Searching for new solar twins: The Ínúi survey for the Northern Sky

Jhon Yana Galarza1*, Ricardo López-Valdivia2, Diego Lorenzo-Oliveira1, Henrique Reggiani3, Jorge Meléndez1, Daniel Gamarra-Sánchez4, Matias Flores5,6,7, Jerry Portal-Rivera4, Paula Miquelarena5,6,7, Geisa Ponte1,8, Kevin C. Schlaufman3, and Teófilo Vargas Auccalla4

1Universidade de São Paulo, Departamento de Astronomia do IAG/USP, Rua do Matão 1226 Cidade Universitária, 05508-900 São Paulo, SP, Brazil
2The University of Texas at Austin, Department of Astronomy, 2515 Speedway, Stop C1400, Austin, TX 78712-1205
3Department of Physics and Astronomy, Johns Hopkins University, 3400 N Charles St., Baltimore, MD 21218
4Seminario Permanente de Astronomía y Ciencias Espaciales, Facultad de Ciencias Físicas, Universidad Nacional Mayor de San Marcos, Avenida Venezuela s/n, Lima 15081, Perú
5Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, San Juan, Argentina
6Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
7Instituto de Ciencias Astronómicas, de la Tierra y del Espacio (ICATE), España Sur 1512, CC 49, 5400 San Juan, Argentina
8CRAAM, Mackenzie Presbyterian University, Rua da Consolação, 896, São Paulo, Brazil

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ABSTRACT

Solar twins are key in different areas of astrophysics, however only just over a hundred were identified and well-studied in the last two decades. In this work, we take advantage of the very precise Gaia (DR2/EDR3), Tycho and 2MASS photometric systems to create the Ínúi survey of new solar twins in the Northern Hemisphere. The spectra of our targets were initially obtained with spectrographs of moderate resolution (ARCES and Goodman spectrographs with $R = 31500$ and 11930, respectively) to find the best solar twin candidates and then observed at McDonald Observatory with higher resolving power (TS23, $R = 60000$) and signal-to-noise ratio (SNR $\sim 300$-$500$). The stellar parameters were estimated through the differential spectroscopic equilibrium relative to the Sun, which allow us to achieve a high internal precision ($\sigma(T_{\text{eff}}) = 15$ K, $\sigma(\log g) = 0.03$ dex, $\sigma([\text{Fe}/\text{H}]) = 0.01$ dex, and $\sigma(v_t) = 0.03$ km s$^{-1}$). We propose a new class of stars with evolution similar to the Sun: solar proxy, which is useful to perform studies related to the evolution of the Sun, such as its rotational and magnetic evolution. Its definition is based on metallicity ($-0.15$ dex $\leq [\text{Fe}/\text{H}] \leq +0.15$ dex) and mass ($0.95 M_\odot \leq M \leq 1.05 M_\odot$) constraints, thus assuring that the star follows a similar evolutionary path as the Sun along the main sequence. Based on this new definition, we report 70 newly identified solar proxies, 46 solar analogs and 13 solar-type stars. In addition, we identified 9 close solar twins whose stellar parameters are the most similar to those of the Sun.

Key words: stars: solar-type – stars: abundances – stars: activity – stars: atmospheres – stars: fundamental parameters – techniques: spectroscopic

