Age and mass of solar twins constrained by lithium abundance *

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ABSTRACT

Aims. We analyze the non-standard mixing history of the solar twins HIP 55459, HIP 79672, HIP 56948, HIP 73815 and HIP 100963, in order to determine as precisely as possible their mass and age.

Methods. We computed a grid of evolutionary models with non-standard mixing at given metallicities with the Toulouse-Geneva code for a range of stellar masses assuming an error bar of ±50K in T eff. We choose the evolutionary model that best fit the observed low lithium abundances observed in the solar twins.

Results. Our best model for each solar twin provides a mass and age solution constrained by their Li content and T eff determination. HIP 56948 is the best solar twin at the present time and our analysis gives a mass of 0.994 ± 0.004 M ⊙ and an age of 4.71 ± 1.39 Gyr.

Conclusions. Non-standard mixing is required to explain the low Li abundances observed in solar-twins. Li depletion due to the additional mixing in solar-twins is strongly mass dependent. An accurate lithium abundance measurement connected with non-standard models provides a more precise information about the age and mass better than that determined only by classical methods.

Key words. Stars: fundamental parameters – Stars: abundances – Stars: evolution – Stars: interiors

1. Introduction

Lithium is easily destroyed by nuclear burning in stellar interiors at temperatures above 2.4×10⁶ K and its surface abundance in main-sequence stars indicates the depth of mixing below their photospheres. As in the Sun, the amount of Li depletion in solar-twins is sensitive to microscopic diffusion, and some extra-mixing process is required to explain the low observed Li abundances, indicating that they also share with the Sun a similar mixing history. Standard solar models predict that the Sun has a convective envelope whose mass is only 2% of the total mass and where the base temperatures are generally too low to destroy lithium. The solar Li problem is the long-standing conflict between the observed photospheric Li depletion of the Sun by 2.21 dex (Grevesse & Sauval 1998) and the low theoretically predicted depletion of stellar evolution models based only on the standard mixing-length prescription.

Over the last few years many discoveries have been made that have changed our understanding of our central G2 type star. Until a few years ago, the Sun was thought to be lithium-poor by a factor of 10 compared to similar one-solar-mass solar type disk stars (Lambert & Reddy 2004), a fact that has led to the suggestion that the Sun is peculiar in its Li abundance and therefore of dubious value for calibrating non-standard models of Li depletion. However, current studies have shown that the Sun seems to be typical when compared to solar twins instead of merely solar type stars, and that solar twins also have low Li abundances (Meléndez & Ramírez 2007, Pasquini et al. 2008).

The history of internal mixing and Li depletion of each star is probably dependent of the evolution of its rotational history and the changes in the convective envelope over time. These parameters are mass and metallicity dependent, and eventual differences in them, from birth, may exist between very similar stars and yet be too small to be measured observationally with conventional techniques. Therefore, the detailed internal modelling of solar twins stars, already established as extremely similar to the Sun in many astrophysical properties, is potentially a powerful tool to boost our comprehension of the complex evolution of the Li abundance in low mass stars.

We know that the Sun is not unique in being a planet host. However, the Sun is still unique in the sense that no other truly solar-like planetary system has been detected to date, although some solar twins, which do not seem to have either hot Jupiters or other giant planets in their habitable zones (e.g. HIP

