.001 $M_\odot$, 
and with metallicities in the -0.030 to 0.050 range with a step of 
0.010, from the zero-age main sequence (ZAMS) to the end of 
the hydrogen exhaustion in the core. Our evolutionary models 
were calibrated to match the observed solar effective tempera-
ture, luminosity, and Li abundance at the solar age. The calibra-
tion method of models is based on the Richard et al. (1996) 
pre-prescription and is described in do Nascimento et al. (2009). In 
the following, we use models with a metallicity of [Fe/H] = 0.01, 
which is a simple average of different estimates of M67 metal-
licity (see Pasquini et al. 2008).

5. Results and discussion

For each star we use an interpolation program to determine the 
mass. The uncertainties in $T_{\text{eff}}$ give rise to uncertain-
ties in mass determination. The mass is interpolated from an 
HR diagram and from a $T_{\text{eff}}$-log N(Li) diagram. The results for 
each star are presented in Table 2. Determination from the $T_{\text{eff}}$-
log N(Li) diagram is more precise because Li abundance, more
than luminosity, depends on mass (see do Nascimento et al. 2009). All stars of the sample have a mass within the range expected for the mass of a solar twin (±5 % of the solar mass).

In the following, we concentrate our analysis on objects YPB637, YPB1194, and YPB1787, which are the three most probable solar twins of the sample. They have a mass, an effective temperature, and Li abundance very close to the solar values. The temperature errors in the Table 2 are those given in Table A2 of Pasquini et al. (2008), which are about 65K.

For these three stars, we calculated an evolutionary model of the mass determined by interpolation in the $T_{\text{eff}}$-$\log N(\text{Li})$ diagram, and we determined the range of masses limited by the observational error in $T_{\text{eff}}$, which gives a value of $1.005^{+0.005}_{-0.005}$ M$_\odot$ for the object YPB637, and $1.004^{+0.006}_{-0.005}$ M$_\odot$ for the object YPB1787. For the object YPB1194, the determination of the Li abundance as an upper limit implies an upper limit for the mass determination: $1.000^{+0.008}_{-0.008}$ M$_\odot$. In Figure 4 we present the $T_{\text{eff}}$-$\log N(\text{Li})$ diagram for YPB1194 as an example with the evolutionary tracks. The tracks of the evolution of the models pass through the observation point, as expected. The position of the observation point on the track and the tracks limited by the error give us an age of $4.42^{+1.55}_{-1.68}$ Gyr for YPB637 and $3.21^{+1.62}_{-2.31}$ Gyr for YPB1787. For YPB1194, the upper limit of the Li abundance gives a lower limit for the age: $3.87^{+2.03}_{-0.008}$ Gyr. In Figure 5 we present Li destruction in the evolutionary model as a function of the age.