1 INTRODUCTION

Since the 1980s, the astronomical community was interested in finding stars with physical parameters similar to those of the Sun, i.e., solar twins. However, a crucial question arose: which parameters should be considered to define an object as solar twin?. Cayrel de Strobel et al. (1981); Cayrel de Strobel & Bentolila (1989); Cayrel de Strobel (1996) defined these objects as stars whose effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), metallicity ([Fe/H]), microturbulence ($v_t$), photometric properties, chemical composition, age, luminosity, rotation, and magnetic fields are similar, if not identical, to those of the Sun. These authors performed the first attempts to find real solar twins exploiting a list of 78 solar analogs obtained by Hardorp (1978) through spectrophotometric observations. However, with these constraints, it was almost impossible to find a real solar twin. A less rigorous definition was carried out by Friel et al. (1993): “every observable and derivable physical quantity must be identical within observational errors to that of the Sun”. Porto de Mello & da Silva (1997), using the Cayrel de Strobel’s definition (Cayrel de Strobel & Bentolila 1989), were able to find the first closest solar twin: 18 Sco. Years later, other authors also claimed to have identified solar twins based on photometric and spectroscopic parameters constraints: HD 143436 (King et al. 2005), HD 98618 (Meléndez et al. 2006), HD 10307 and HD 34411 (Galeev et al. 2004), and finally HD 101364 and HD 133600 (Meléndez & Ramírez 2007), the latter ones not only reproduce the solar fundamental parameters but also a low lithium abundance. On the other hand, Ramírez et al. (2009) introduced a concept of solar twin based only on spectroscopic stellar parameters constraints (i.e., only $T_{\text{eff}}$, $\log g$, and [Fe/H]), which is useful for achieving high precision differential abundances relative...
to the Sun; however, this definition introduces a slight bias in the mass-age-[Fe/H] space that will be discussed later. One of the last definitions comes from Datson et al. (2012, 2014, 2015), where a solar twin is defined as a star whose stellar parameters (estimated only with high resolution spectrographs) are indistinguishable from solar within the errors. A very comprehensive discussion about the concept of solar twins and solar analogs is given in Porto de Mello et al. (2014). These authors suggest that solar twins should not be only indistinguishable from the Sun, but also follow a similar evolutionary history. In brief, the literature is full of different definitions of solar twins, but until now it is not yet clear which parameters should define a real solar twin, thus hindering the efforts for finding these objects as well as studies such as gyrochronology and magnetic activity evolution (e.g., Lorenzo-Oliveira et al. 2018).

To date, despite different definitions in the literature, approximately 100 solar twins have been identified by different authors (e.g., Pasquini et al. 2008; Meléndez et al. 2009, 2014a; Ramírez et al. 2009; do Nascimento et al. 2013a; Ramírez et al. 2014; Takeda & Tajitsu 2009; Baumann et al. 2010; Önehag et al. 2011; Sousa et al. 2011; González Hernández et al. 2010; Datson et al. 2012; Porto de Mello et al. 2014; Galarza et al. 2016; Giribaldi et al. 2019) and their applications in different astrophysical fields have had significant impacts on our knowledge about stars and the Sun. For example, they are useful for setting the zero point of fundamental photometric calibrations (Holmberg et al. 2006; Casagrande et al. 2010; Ramírez et al. 2012; Datson et al. 2014; Casagrande et al. 2020), studying the mineralogy of asteroids by subtracting the Sun’s reflected light on them (e.g., Lazzaro et al. 2004; Jasmin et al. 2013), testing stellar interiors through asteroseismology (Chaplin et al. 2011; Bazot et al. 2012, 2018), measuring distances (Jofré et al. 2015), and even improving spectroscopic methods for stellar parameters determination (Saffe et al. 2018). More recently, Yana Galarza et al. (2021) detected for the first time a differential odd-even effect in a solar twin, providing new insights to understand the supernova nucleosynthesis history.

The study of solar twins has also contributed to the understanding of the chemical evolution of the Galactic disk (da Silva et al. 2012; Nissen 2015; Spina et al. 2016b, 2018; Bedell et al. 2018; Nissen et al. 2020; Botelho et al. 2020), and the study of the neutron-capture elements (Meléndez et al. 2014b; Yana Galarza et al. 2016). As a result, new chemical clocks as the [Y/Mg]-age correlation initially proposed by da Silva et al. (2012) and improved by several authors (e.g., Nissen 2015; Tucci Maia et al. 2016; Feltzing et al. 2017; Spina et al. 2018; Jofré et al. 2020; Nissen et al. 2020) and the Li-age correlation (Baumann et al. 2010; Carlos et al. 2016, 2019) have been established. Biology principles (Phylogenetics of solar twins) have also been applied to investigate the chemical evolution of the Milky Way (Jofré et al. 2017; Jackson et al. 2020).

