THE FUTURE OF THE SUN: AN EVOLVED SOLAR TWIN REVEALED BY CoRoT

J.-D. do Nascimento, Jr.1, Y. Takeda2, J. Meléndez1, J. S. da Costa1, G. F. Porto de Mello4, and M. Castro1

1 Departamento de Física Teórica e Experimental (DFTE), Universidade Federal do Rio Grande do Norte (UFRN), CP 1641, 59072-970 Natal, RN, Brazil; dias@dfte.ufrn.br
2 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
3 Departamento de Astronomia do IAG/USP, Universidade de São Paulo, Rua do Matão 1226, 05508-900 São Paulo, SP, Brazil
4 Observatório do Valongo, UFRJ, Ladeira do Pedro Antônio 43, 20080-090 Rio de Janeiro, RJ, Brazil

Received 2013 April 29; accepted 2013 May 14; published 2013 June 26

ABSTRACT

The question of whether the Sun is peculiar within the class of solar-type stars has been the subject of active investigation over the past three decades. Although several solar twins have been found with stellar parameters similar to those of the Sun (albeit in a range of Li abundances and with somewhat different compositions), their rotation periods are unknown, except for 18 Sco, which is younger than the Sun and with a rotation period shorter than solar. It is difficult to obtain rotation periods for stars of solar age from ground-based observations, as a low-activity level implies a shallow rotational modulation of their light curves. CoRoT has provided space-based long time series from which the rotation periods of solar twins as old as the Sun could be estimated. Based on high-signal-to-noise, high-resolution spectroscopic observations gathered at the Subaru Telescope, we show that the star CoRoT ID 102684698 is a somewhat evolved solar twin with a low Li abundance. Its rotation period is 29 ± 5 days, compatible with its age (6.7 Gyr) and low lithium content, A Li ≲ 0.85 dex. Interestingly, our CoRoT solar twin seems to have enhanced abundances of the refractory elements with respect to the Sun, a typical characteristic of most nearby twins. With a magnitude V ≃ 14.1, ID 102684698 is the first solar twin revealed by CoRoT, the farthest field solar twin so far known, and the only solar twin older than the Sun for which a rotation period has been determined.

Key words: stars: abundances – stars: atmospheres – stars: fundamental parameters – stars: rotation – Sun: fundamental parameters

Online-only material: color figures

1. INTRODUCTION

Modern stellar astrophysics is producing an amount of data never seen before. Two space missions, CoRoT (Baglin et al. 2006) and Kepler (Borucki et al. 2010), are providing precise light curve observations for thousands of main-sequence stars from which rotation periods P rot and solar-like oscillations can be studied in detail. CoRoT observes toward the intersection between the equator and the Galactic plane and has identified thousands of solar-type dwarf stars. Among them, there are stars with fundamental parameters very similar to the Sun, the so-called solar twins. With CoRoT we can estimate periodic stellar variability in the range of 1–50 days, a modulation that is a signature of the presence of spots on the star’s surface.

Although recent works have greatly expanded the number of solar twins and studied in detail their physical parameters and chemical abundances, their P rot are mostly unknown, except for the solar twin 18 Sco (Porto de Mello & da Silva 1997), which seems to have physical characteristics similar to solar (Bazot et al. 2011), an Li abundance about three times solar (Meléndez & Ramírez 2007; Takeda & Tajitsu 2009), a younger age (Baumann et al. 2010) and P rot somewhat faster than the Sun (Frick et al. 2004; Petit et al. 2008), and a Sun-like activity cycle with a shorter length (Hall et al. 2007).

Besides the astrophysical importance of solar twins to assess to which point the Sun could be considered as a “typical” solar-type star (Gustafsson 1998, 2008), solar twins are also important to calibrate fundamental relations between colors and temperature (Porto de Mello & da Silva 1997; Meléndez et al. 2010; Ramírez et al. 2012; Casagrande et al. 2012), and to test non-standard stellar evolution models (e.g., do Nascimento et al. 2009; Castro et al. 2011). A bona fide sample of solar twins with determined P rot is also important to study the “Sun in Time” (see Dorren & Guinan 1994, Ribas et al. 2010), i.e., the evolution of the Sun through solar twins covering a range of ages.