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All models are available in electronic form at the Vizier database via http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=...
79672 (18 Sco), HIP 56948; Meléndez & Ramírez (2007), are excellent candidates for hosting earthlike planets, and therefore they should be analyzed in detail both from the theoretical and observational point of view. The quest to find stellar analogues to the Sun or real solar twins has been going on for a long time (Cayrel de Strobel 1996, Porto de Mello & da Silva 1997). Recent high resolution, high signal-to-noise results in this field by Meléndez & Ramírez (2007) have shown HIP 56948 to be the best solar twin known to date both in stellar parameters and in chemical composition, including a low lithium abundance. The depletion of Li in field solar-analog G dwarf stars, seems to reveal our limited understanding of the physics acting in the interiors of stars. In order to explain the unexpected main sequence Li depletion of F and early-G type stars, a number of models and extra-mixing processes have been proposed, which include mass loss (Swenson & Faulkner 1992), diffusion (Michaud 1986; Chaboyer et al. 1995), meridional circulation (Charbonnel & Talon 1999 and references therein), angular momentum loss, and rotationally driven mixing (Schatzman & Baglin 1991; Vauclair 1991; Pinsoneault et al. 1992; Deliyannis & Pinsonneault 1997; Charbonnel & do Nascimento 1998), gravity waves (García López & Spruit 1991; Montalban & Schatzmann 2000), tachocline (Brun et al. 1999; Piau et al. 2003), and combinations of these (Charbonnel & Talon 2005; ). In this work, we present evolutionary solar-like models with microscopic diffusion and rotation-induced mixing in the radiative interior. This mixing due to the meridional circulation with a feedback effect of the $\mu$-currents is described in Zahn (1992), Vauclair & Théado (2003) and Théado & Vauclair (2003a). We introduce also macroscopic motions due to the tachocline (Richard et al. 2004), where the shear turbulence mixes up and homogenizes with the convective zone the material transported by the meridional circulation. The diffusion-circulation coupling has allowed to reproduce both sides of the Li-dip (Théado & Vauclair 2003b) and the addition of a tachocline gives very good agreement with helioseismic observations in solar models (Richard et al. 2004). Since Li is likely an indicator of the complex processes taking place in the past between the stellar external layers and the hotter interior, its abundance can be used to identify true solar twins, in the sense that solar twins are expected to share not only the present parameters of the Sun but also the essential aspects of its evolution.

The present working sample is described in §2, where we redetermine the evolutionary status and individual masses of the sample by using the HIPPARCOS parallaxes and by comparing the observational Hertzsprung-Russell diagram with evolutionary tracks. In §3, we describe the evolutionary models with non-standard physics. In §4, we present the lithium abundance main features and we compare the observations with theoretical predictions. Finally the conclusions are outlined in §5.

2. Solar twin sample

Our analysis is based on the three solar twins, HIP 55459, HIP 79672 and HIP 100963, analyzed by Takeda et al. (2007) and the four solar twins, HIP 55459, HIP 79672, HIP 56948 and HIP 73815, studied by Meléndez & Ramírez (2007). Two stars, HIP 55459 and HIP 79672, are present in both samples. Thus, the sample consists of 5 solar twins. Following the same procedure from do Nascimento et al. (2000), we used the new HIPPARCOS trigonometric parallax measurements (van Leeuwen 2007) to locate precisely the objects in the HR diagram. Intrinsic absolute magnitudes $M_V$ were derived from the parallaxes and the $m_V$ magnitudes were given by HIPPARCOS. We computed the stellar luminosity and the associated error from the sigma error on the parallax. The uncertainties in luminosity lower than $\pm 0.1$ had an effect of $\pm 0.03$ in the determination of the masses.

In Takeda et al. (2007), HIP 55459, HIP 79672 and HIP 100963 come from the sample of 118 solar-analogue stars, observed by HIDES (Izumiura 1999) at the coudé focus of the 188 cm reflector of Okayama Astrophysical Observatory (OAO). These three stars are G main-sequence stars, considered as solar twins. However, they present a Li abundance a factor of 3 to 4 higher than solar. Meléndez & Ramírez (2007) presented HIP 55459, HIP 79672, HIP 56948 and HIP 73815, observed with the 2.4m Harlan J. Smith Telescope at McDonald Observatory. HIP 56948 and HIP 73815 are considered by the authors as the best solar twins ever found, due to their Li abundances as low as the solar value. Atmospheric parameters of all these stars are in excellent agreement with the Sun, lower than 1.3% for the $T_{\text{eff}}$ and a few hundredths dex for $\log(L/L_\odot)$ and $[\text{Fe/H}]$.

Two observed trends provide a first order explanation concerning the Li abundance in these solar twins. Indeed, HIP 55459 and HIP 79672 are found slightly more massive than the Sun by $\approx 3-4 \%$ (Takeda et al. 2007; Meléndez & Ramírez 2007), which could be an explanation for the overabundance of Li compared to the solar lithium, the external convective zone being shallower. The other trend concerns the age of the stars since HIP 56948 and HIP 73815 are older than the Sun and present a stronger Li-depletion. The sample of solar-twins is summarized in Table 1.

3. Stellar evolutionary models

For the purposes of this study, stellar evolution calculations were computed with the Toulouse-Geneva stellar evolution code TGEC (Hui-Bon-Hoa 2008). Details on the physics of these models can be found in Richard et al. (1996, 2004), do Nascimento et al. (2000) and Hui-Bon-Hoa (2008). We describe here the input standard physics, non-standard processes, diffusion and rotation-induced mixing, added in the models.