5.1. Age determination of open cluster M67

The usual way to determine the age of an open cluster is to fit a theoretical isochrone with the observed main sequence and turn-off stars in a color-magnitude diagram. The position of the observed points in the diagram depends on the adopted interstellar reddening for the cluster, and the position of the isochrone varies according to metallicity and distance modulus. The “hook” of the turn-off is reproduced by calibrating the overshooting of the convective core. Hobbs & Thorburn (1991) determined an age of $5.2 \pm 1.0$ Gyr from the high-dispersion echelle spectra of five stars located along the main sequence of M67. In Montgomery et al. (1993), the authors present a CCD photometry survey of M67. They derived a reddening $E(B-V) = 0.05 \pm 0.01$ and a metallicity $[Fe/H] = -0.05 \pm 0.03$. From cluster fitting to theoretical isochrones in a color-magnitude diagram, they found an age between 3 and 5 Gyr, but none of the isochrones fit the data consistently. Dinescu et al. (1995) used the sample of Montgomery et al. (1993), cleaned up by cross-identification with the proper motion membership study of Girard et al. (1989). They determined a distance modulus and the age of open cluster M67 by fitting the observed main sequence for single stars to the theoretical evolutionary tracks. They estimate an age of $4.0 \pm 0.5$ Gyr, and found that earlier models with overshoot of at most 0.1 $H_P$ seem to reproduce the observations better. Yadav et al. (2008) find an age between 3.5 and 4.8 Gyr, by comparing their CMD, established from twophase archival observations with the Wide-Field Imager at the 2.2 m MPG/ESO telescope and reduced with new astrometric
techniques, as described in [Anderson et al. 2006], to the following sets of theoretical isochrones: the BaSTI models provided by [Pietrinferni et al. 2004] with $E(B-V) = 0.02$ and $[\text{Fe}/\text{H}] = 0.06$, the Padova models published by [Girardi et al. 2000] with $E(B-V) = 0.02$ and $[\text{Fe}/\text{H}] = 0.00$, the Yonsei-Yale isochrones provided by [Yi et al. 2001] in their second release with $E(B-V) = 0.02$ and $[\text{Fe}/\text{H}] = 0.00$, and the Victoria-Regina models published by [VandenBerg et al. 2006] with $E(B-V) = 0.03$ and $[\text{Fe}/\text{H}] = -0.03$. They confirm that the convective core overshoot in M67 should be small, as pointed out by [Sandquist 2004] and [VandenBerg & Stetson 2004]. VandenBerg et al. (2007) investigated the possibility of using the morphology of the M67 turn-off to put constraints on solar metallicity. Their models and isochrones computed on the assumption of a low-metal mix based on the solar abundances derived by [Asplund et al. 2005], and adopting a metallicity $[\text{Fe}/\text{H}] = 0.00$, a reddening $E(B-V) = 0.038$, and a distance modulus $(m-M)_0 = 9.70$, do not predict the turnoff gap in the CMD. The same analysis using a 3.9 Gyr isochrone assuming the Grevesse & Sauval (1998) mix of heavy metals provides a good match to the morphology of the M67 CMD. [Magic et al. 2010] confirm these results, but found that other physics in the models, e.g. element diffusion, nuclear reactions, prescription of core overshooting, also influence the stellar mass at which convective cores start to develop, and alter this result to the extent that isochrones constructed with models using low CNO solar abundances can also reproduce the turn-off morphology in M67. They find ages between 3.9 and 4.8 Gyr.

For each solar twin, we determined an age from the computed stellar model with mass previously determined. We found three different ages in a narrow range of 1.2 Gyr. The age that best fits the color-magnitude diagram is 3.87 Gyr, the upper limit of the age of YPB1194, the best solar twin candidate (see Sect. 5.2). We used the two other age determinations to determine an error bar. Hence, our estimation for the age of open cluster M67 is $3.87^{+0.55}_{-0.66}$ Gyr, which is in very good agreement with the most recent results (VandenBerg et al. 2007; Yadav et al. 2008; Magic et al. 2010).

5.2. The color-magnitude diagram

Figure 6 presents the color-magnitude diagram of open cluster M67. The isochrones are constructed from computed models of metallicity $[\text{Fe}/\text{H}] = 0.01$ and masses from 0.90 to 1.31 $M_\odot$. The models of mass 1.19 $M_\odot$ and higher are computed with a convective core overshooting parameter $\alpha_{ov} = 0.01 H_P$, whose occurrence is needed to provide a satisfactory match to the observed CMDs (see Kalirai et al. 2001, and references therein).
A very small convective core overshoot is needed to match the features near the main sequence turnoff region, in agreement with Casagrande et al. (2004), VandenBerg & Stetson (2004), and Yadav et al. (2008). We used equation (3) and Table 4 of Yadav et al. (2008). We determined the absolute visual magnitude with Sandquist (2004), VandenBerg & Stetson (2004), and Yadav et al. (2008). Using a distance modulus (m − M)0 = 9.68 and a reddening E(B − V) = 0.02 mag. The value of the distance modulus is in good agreement with former determinations (VandenBerg et al. 2007; Yadav et al. 2008). The reddening is lower than the value obtained by Taylor (2007) but, as pointed out by Yadav et al. (2008), given the intrinsic uncertainties in calibration of E(B − V), the true reddening could be anywhere between 0.02 and 0.04 mag.