Despite the fact that until 1997 only one solar twin was known (Porto de Mello & da Silva 1997), the search for solar twins (Hardorp 1978; Cayrel de Strobel 1996; Soubiran & Triaud 2004) has been greatly expanded in the last few years, and currently more than two dozen solar twins are known (e.g., Meléndez et al. 2006, 2009; Takeda et al. 2007; Meléndez & Ramírez 2007; Ramírez et al. 2009; Datson et al. 2012). However, only for 18 Sco, a solar twin younger than the Sun, has the P rot been determined (Frick et al. 2004; Petit et al. 2008). The discovery of mature solar twins with ages similar to the Sun’s or higher is highly desirable in order to study the rotational evolution of the Sun.

Here we report the discovery of a new solar twin from the CoRoT database. This study is part of a survey of solar twins and analogs based on CoRoT and Kepler data for which we are currently gathering high-resolution optical spectra. In Section 2, we describe the selection process and the observations, in Section 3 we describe the analysis and discuss the results, and in Section 4 we present the conclusions.

2. SELECTION OF CANDIDATES, OBSERVATIONS, AND INITIAL ANALYSIS

We selected solar twin candidates from a sample of more than 150,000 stars listed in the CoRoT (Auvergne et al. 2009) database by employing precise 2MASS photometry, as in Nascimento et al. (2012), and using the rotational modulation of the CoRoT light curves. We also used the stellar parameters
To determine the CoRoT for scientific analysis. These light curves were delivered by the available public data level 2 (N2) light curves that are ready to summarize the results of our chosen targets. We used the 5600 K Tc Sarro et al. (2013). a V magnitude from CoRoT Exo-dat. b This Letter. c Sarro et al. (2013).

$T_{\text{eff}}$ and log g given in Sarro et al. (2013), and chose stars with $5600 \, K \leq T_{\text{eff}} \leq 5950 \, K$ and $4.4 \leq \log g \leq 4.6$. Table 1 summarizes the results of our chosen targets. We used the available public data level 2 (N2) light curves that are ready for scientific analysis. These light curves were delivered by the CoRoT pipeline after nominal corrections (Samadi et al. 2006). To determine the $P_{\text{rot}}$ for our sample, we used the Lomb–Scargle algorithm (Scargle 1982). The light curve coverage allows us to detect reliably periods longer than 2 days and shorter than 50 days. The uncertainties in $P_{\text{rot}}$ are determined by the frequency resolution in the power spectrum and the sampling error. Our final sample is composed of 29 solar twin candidates. The derived periods and their respective errors are presented in Table 1. The $P_{\text{rot}}$ uncertainty comes mainly from the time series limitation. To achieve the largest possible sample of solar twins with determined $P_{\text{rot}}$ ranging from 2 to 50 days, we analyzed all light curves in the CoRoT Exo-dat (Deleuil et al. 2009) as described by do Nascimento et al. (2012).

To characterize a solar twin, it is absolutely necessary to perform a detailed spectroscopic analysis. Hence, for our three most promising solar twin candidates we obtained high-resolution