3.1. Input physics

We used the OPAL2001 equation of state by Rogers & Nayfonov (2002) and the radiative opacities by Iglesias & Rogers (1996), completed with the low temperature atomic and molecular opacities by Alexander & Ferguson (1994). The nuclear reactions are from the analytical formulae of the NACRE (Angulo et al. 1999) compilation, taking into account the three pp chains and the CNO tricycle, with the Bahcall & Pinsonneault (1992) screening routine. Convection is treated according to the Böhm-Vitense (1958) formalism of the mixing
Fig. 1. Solar twins stars observed by Méndez & Ramírez (2007) in the Hertzsprung-Russell diagram. Luminosities and related errors have been derived from the Hipparcos parallaxes. The typical errors on $T_{\text{eff}}$ are indicated in Tab[I]. The shaded zone represents the range of masses of TGEC models (the maximum and the minimum masses are indicated) limited by the 1-$\sigma$ observational error bars.

length theory with a mixing length parameter $\alpha = l/H_{\rho} = 1.74$, where $l$ is the mixing length and $H_{\rho}$ the pressure height scale. For the atmosphere, we use a gray atmosphere following the Eddington relation, which is a good approximation for main-sequence solar-type stars (VandenBerg et al. 2008).

The abundance variations of the following chemical species are individually computed in the stellar evolution code: H, He, C, N, O, Ne and Mg. Li and Be are treated separately only as a fraction of the initial abundance. The heavier elements are gathered in a mean species $Z$. The initial composition follows the Grevesse & Noels (1993) mixture, with an initial helium abundance $Y_{\text{ini}} = 0.268$. We chose to use the "old" abundances of Grevesse & Noels (1993) instead of the "new" mixture of Asplund et al. (2005). This choice is motivated by the disagreement of these new abundances with the helioseismic inversions for the sound-speed profile, the surface helium abundance, and the convective zone depth. Furthermore, Caffau et al. (2009) have recently revised the solar metallicity using 3D hydrodynamical models to $Z=0.0156$ and $Z/X=0.0213$. These values are closer to the ones of Grevesse & Noels (1993).

Diffusion and rotation-induced mixing

The microscopic diffusion is computed in the atom test approximation. All models include gravitational settling with diffusion coefficients computed as in Paquette et al. (1986). Radiative accelerations are not computed here, as we only fo-
Fig. 2. Solar twins observed by Takeda et al. (2007), the caption is as in Figure 1.

Rotation-induced mixing is computed as described in Théado & Vauclair (2003a). This prescription is an extension of Zahn (1992) and Maeder & Zahn (1998), and introduces the feedback effect of the $\mu$-currents in the meridional circulation, due to the diffusion-induced molecular weight gradients. It introduces two free parameters in the computations ($C_h$ and $\alpha_{\text{turb}}$ : cf. Eq. (20) of Théado & Vauclair 2003a).

The evolution of the rotation profile follows the Skumanich’s law (Skumanich 1972), with an initial surface rotation velocity on the ZAMS equal to $V_i = 100 \, \text{km.s}^{-1}$. Other prescriptions have been tested by other authors to model the lithium destruction. Charbonnel & Talon (1999) and Palacios et al. (2003) have included the angular momentum transport induced by the mixing. However, as rotation-induced mixing alone cannot account for the flat rotation profile inside the Sun, these authors have later introduced the possible effect of internal gravity waves triggered at the bottom of the convective zone (e.g. Talon & Charbonnel 2005), which allows to reproduce the hot side of the Li-dip. Other authors suggest that the internal magnetic field is more important than internal waves to transport angular momentum (Gough & McIntyre 1998). In any case, when adjusted to the solar case, all these prescriptions are able to reproduce the lithium depletion observed in the Hyades, and the results are ultimately quite similar (Talon & Charbonnel 1998, Théado & Vauclair 2003b).

We also include a shear layer below the convective zone, treated as a tachocline (see Spiegel & Zahn 1992): this layer is parameterized with an effective diffusion coefficient decreas-
The observations used in this work are represented by *. The sources of the observations are: (a) Porto de Mello & da Silva (1997), (b) Luck & Heiter (2005), (c) Valenti & Fisher (2005), (d) Masana et al. (2006), (e) Meléndez et al. (2006), (f) Holmberg et al. (2007), (g)* Meléndez & Ramírez (2007), (h) Robinson et al. (2007), (i)* Takeda et al. (2007), (j) Takeda & Tajitsu (2009).