Significant contributions come from the works of do Nascimento et al. (2013b, 2020) and Lorenzo-Oliveira et al. (2019, 2020) in the field of gyrochronology using solar twins, giving important clues to understand the rotational evolution of the Sun. A controversial diagnostic of stellar ages is the age-chromospheric activity relation (Mamajek & Hillenbrand 2008; Pace 2013), whose applicability is extended for stars with $\sim$6–7 Gyr (Lorenzo-Oliveira et al. 2016). Besides, the analysis of solar twins could help us to place the $\sim$11 yr solar cycle in context (Hall et al. 2007, 2009; Flores et al. 2018). Meléndez et al. (2009) reported chemical anomalies in the Sun when it is compared to solar twins, thereby establishing the basis for studying the planet-stellar chemical composition connection (e.g., Ramírez et al. 2009; González Hernández et al. 2010, 2013; Schuler et al. 2011; Adibekyan et al. 2014; Maldonado et al. 2015; Spina et al. 2016b; Nissen 2015; Nissen et al. 2017; Liu et al. 2016; Bedell et al. 2018; Maia et al. 2019; Cowley et al. 2020). Finally, the study of solar twins is also expanded to the field of exoplanets. For instance, Bedell et al. (2015, 2017) and Meléndez et al. (2017) have demonstrated that with the high precision achieved in stellar parameters in solar twins, it is possible to get very precise exoplanet properties (mass and radius). Additionally, it is also feasible to study habitability and evolution of exoplanets through radioactive elements such as thorium (e.g., Unterborn et al. 2015; Botelho et al. 2019). As widely discussed above, the identification of new solar twins is essential to the advancement of diverse astronomical fields. Therefore, in this work we present the INa³ catalog of new solar twins, solar analogs, and solar-type stars identified in the Northern Hemisphere. The INa³ survey provides reliable and precise spectroscopic stellar parameters, chromospheric activity levels, and photometric rotational periods when its determinations through high-precision light curves are possible.

### 2 SAMPLE SELECTION

Inspired by seminal works for searching solar twins (e.g., Hardorp 1978; Cayrel de Strobel et al. 1981; Meléndez & Ramírez 2007; Ramírez et al. 2009; Porto de Mello et al. 2014), in this era of large surveys, we take advantage of the precise photometric systems of Gaia DR2/EDR3 (Gaia Collaboration et al. 2018, 2020), Tycho (Høg et al. 2000), and 2MASS (Skrutskie et al. 2006) to search these stellar objects. However, unlike these initial studies mainly based on photometric comparisons with the Sun, our methodology consist in performing color constraints from the well characterized solar twins of Ramírez et al. (2014). To do so, we cross-matched the solar twin sample with the TGAS (Tycho-Gaia Astrometric Solution, Marrese et al. 2017) catalog updated with the Gaia EDR3 magnitudes, resulting in 63 common objects. In our study we also found a simple photometric relationship from Gaia EDR3 $G$ (updated from our initial relations using DR2) to Tycho $V$ and Johnson $V$ (Kharchenko 2001):

$$V_T G = G \times 0.9942(\pm 0.0021) + 0.2657(\pm 0.0156)$$

$$(1)$$

$$V_G = G \times 0.9940(\pm 0.0014) + 0.1929(\pm 0.0097).$$

$$(2)$$

| Table 1. Gaia Absolute Magnitude ($M_G$) and Photometric color constraints established using known solar twins (Ramírez et al. 2014). $V_T G$ is the $V$ magnitude based on Eq. (1), while $B_T$ represent the Tycho $B$ magnitude, $G_{BP}$ and $G_{Rp}$ are Gaia EDR3 magnitudes in the BP and RP passbands, and $J$, $H$, $K_S$ are 2MASS magnitudes. |
|---------------------------------------------------------------|
| $M_G$ | $B_T$ | $G_{BP}$ | $G_{RP}$ | $J$ | $H$ | $K_S$ |
| 3.755 ≤ $M_G$ ≤ 5.331 | 0.254 ≤ $G_{BP} - G$ ≤ 0.377 | 0.455 ≤ $G - G_{BP}$ ≤ 0.589 | 0.761 ≤ $G_{BP} - G_{RP}$ ≤ 0.907 | 0.960 ≤ $G - J$ ≤ 1.315 | 1.207 ≤ $G - H$ ≤ 1.708 | 1.284 ≤ $G - K_S$ ≤ 1.791 |
| 0.166 ≤ $J - H$ ≤ 0.506 | 0.281 ≤ $J - K_S$ ≤ 0.550 | −0.002 ≤ $H - K_S$ ≤ 0.180 | 0.473 ≤ $B_T - V_T G$ ≤ 0.947 |