### Table 1

| CoRoT ID | CoRoT V | V$^a$ | T$_{\text{eff}}$ | log g | $P_{\text{rot}}^b$ |
|----------|---------|------|-----------------|-------|-----------------|
| CoRoT ID | CoRoT V | V$^a$ | T$_{\text{eff}}$ | log g | $P_{\text{rot}}^b$ |
| 102684698 | LRA01 | 14.14 | 5822 ± 20$^b$ | 4.31$^b$ | 29 ± 5 |
| 100543340 | LRa01 | 15.22 | 5746$^c$ | 4.4$^c$ | 5.5 ± 1 |
| 100567226 | LRa01 | 15.97 | 5798$^c$ | 4.6$^c$ | 11.5 ± 1 |
| 100632124 | LRa01 | 13.34 | 5633$^c$ | 4.4$^c$ | 21.0 ± 2 |
| 100746852 | LRa01 | 16.27 | 5835$^c$ | 4.6$^c$ | 23.9 ± 2 |
| 1008234807 | LRa01 | 15.42 | 5751$^c$ | 4.5$^c$ | 14.3 ± 1 |
| 100839384 | LRa01 | 15.41 | 5925$^c$ | 4.5$^c$ | 20.0 ± 1 |
| 101030785 | LRa01 | 14.73 | 5869$^c$ | 4.6$^c$ | 10.6 ± 1 |
| 102656897 | LRa01 | 16.55 | 5757$^c$ | 4.5$^c$ | 36.8 ± 8 |
| 102709990 | LRa01 | 14.11 | 5908$^c$ | 4.5$^c$ | 21.5 ± 1 |
| 102731845 | LRa01 | 14.06 | 5760$^c$ | 4.4$^c$ | 38.3 ± 5 |
| 102739288 | LRa01 | 16.38 | 5718$^c$ | 4.4$^c$ | 6.0 ± 1 |
| 102769572 | LRa01 | 16.26 | 5750$^c$ | 4.4$^c$ | 4.3 ± 1 |
| 105283591 | LRc02 | 15.25 | 5900$^c$ | 4.6$^c$ | 7.0 ± 1 |
| 105398310 | LRc02 | 14.49 | 5803$^c$ | 4.5$^c$ | 17.0 ± 1 |
| 105572582 | LRc02 | 15.56 | 5610$^c$ | 4.4$^c$ | 12.5 ± 1 |
| 105597575 | LRc02 | 12.57 | 5740$^c$ | 4.5$^c$ | 13.3 ± 1 |
| 105693572 | LRc02 | 13.01 | 5761$^c$ | 4.6$^c$ | 29.1 ± 10 |
| 105735736 | LRc02 | 14.42 | 5841$^c$ | 4.6$^c$ | 26.3 ± 1 |
| 105806662 | LRc02 | 15.03 | 5610$^c$ | 4.4$^c$ | 15.0 ± 1 |
| 105949587 | LRc02 | 14.45 | 5768$^c$ | 4.4$^c$ | 6.5 ± 5 |
| 106022496 | LRc02 | 16.61 | 5641$^c$ | 4.5$^c$ | 12.5 ± 1 |
| 106024409 | LRc02 | 14.69 | 5677$^c$ | 4.4$^c$ | 11.2 ± 1 |
| 106055448 | LRc02 | 13.57 | 5677$^c$ | 4.4$^c$ | 6.1 ± 1 |
| 110656843 | LRa02 | 16.33 | 5641$^c$ | 4.6$^c$ | 8.5 ± 1 |
| 110656049 | LRa02 | 15.1 | 5841$^c$ | 4.6$^c$ | 17 ± 1 |
| 110677427 | LRa02 | 14.1 | 5878$^c$ | 4.5$^c$ | > 30 |
| 111082975 | LRa02 | 15.99 | 5756$^c$ | 4.5$^c$ | 12.0 ± 2 |
| 111083972 | LRa02 | 12.99 | 5749$^c$ | 4.5$^c$ | 2.8 ± 1 |

Notes. The uncertainties in $P_{\text{rot}}$ are determined by the frequency resolution in the power spectrum and the sampling error. The error of our measurement is defined by the probable error, which in turn is defined as $0.2865 \cdot \text{FWHM}$ (full width at half-maximum of the peak), assuming Gaussian statistics around the Lomb–Scargle peak as reported by do Nascimento et al. (2012).