We calculated the evolution of models of different masses 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 temperature and luminosity at the solar age. The calibration method of the models is based on the Richard et al. (1996) prescription: for a 1.00 $M_\odot$ star, we adjusted the mixing-length parameter $\alpha$ and the initial helium abundance $Y_{ini}$ to match the observed solar luminosity and radius at the solar age. The observed values we used are those of Richard et al. (2004): $L = 3.8515 \pm 0.0055 \times 10^{33}$ erg s$^{-1}$, $R = 6.95749 \pm 0.00241 \times 10^{10}$ cm and Age = 4.57 $\pm$ 0.02 Gyr. For our best solar model, we obtained: $L = 3.8499 \times 10^{33}$ erg s$^{-1}$ and $R = 6.95938 \times 10^{10}$ cm at Age = 4.576 Gyr.

The free parameters of the rotation-induced mixing determine the efficiency of the turbulent motions. They are adjusted to produce a mixing both: 1) efficient and deep enough to smooth the helium gradient below the outer convective zone; 2) weak and shallow enough to avoid the destruction of Be. Following Grevesse & Sauval (1998), the Be abundance of the Sun is log $N$(Be) = 1.40 $\pm$ 0.09, and Balachandran & Bell (1998) show that, after correcting for the continuous opacity in the ultraviolet region of the spectrum, solar beryllium is not depleted at all with respect to the meteoritic value. However, the source of "extra UV" opacity has never been identified and it is justified assuming that the OH lines in the UV and the IR are both formed in LTE. We obtained a slight Be destruction by a factor of 1.25 with respect to the meteoritic value, which is well within the error in the determination of the solar Be abundance.

The calibration of the tachocline allows to reach the solar lithium depletion (log $N$(Li) = 1.10 $\pm$ 0.10, e.g Grevesse & Sauval 1998), and we obtained for our best solar model : log $N$(Li) = 1.13.

We checked also that the sound velocity profile of our best model is consistent with the one deduced from helioseismology inversions by Basu et al. (1997). Our calibration achieved an excellent agreement with the helioseismology, better than 1% in most of the star, except in the deep interior, where it reaches 1.5%.

The input parameters for the other masses are the same as for the 1.00 $M_\odot$ model.

### 3.2. Models and calibration

**Table 1. Parameters of the observed solar twins.**

| Name | $T_{eff}$ (K) | $(L/L_\odot)$ | [Fe/H] | log $N$(Li) | Age (Gyrs) | Mass ($M_\odot$) | source |
|------|---------------|----------------|--------|-------------|-------------|-----------------|--------|
| HIP 55459 (HD 98618) | 5812 ± 50 | 1.081 ± 0.069 | 0.066 | 49 ± 2.9 | 1.040 ± 0.150 | (c) |
| HIP 79672 (18 Sco) | 5762 ± 50 | 1.043 ± 0.027 | 0.05 ± 0.03 | 4.57 ± 0.35 | 1.02 ± 0.04 | (a) |
| HIP 100963 | 5799 ± 50 | 0.968 ± 0.043 | -0.002 | 1.72 ± 0.07 | 5.13 ± 0.05 | 1.00 ± 0.02 | (i)* |
| HIP 56948 | 5785 ± 36 | 1.15 ± 0.14 | 0.020 | 1.08 ± 0.13 | 5.8 ± 1.0 | 1.00 ± 0.03 | (g)* |
| HIP 73815 | 5810 ± 36 | 1.21 ± 0.14 | 0.010 | 0.95 ± 0.20 | 6.3 ± 1.0 | 1.00 ± 0.03 | (g)* |

The free parameters of the rotation-induced mixing determine the efficiency of the turbulent motions. They are adjusted to produce a mixing both: 1) efficient and deep enough to smooth the helium gradient below the outer convective zone; 2) weak and shallow enough to avoid the destruction of Be. Following Grevesse & Sauval (1998), the Be abundance of the Sun is log $N$(Be) = 1.40 $\pm$ 0.09, and Balachandran & Bell (1998) show that, after correcting for the continuous opacity in the ultraviolet region of the spectrum, solar beryllium is not depleted at all with respect to the meteoritic value. However, the source of "extra UV" opacity has never been identified and it is justified assuming that the OH lines in the UV and the IR are both formed in LTE. We obtained a slight Be destruction by a factor of 1.25 with respect to the meteoritic value, which is well within the error in the determination of the solar Be abundance.