1 INa³ means Sun in the Inca-Andean-Quechua cosmovision.
where $V_TG$ is the transformation between $G$ and Tycho $V$, while $V_G$ is the conversion between $G$ and Johnson $V$ (see Figure 1). The dispersion and the reduced chi-squared ($\chi^2_{\text{red}}$) of the linear fit are 0.018 mag and 1.608 for Eq. (1), and 0.014 mag and 1.554 for Eq. (2), respectively. It is important to highlight that these relationships are valid only for solar twins\(^2\). Besides, $V_TG$ is used only to establish the color constraints showed in Table 1, while $V_G$ is useful to estimate isochronal ages as it will be discussed later. In this way, we established the bounds of our color constraints, which are shown in Table 1.

The sample selection technique consists in first cross-matching the Gaia DR2 (updated to EDR3 in Table 1) with the 2MASS and Tycho catalogs within a region of 100 pc from Earth and with $G$ values ranging from 5 to 9 mag. Then, we applied our color constraints in the cross-matched sample and found 3100 objects. These objects compose our preliminary sample of solar twin candidates and are plotted as red circles in the Gaia EDR3 Hertzsprung-Russell diagram\(^3\) of Figure 2. We did not apply reddening corrections for our sample, since it is within 100 pc and thus has negligible reddening. This is supported by Vergely et al. (2010) and Lallement et al. (2014), who found a gradient of $dE(B-V)/dr = 0.0002$ mag per pc (see Figure 2 in Lallement et al. 2014). A similar result is found by Green et al. (2019), who created a precise dust map using the Pan-STARRS1, 2MASS, and Gaia DR2 (including its parallaxes) photometric bands. On the other hand, Reis et al. (2011) reported interstellar absorption ($E(B-V) > 0.056$) in the local bubble for regions on the Galactic plane ($d > 60$ pc) with latitudes from $l \geq 270^\circ$ up to $l \leq 45^\circ$. However, the stars of the 4mil survey that fall in this region have $d < 50$ pc and thus $E(B-V) = 0$.

Finally, as our photometric methodology (see Table 1) for searching solar twins is based only on stellar parameter constraints (Ramírez et al. 2009), it is expected to have a bias in our results (see the irregular polygon in Figure 2), as our criteria are not symmetric relative to the main sequence evolution of a one-solar-mass solar-metallicity star. This will be discussed more extensively in the subsection 4.2.

### 3 SPECTROSCOPIC OBSERVATIONS AND DATA REDUCTION

We obtained spectra of high signal-to-noise ratio (SNR $\sim 400$) of our candidates with the Goodman High Throughput Spectrograph (Clemens et al. 2004), on the SOAR Telescope. From these spectra, we could retrieve a reliable initial guess of the spectroscopic parameters. The methodology consists in estimating [Fe/H] through spectral synthesis with the SP_ACE spectral analysis tool\(^4\) using the colour–temperature–metallicity calibrations established by Casagrande et al. (2010), and trigonometric log $g$ from Gaia EDR3 parallaxes with bolometric corrections given in Meléndez et al. (2006). Our technique was tested using several known solar twins and the results are consistent (within the uncertainties) with those estimated with high precision spectra (e.g., Spina et al. 2018). We also used the ARC Echelle Spectrograph (ARCES) on the 3.5-meter Apache Point Observatory telescope to explore the northern sky since the observations with the SOAR telescope are inaccessible to DEC $\geq +25^\circ$. Thanks to these initial observations, we created a sample of 150 objects with the best solar twin candidates which were later observed with the Robert G. Tull Cool Spectrograph (hereafter TS23, Tull et al. 1995) on the McDonald Observatory. The number of stars