A detailed model-atmosphere analysis of ID 102684698 (CoRoT Sol 1) was performed to verify the outcome of the high signal-to-noise ratio (S/N ~ 100) spectra in 2012 September 9 and 2013 March 25 (Hawaii Standard Time) employing the High Dispersion Spectrograph (Noguchi et al. 2002) placed at the Nasmyth platform of the 8.2 m Subaru Telescope. Standard data reduction procedures (bias subtraction, flat fielding, scattered-light subtraction, spectrum extraction, wavelength calibration, continuum normalization) were applied to the spectra using IRAF. For stars ID 102684698 and ID 102630220 we achieved S/N ~ 110 and 100, respectively, while for ID 110688932 the spectrum has only S/N ~ 30, albeit for the latter it is clear that its lines are much broader than those in the Sun and that its Li λ6707.8 line is much stronger. Thus, ID 110688932 is not a solar twin. The candidate ID 102630220 is a double-lined star, i.e., probably a spectroscopy binary and it was also discarded. Interestingly, a direct comparison of a solar spectrum (using the Moon), also observed with the same spectrograph at Subaru but at higher resolution ($R \sim 90,000$; Takeda & Tajitsu 2009), shows that ID 102684698 has an overall spectrum similar to the Sun, and, more excitingly, it shows a weak Li feature, as in the Sun. Thus, with this model-independent analysis we determined that it is a potentially good solar twin. Sample spectra of the CoRoT solar twin candidates and other solar twins observed at Subaru (Takeda & Tajitsu 2009) are shown in Figure 1.

3. THE SOLAR TWIN CoRoT ID 102684698

A detailed model-atmosphere analysis of ID 102684698 (CoRoT Sol 1) was performed to verify the outcome of the empirical comparisons and to estimate precise stellar parameters, as in Ribas et al. (2010) and Meléndez et al. (2012).
The Li abundance was derived from the Li resonance transition at λ6707.8. A synthetic spectrum was fitted to the Subaru spectrum for the set of purely spectroscopic atmospheric parameters. $T_{\text{eff}} = 5822 \pm 20$ K, $\log g = 4.31 \pm 0.04$, $[\text{Fe/H}] = +0.09 \pm 0.02$, and $\xi = 1$ km s$^{-1}$. We used Castelli & Kurucz (2004) model atmospheres and mostly laboratory gf-values (Meléndez et al. 2012) with synthetic spectra computed using the 2002 version of MOOG (Sneden 1973). We obtained stellar parameters and chemical abundances by differential spectroscopic equilibrium, as described in Meléndez et al. (2012), i.e., using differential excitation equilibrium of Fe i lines to obtain $T_{\text{eff}}$ and differential ionization equilibrium of Fe i and Fe ii to obtain $\log g$. The surface gravity was also verified using Ti i/Ti ii and Cr i/Cr ii. For the spectroscopic atmospheric parameters, we derived $A_{\text{Li}} \approx 0.85$ (Figure 2) in the usual scale, where $A_{\text{Li}} = \log n_{\text{Li}}/n_{\text{H}} + 12$. As in our previous works on solar twins, the analysis was performed differentially, i.e., the equivalent widths of the ID 102684698 star and the Sun were measured line-by-line. Notice that although the same spectrophotograph was used to gather both spectra, the resolving power is higher for the solar spectrum ($R \sim 90,000$) than for the CoRoT target ($R \sim 60,000$). However, all the lines were carefully measured by hand only after an inspection of a given line was performed both in the Sun and in the ID 102684698, in order to determine both the continuum and the part of the profile that would be used for the measurement, thus minimizing any potential systematic problem. The model-atmosphere analysis confirmed our empirical results, showing that ID 102684698 indeed has stellar parameters similar to solar but with a lower $\log g$, probably showing that it is somewhat more evolved than the Sun. The parameters derived for the first CoRoT solar twin, ID 102684698, and our list of solar twin candidates are given in Table 1. Interestingly, ID 102684698 has an abundance pattern that seems different from solar and closer to that of other solar twins. This seems to expand the idea that the Sun has a peculiar solar composition. Based on nearby solar twins, Meléndez et al. (2009) and Ramírez et al. (2009) showed that the Sun seems to be deficient in the refractory elements. As shown in Figure 3, the Sun also shows the same deficiency of refractory elements when compared to ID 102684698, the farthest field solar twin known so far.