The calibration of the tachocline allows to reach the solar lithium depletion (log $N$(Li) = 1.10 $\pm$ 0.10, e.g Grevesse & Sauval 1998), and we obtained for our best solar model : log $N$(Li) = 1.13.

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The input parameters for the other masses are the same as for the 1.00 $M_\odot$ model.

### 4. Results and discussion

Lithium is a key element because it is easily destroyed in stellar interiors. Its abundance indicates the amount of internal mixing
in the stars and its destruction is strongly mass-age dependent. Nowadays, it is well established on empirical arguments that a non-standard mixing mechanism must be at work to explain the low Li abundances in solar-type stars.

For each star in our sample, we first computed a grid of models as described above with a step of mass of 0.001 Mₜ and with masses limited by the 1-σ observational error bars in the HR diagram (Figures 1 and 2). The metallicity of the models matches that observed for each solar twin. This first comparison in the HR diagram between the observations of solar twins and the models gives us a first estimation of their mass and age, and of the precision of our method. First, the masses found are in the range of masses that define the mass of a solar twin (≤ 2.5% of the solar mass). The precision on the mass determination is directly linked to the precision of the Tₑff estimations from the observations. In the case of the stars observed by Méndez & Ramírez (2007), the error associated to the effective temperature is ±36 K and we obtain an average range of masses < ∆M > ~ 0.036 Mₜ, in the limits of the Tₑff errors. In the case of the stars from Takeda et al. (2007), the error associated to Tₑff is ±50 K and the average range of masses is < ∆M > ~ 0.056 Mₜ. This first estimation is quite satisfactory, but using the observed Li abundance we are able to reach an even higher precision.

Figures 3 and 4 show the lithium destruction of our models and the observed abundance for each solar twin as a function of the effective temperature. The shaded zone represents the range of masses of TGEC models (the maximum and the minimum masses are indicated) limited by the 1-σ observational error bars. A model (dot-dashed lines) of 1.013 Mₜ (HIP 55459), 1.015 Mₜ (HIP 79672), 0.994 Mₜ (HIP 56948) and 0.992 Mₜ (HIP 73815), passes through the observed point. The positions of the solar twin, the Sun and the lithium destruction of a solar model (dashed line) are indicated.

**Fig. 3.** Solar twins observed by Méndez & Ramírez (2007): lithium destruction along the evolutionary tracks as a function of the effective temperature. The shaded zone represents the range of masses of TGEC models (the maximum and the minimum masses are indicated) limited by the 1-σ observational error bars. A model (dot-dashed lines) of 1.013 Mₜ (HIP 55459), 1.015 Mₜ (HIP 79672), 0.994 Mₜ (HIP 56948) and 0.992 Mₜ (HIP 73815), passes through the observed point. The positions of the solar twin, the Sun and the lithium destruction of a solar model (dashed line) are indicated.
Fig. 4. Solar twins observed by Takeda et al. (2007), the caption is as in Figure 3.

of the effective temperature. The error associated to log N(Li) is about 0.1 dex. As for figures 1 and 2 we plot the zone containing the grid of models with masses limited by the 1-σ error bars. It gives us for each star a ΔM even smaller (< ΔM > ∼ 0.008 M⊙ for Méndez & Ramírez (2007) stars and < ΔM > ∼ 0.012 M⊙ for Takeda et al. (2007) stars).

We also computed a model track passing through the observed position of the star in the Teff - Li diagram. It gives us the most probable modelling of the observed star, and the values of our mass and age estimations.

The uncertainties concerning the external parameters of our models are difficult to evaluate and have different sources. Using a more sophisticated atmosphere model than the 1-D grey atmosphere computations, or changing the internal physics could modify the derived effective temperature. But the present models and their parameters have been calibrated so as to precisely account for the solar observed external parameters, the solar sound velocity profile and for the solar lithium depletion, with a solar model. The uncertainties we deduced for the mass and age estimations are calculated with the values of mass and age from the two extreme models in the diagrams Li-Teff. These uncertainties are lower limits since only two parameters are being sampled.