\(^{2}\) A similar relationship was found between Gaia DR2 $G$ and Johnson $V$: $V_G = G \times 0.9901(\pm 0.0014) + 0.2346(\pm 0.0097)$

\(^{3}\) Our HR diagram is based on https://vlas.dev/post/gaia-dr2-hrd/

\(^{4}\) http://dc.g-vo.org/SP_ACE

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Figure 1. Photometric relationship between Johnson/Tycho $V$ vs. Gaia EDR3 $G$ magnitudes, which are valid only for solar twins. Both the red line and the red dashed lines represent the linear fit to the data considering errors in both axis, while the black line is the 1:1 relation. Error bars are smaller than the symbols.

Figure 2. Gaia EDR3 HR diagram of $\sim 1.4$ million stars within 200 pc from the Solar System (the data were obtained using the astroquery package). The colormap represents the stellar density distribution created from the 2D-histogram function of the matplotlib library. The red circles are the solar twin candidates found after applying our color constraints. The Sun is plotted as a yellow solar standard symbol.
observed with each instrument and the internal precision achieved in stellar parameters are summarized in Table 2. In the following are detailed the spectroscopic observations performed in each observatory.

### 3.1 SOAR Telescope at Cerro Pachon

The spectra of the first potential solar twin candidates were obtained using the Goodman spectrophotograph on the 4.1-meter SOAR Telescope under the programs SO2017B-004, SO2018A-005, SO2019A-007, and SO2019B-005 from 2017 to 2019. The solar spectrum was obtained after a short exposure of the Moon. The instrument was configured to use the red camera and the grating of 2100 lines/mm, resulting in a moderate resolving power $R = \lambda / \Delta \lambda = 12000$ and wavelength coverage of 630 Å centered at Hα. The Goodman spectra were reduced using IRAF\(^5\) following the standard procedure, i.e., creation of the master flat, flatfield correction, sky subtraction, order extraction, etc. The radial velocity correction was performed using the rvidlines and dopcor task of IRAF. The obtained spectra were also normalized using IRAF's continuum task with orders ranging from two to five.

### 3.2 Apache Point Observatory

We also obtained the spectra of the solar twin candidates using the ARCES on the 3.5-meter telescope at the Apache Point Observatory. The observations were carried out from 2019 to 2020. The solar spectra were obtained by observing the sky at twilight time. We used the CERES\(^6\) pipeline in order to perform the standard reduction of the ARCES spectra. The ARCES spectrograph provides spectra of $R \sim 31500$ and covers the entire visible wavelength (from 3200-10000 Å). The SNR achieved ranges from 200 to 300 at ~6000 Å.

### 3.3 McDonald Observatory

All the observations were taken during the years of 2018-2020 using the TS23 configured in its high resolution mode on the 2.7-meter Harlan J. Smith Telescope at McDonald Observatory. The spectra of the Sun were obtained through the reflected light from the Moon. As the McDonald Observatory does not have an official pipeline to reduce the TS23 spectra, we have developed our own scripts\(^7\) based on the practical reduction notes of the Dr. Chris Sneed, Dr. Ivan Ramírez, and Dr. Diego Lorenzo-Oliveira. The code consists of a number of semi-automatic python scripts that performs bias subtraction, flat fielding, order extraction, and wavelength calibration using PyRAF (Science Software Branch at STScI 2012). The resulting spectra are free of fringing defects and have $R = 60000$, SNR ~300-500 at ~6500 Å, and cover a wide spectral range (from 3750-9900 Å).