From the stellar parameters we obtained the mass and age of ID 102684698. As it seems somewhat more evolved than the Sun (lower $\log g$), the results from the isochrones are more reliable than for less evolved stars. We obtain a mass of 1.03 $\pm$ 0.03 $M_\odot$ and an age of 6.7 $\pm$ 0.6 Gyr, i.e., a one-solar-mass star somewhat more evolved than the Sun. That age is in the same scale as our previous works on solar twins, showing that our CoRoT twin is definitively older than the well-known solar twins 18 Sco (2.7 $\pm$ 1.0 Gyr) or HIP 56948 (3.5 $\pm$ 0.7 Gyr) (Meléndez et al. 2012). The mass and age of ID 102684698 were also estimated using Toulouse Geneva Evolution Code (TGEC) models constrained by Li abundance (Figure 4) as in Nascimento et al. (2009). More details of the physics used can be found in Richard et al. (1996, 2004), Hui-Bon-Hoa (2008), and do Nascimento et al. (2009, 2012). This analysis agrees with a one-solar-mass twin about 2 Gyr older than the Sun.

### 3.1. The Lithium Abundance of CoRoT ID 102684698

The stellar Li abundance is at once instructive and complex to interpret. The Li depletion in stars depends on several ingredients such as mass, age, metallicity, rotation, magnetic fields, mass loss, convection treatment, and extra-mixing mechanisms (e.g., D’Antona & Mazzitelli 1984; Deliyannis & Pinsonneault 1997; Ventura et al. 1998; Charbonnel & Talon 2005). For many years, the Sun was thought to be peculiar in its low Li content. This idea was also supported by two high-lithium, but otherwise very similar to the Sun, solar twins (HD 98168 and 18 Sco) that have an Li abundance about three times higher than the Sun (Meléndez et al. 2006). Recent studies by Takeda et al. (2007) and Meléndez & Ramírez (2007).
show that this is not the case, as they have found solar twins with low Li abundances (HIP 56948 and HIP 73815). Takeda et al. (2007) show that HIP 100963 is a quasi-solar twin with higher Li abundance (about six times solar). The spread in Li abundances among the known solar twins represents an opportunity to study transport mechanisms inside stars. There are already several models (do Nascimento et al. 2009; Charbonnel & Talon 2005) that show for a fixed mass a depletion of Li with increasing age, which seems to be confirmed by observations in solar twins (Baumann et al. 2010).

4. CONCLUSIONS

We have found the first solar twin revealed by CoRoT and the farthest field solar twin known so far (Pasquini et al. 2008 identified the farthest solar twins in M67), and the only solar twin older than the Sun for which a $P_{\text{rot}}$ has been determined. ID 102684698 (CoRoT Sol 1) has stellar parameters and mass similar to solar, while its age is somewhat higher than solar. Its $P_{\text{rot}}$ is also slightly higher than the Sun’s, i.e., consistent with an age somewhat older than solar, and its low Li abundance is also compatible with an evolved Sun. Its abundance pattern shows that the refractory elements are more enhanced than in the Sun, meaning that our CoRoT twin is similar to that of nearby solar twins, i.e., the Sun seems to be a chemically peculiar star. We are gathering higher S/N spectra of our CoRoT solar twin and other solar twin candidates in order to compare with better precision how typical the Sun is compared to distant solar twins and to establish the rotational evolution of the Sun. This study of an unbiased sample of solar twins with high-precision monitoring of stellar activity cycles for stars with well-

determined $P_{\text{rot}}$ could better constrain models of Li depletion as well as the gyrochronology (Barnes 2003, 2010; Meibom et al. 2011, 2013) relations. As done for 18 Sco (Bazot et al. 2011), asteroseismology seems to be a very promising approach to classify solar twins and can provide useful complementary information to validate potential solar twin candidates.

The CoRoT (Convection, Rotation and planetary Transits) space mission, launched on 2006 December 27, was developed and is operated by the CNES, with participation of the Science Programs of ESA, ESA’s RSSD, Austria, Belgium, Brazil, Germany, and Spain. Based on observations obtained at the Subaru telescope (programs S12B-146S). We thank the Subaru resident astronomers and telescope operators for continuous support. J.D.N.Jr. and G.F.P.M. acknowledge financial support from INCT and CNPq/Brazil. J.D.N.Jr. acknowledges support from CNPq Universal-B 485880/2012-1. J.M. acknowledges support from FAPESP 2010/17510-3 and 2012/24392-2. We thank the referee for providing constructive comments and suggestions that improved the manuscript.

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