In this context, the original result of our analysis is that the masses and log N(Li) values associated with a non standard model at a given Teff give us a mass solution more precise than a mass determined only based on the HR diagram position.

4.1. Comparison with previous results

HIP 55459 was already observed by Valenti & Fisher (2005) and Méndez et al. (2006). The values we used for our analysis are from Takeda et al. (2007) and from Méndez & Ramírez (2007) (see Tab1). The Li abundance appears to be
enhanced compared to the Sun, however from the observations and the comparison with the evolutionary models, the star appears to be significantly more massive than the Sun with an age from 4.27 ± 1.94 Gyr to 5.77 ± 0.81 Gyr. Our estimated mass, 1.018 ± 0.007 \( M_\odot \) comparing with Takeda et al. (2007) and 1.013±0.005 M\(_\odot\) comparing with Meléndez & Ramírez (2007), is lower than all other determinations (see Tab[2]). However, in the determination by comparison with the observations of Takeda et al. (2007), we were unable to obtain an evolutionary track consistent with the hot side of the error bar as seen in the left upper box of Figure[4]. HIP 79672 is the oldest star considered as a solar twin. It was observed by Porto de Mello & da Silva (1997), Valenti & Fisher (2005), Luck & Heiter (2005) and Meléndez et al. (2006). In this work we used the values from Takeda et al. (2007) and from Meléndez & Ramírez (2007) (see Tab[1]). The log \( N/\text{Li} \) of 18 Sco gives us a picture of a star between 0.7% and 1.5% more massive than the Sun. The age is difficult to estimate as we found 2.89 ± 1.09 Gyr with the observations of Takeda et al.(2007) and 5.03 ± 1.29 Gyr with Meléndez & Ramírez (2007) (see Tab[3]). Such uncertainties of the present estimations come from the discrepancies between Meléndez & Ramírez (2007) and Takeda et al. (2007), especially the effective temperature estimation.

We can observe in both cases above that all lithium determinations are very close. Thus, the principal discrepancy between mass and age estimated from observations of Meléndez & Ramírez (2007) and Takeda et al. (2007) comes from the \( T_{\text{eff}} \) difference.

HIP 100963 was observed by Masana et al. (2006) and we used the observations of Takeda et al. (2007) (see Tab[1]). The estimated age is around 5.13 Gyr. Our estimation comparing with this last observation gives a star with a mass very close to the solar one (\( M = 0.998 \pm 0.006 \ M_\odot \)) but younger (between 2.01 and 3.80 Gyr) which is consistent with the observed lithium abundance (see Tab[2]). HIP 56948 is currently the best solar twin. Observations of this star have been made by Holmberg et al. (2007) and Masana et al. (2006). The latest observations from Meléndez & Ramírez (2007) are used in this work (see Tab[1]). We confirm that HIP 56948 appears to be an excellent solar twin with a mass \( M = 0.994\pm0.004 \ M_\odot \) and an age \( = 4.71\pm1.39 \text{ Gyr} \) that is even closer than the age determined by Meléndez & Ramírez (2007) \( (5.8 \pm 1.0 \text{ Gyr}) \); see Tab[2]. Indeed, if the mixing processes involved in the interior are the same in both Sun and HIP 56948, the fact that these two stars have roughly the same Li content, and that HIP 56948 is slightly less massive, suggests that the latter is slightly younger.

HIP 73815 was analyzed by Robinson et al. (2007). We used the values of Meléndez & Ramírez (2007) (see Tab[1]). The abundance log \( N/\text{Li} \) is consistent with a solar twin of \( 0.992\pm0.005 \ M_\odot \) and an age of \( 5.76\pm1.13 \text{ Gyr} \) (see Tab[2]). Recently, Takeda & Tajitsu (2009) proposed new determinations of the external parameters of HIP 56948, HIP 79672, and HIP 100963 (see Tab[1]). The new determination of \( T_{\text{eff}} \) for HIP 79672 is much closer to the one of Meléndez & Ramírez (2007). A new estimation should reduce the discrepancies we found between the two determination for both mass and age. The new determination of \( T_{\text{eff}} \) of HIP 100963 is close to the old one and should not change largely our estimation. Concerning HIP 56948, these determinations are very close to the ones of Meléndez & Ramírez (2007), and a study with our method should confirm the status of best solar twin.

Our results are summarized in Table[2] and Figure[5].