\(^5\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of the Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

\(^6\) https://github.com/rabrahm/ceres

\(^7\) https://github.com/ramstojh

### 4 FUNDAMENTAL PARAMETERS

#### 4.1 Equivalent Widths and Stellar Parameters

In order to perform the standard treatment and analysis of the TS23 spectra, we have developed semi-automatic python scripts\(^8\), whose structure is a combination of two tools: iSpec\(^9\) and IRAF. In summary, the scripts use the iSpec tool to perform the radial/barycentric velocity correction, and the continuum and combine tasks of IRAF to normalize and combine the TS23 spectra. All the processes mentioned above are automatic resulting in spectra of high quality and SNR (~300-500 at 6500 Å). The scripts are also capable of measuring Equivalent Widths (EWS) through Gaussian fits to the line profile using the K zapem kmpfit Package\(^9\) in windows of 6 Å; however, this process is manually performed in order to achieve a higher precision. The method is based on line-by-line equivalent width measurements between the Sun and the object of interest, choosing consistent pseudo-continuum regions for both objects (e.g., Meléndez et al. 2009; Bedell et al. 2014; Yana Galarza et al. 2016; Spina et al. 2018). Besides, the script generates an output file containing information about the local continuum, limits of the Gaussian fits, $\chi^2$ test, excitation potential, oscillator strength, and laboratory log($gf$) values (see Meléndez et al. 2014b). On the other hand, the ARCES spectra are already corrected by radial velocity shifts, we used our python scripts only to measure the EWS, rigorously following the same procedure already explained above.

As in our previous works (e.g., Ramírez et al. 2014; Yana Galarza et al. 2019), we employed the automatic \(q^2\) (qoyllur-quipu)\(^10\) python code to determine the spectroscopic stellar parameters ($T_{\text{eff}}$, log g, [Fe/H], $v_t$) for our sample. In short, the code estimates the iron abundances using the line list from Meléndez et al. (2014b) and the 2019 version of the local thermodynamic equilibrium (LTE) code MOOG (Sneden 1973) with the Kurucz OFNIEW model atmospheres (Castelli & Kurucz 2003). Then, the \(q^2\) employs the spectroscopic equilibrium, which is a standard technique of iron line excitation and ionization equilibrium. As a result, we obtain very reliable stellar parameters with high internal precision $\sigma(T_{\text{eff}}) = 15$ K, $\sigma(\log g) = 0.03$ dex, $\sigma([\text{Fe/H}]) = 0.01$ dex, and $\sigma(v_t) = 0.03$ kms\(^{-1}\). The masses were inferred from an isochrone analysis, which is described in detail in subsection 4.3. Our inferred stellar parameters can be found in Table A1. In order to test the precision of the scripts and the reliability of the results, we compared our stellar parameters with those from Ramírez et al. (2013, 2014) and Spina et al. (2016a, 2018). As shown in Figure 3, there is a good agreement between our results and those obtained using spectrographs of even higher resolution (e.g., HARPS spectrograph with $R \sim 115000$ in Spina et al. (2018)) than the TS23.

### Table 2. Number of stars observed with each instrument and the internal precision achieved in stellar parameters. (*) Number of stars observed in the Northern Hemisphere with $-18^\circ \leq \Delta \text{DEC} \leq +25^\circ$.  

| Instrument | Observed stars | $\sigma(T_{\text{eff}})$ (K) | $\sigma(\log g)$ (dex) | $\sigma([\text{Fe/H}])$ (dex) |
|------------|----------------|-----------------------------|------------------------|-----------------------------|
| Goodman    | 160*           | 190                         | 0.20                   | 0.15                         |
| ARCES      | 20             | 100                         | 0.11                   | 0.08                         |
| TS23       | 147            | 15                          | 0.03                   | 0.01                         |