6. Conclusions

In this paper, we applied the method developed by do Nascimento et al. (2009) to the solar analogs of open cluster M67 identified by Pasquini et al. (2008), in order to determine their masses as accurately as possible. We identified three objects, YPB637, YPB1194, and YPB1787, whose effective temperature, luminosity, mass, and Li abundance values are very close to the solar ones. For these three solar twins we derived ages of 4.42^{+1.55}_{−1.68} Gyr for YPB637, and 3.21^{+1.62}_{−1.31} Gyr for YPB1787. For YPB1194, the lower limit of the age is 3.87^{+2.03}_{−1.56} Gyr. These estimations allowed us to construct isochrones on a color-magnitude diagram for open cluster M67, using the sample of Yadav et al. (2008). The isochrone 3.87 Gyr matches both the main-sequence and the turn-off regions, using a distance modulus (m − M)0 = 9.68 and a reddening E(B − V) = 0.02 mag. The three solar twins allowed us to estimate the age of the open cluster as 3.87^{+0.56}_{−0.56} Gyr. We thus confirm the importance of M67 as a cluster with a slightly lower age than the solar one, and the mass of the solar twin candidates is also very similar to solar; therefore, M67 is an important cluster when searching for solar twins.

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Table 1. Parameters of the observed solar analogues in M67.

| Object | \(T_{\text{eff}}\) (K) | \((L/L_\odot)\) | \(\log N(\text{Li})\)\text{NLTE} | \(\log N(\text{Li})\)\text{moog} |
|--------|----------------|-----------------|-----------------|-----------------|
| 285    | 5836 ± 67     | 1.11^{+0.106}_{-0.106} | <0.6            | 0.6             |
| 637    | 5806 ± 65     | 1.089^{+0.011}_{-0.010} | 1.4             | 1.5             |
| 1101   | 5756 ± 60     | 0.925^{+0.008}_{-0.008} | <0.6            | <0.6           |
| 1194   | 5766 ± 64     | 0.976^{+0.010}_{-0.010} | <0.6            | <1.3           |
| 1303   | 5716 ± 64     | 0.960^{+0.010}_{-0.010} | <0.6            | 1.2             |
| 1304   | 5704 ± 64     | 0.886^{+0.004}_{-0.004} | <0.5            | <0.8           |
| 1315   | 5874 ± 58     | 1.286^{+0.13}_{-0.13}   | 1.4             | 1.8             |
| 1392   | 5716 ± 63     | 0.821^{+0.008}_{-0.008} | <0.6            | <0.6           |
| 1787   | 5768 ± 70     | 1.03^{+0.011}_{-0.009}  | 1.0             | 1.6             |
| 2018   | 5693 ± 74     | 1.035^{+0.009}_{-0.009} | <0.5            | <1.3           |

1 Note: Cols 1-4 from Pasquini et al. (2008).
* Our determinations of the Li abundances using the MOOG program.

Table 2. Results of mass determination from interpolation in the \(T_{\text{eff}}\)-\(\log N(\text{Li})\) diagram.

| Object | Mass \((M_\odot)\) |
|--------|-----------------|
| 285    | 1.001^{+0.011}_{-0.011} |
| 637    | 1.005^{+0.012}_{-0.012} |
| 1101   | 0.988^{+0.008}_{-0.008} |
| 1194   | 0.999^{+0.007}_{-0.007} |
| 1303   | 0.985^{+0.009}_{-0.009} |
| 1304   | 0.983^{+0.009}_{-0.009} |
| 1315   | 1.018^{+0.012}_{-0.012} |
| 1392   | 0.985^{+0.006}_{-0.006} |
| 1787   | 1.004^{+0.008}_{-0.008} |
| 2018   | 0.982^{+0.006}_{-0.006} |