**Fig. 5.** Comparison between masses and ages determined by TGEC models (filled symbols) and masses and ages estimated by the observations (open symbols). Squares correspond to the solar twins by Meléndez & Ramírez (2007) and circles to the solar twins by Takeda et al. (2007). The errors bars are as described in the text.

**5. Conclusions**

Although being a fundamental parameter in studies of stellar evolution, the mass of single stars cannot be derived directly from the observations. The mass is a crucial parameter to characterize a solar twin. In this work, we have analyzed the 5 best solar twins selected from the literature, and we developed a method constrained by the Li abundance observations to determine the mass and age of the stars. Our mass determination is based on the fact that the Li depletion in low mass stars is strongly mass dependent. Indeed, the Li depletion in solar-type stars is due to the microscopic diffusion and the rotation-induced mixing. Li atoms diffuse below the outer convective zone and the Li atoms are diluted up to 2 orders of magnitude below the solar value. Furthermore, Li is destroyed by the proton-proton chain reaction. The amount of Li depletion is strongly mass dependent, and the depletion is maximum in solar-type stars due to the microscopic diffusion. The Li depletion is expected to be lower for stars much more massive than the Sun. For the mass determinations, we have used the Li depletion in the solar twins and the Li depletion is expected to be lower for stars much more massive than the Sun.

The new determination of \( T_{\text{eff}} \) of HIP 100963 is close to the old one and should not change largely our estimation. Concerning HIP 56948, these determinations are very close to the ones of Meléndez & Ramírez (2007), and a study with our method should confirm the status of best solar twin.
zone and if this latter is deep enough, the meridional circulation transports them from the bottom of the convective zone to the destruction layers. This process allows an explanation of the low Li abundance observed in the Sun and some solar twins. We used accurate lithium abundance observations compared with non-standard models to provide precise information about the age and mass of these stars, better than determined by classical methods. For each solar twin, we computed the Li abundance associated with non-standard models provides more precise and older than the Sun. HD 98618 and 18 Sco are found 1.39 Gyr. We confirm HIP 56948 is the best solar twin at the present time, its age of 4.71 ± 0.23 Gyr. The present work has shown that accurate lithium abundance determination and age determinations from TGEC models compared to observations of (a) Takeda et al. (2007) and (b) Meléndez & Ramírez (2007) are an excellent solar twin but our analysis, constrained by the Li content, gives us a star slightly less massive and older than the Sun. HD 98618 and 18 Sco are found slightly more massive than the Sun, which is consistent with their high Li abundance. HIP 100963 seems to be a young Sun. In short, the present work has shown that accurate lithium abundance associated with non-standard models provides more precise information about age and mass of solar twins, better than that determined only by classical methods. Such an aspect, shows that the physical properties of the stellar interior should be taken in consideration for a more realistic characterization of a solar twin star.

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Table 2. Mass and age determinations from TGEC models compared to observations of (a) Takeda et al. (2007) and (b) Meléndez & Ramírez (2007)

| Name     | Mass [M_☉] (a) | Mass [M_☉] (b) | Age [Gyr] (a) | Age [Gyr] (b) |
|----------|----------------|----------------|--------------|--------------|
| HIP 55459| 1.03^{+0.05}_{-0.04} | 1.018 ± 0.007  | 3.80^{+0.05}_{-0.10} | 4.27^{+0.12}_{-0.14} |
| (HD 98618) | 1.03 ± 0.03 | 1.013 ± 0.005  | 4.7 ± 1.0     | 5.77^{+0.34}_{-0.24} |
| HIP 79672| 1.02^{+0.03}_{-0.02} | 1.007 ± 0.006  | 4.57^{+0.04}_{-0.07} | 2.89_{-0.03}^{+0.01} |
| (18 Sco) | 1.04 ± 0.03 | 1.015 ± 0.006  | 3.4 ± 1.0     | 5.03_{-0.20}^{+1.25} |
| HIP 100963| 1.00^{+0.03}_{-0.02} | 0.998 ± 0.006  | 5.13^{+0.00}_{-0.29} | 3.07^{+0.14}_{-0.19} |
| HIP 56948| 1.00 ± 0.03 | 0.994 ± 0.004  | 5.8 ± 1.0     | 4.71_{-0.13}^{+1.13} |
| HIP 73815| 1.00 ± 0.03 | 0.992 ± 0.005  | 6.3 ± 1.0     | 5.76_{-0.79}^{+0.05} |
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