\(^8\) https://www.blancocuaresma.com/s/iSpec

\(^9\) https://www.astro.rug.nl/software/kapteyn/

\(^10\) https://github.com/astroChasqui/q2

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As discussed earlier, the concept of solar twins changed over time (e.g., Cayrel de Strobel et al. 1981; Friel et al. 1993; Datson et al. 2012; Ramírez et al. 2014), and most of them are generally based on photometric and spectroscopic stellar parameters constraints but not on fundamental parameters that drive evolutionary states. The lack of the latter introduces a bias in the mass of the known solar twins, i.e., on fundamental parameters that drive evolutionary states. The lack of photometric and spectroscopic stellar parameters constraints but not in Figure 3. Comparison between our stellar parameters and those obtained by Ramírez et al. (2013, 2014) (squares and triangles) and Spina et al. (2016a, 2018) (stars and circles). The dashed lines represent the 1:1 ratio, while the green lines are the linear fits for $T_{\text{eff}}$ (left panel, $r_m s = 12$ K), log g (middle panel, $r_m s = 0.03$ dex), and [Fe/H] (right panel, $r_m s = 0.02$ dex).

### 4.2 New solar twins

As discussed earlier, the concept of solar twins changed over time (e.g., Cayrel de Strobel et al. 1981; Friel et al. 1993; Datson et al. 2012; Ramírez et al. 2014), and most of them are generally based on photometric and spectroscopic stellar parameters constraints but not on fundamental parameters that drive evolutionary states. The lack of the latter introduces a bias in the mass of the known solar twins, i.e., on fundamental parameters that drive evolutionary states.

The lack of photometric and spectroscopic stellar parameters constraints but not in Figure 3. Comparison between our stellar parameters and those obtained by Ramírez et al. (2013, 2014) (squares and triangles) and Spina et al. (2016a, 2018) (stars and circles). The dashed lines represent the 1:1 ratio, while the green lines are the linear fits for $T_{\text{eff}}$ (left panel, $r_m s = 12$ K), log g (middle panel, $r_m s = 0.03$ dex), and [Fe/H] (right panel, $r_m s = 0.02$ dex).

### 4.3 Age and Mass

Isochronal mass and age determinations helped us to better understand the evolution of stars, calibrate age correlations as gyrochronology and magnetic activity evolution, and to understand the Chemical Evolution of the Galaxy. However, this method relies on isochrones of stellar evolution models and input stellar parameters ($T_{\text{eff}}$, absolute magnitude ($M_V$) and [Fe/H]) (e.g., Lachaume et al. 1999; Takeda et al. 2007) that usually give large uncertainties (~3-4 Gyr), biases, or sometimes serious spurious age results because...
the $M_V$ is generally estimated from photometry of moderate precision. In order to increase the precision in the method, Ramírez et al. (2013, 2014) replaced the $M_V$ by the spectroscopic log $g$. Using the $q^2$ code, that performs probability distribution functions of ages and masses from the $Y^2$ isochrones, these authors not only were able to achieve precise age values, but also greatly reduce their uncertainties to ~1-2 Gyr (e.g., see the compelling example of HIP 56948 in Meléndez et al. 2012). Spina et al. (2018) improved the $q^2$ interpolation method by including $\alpha$-enhancements, spectroscopic log $g$, and $M_V$ (estimated through Hipparcos/Gaia parallaxes) as input parameters (see their Eq. 3). As a result, these authors further reduce the uncertainties to ~1.0 Gyr (~0.5 Gyr using Gaia DR2 parallaxes). Despite the improvements performed by Ramírez et al. (2014) and Spina et al. (2018) to the isochronal age estimator, there is still a strong dependency on the precision of the spectroscopic log $g$ which at the same time is sensitive to EWs measurements and therefore also to the ionization balance.

In this work, we estimate isochronal ages using both the improved $q^2$ and the Bayesian inference. The improved $q^2$ uses stellar parameters, parallaxes and Johnson $V$ magnitudes as input parameters. In our age estimations we use the precise Gaia EDR3 parallaxes, which are corrected by subtracting $-15 \pm 18$ $\mu$as as suggested by Stassun & Torres (2021). Besides, as the Johnson $V$ is not as precise as Gaia $G$, we used the $V_G$ (estimated from Eq. (2) and with $\sigma(V_G) \sim 0.015$) when the uncertainties of Johnson $V$ are greater than 0.015. It helps us to improve the $q^2$ ages estimation and it is also useful when Johnson $V$ is not available. We found a dispersion of only ~0.04 Gyr between the $q^2$ ages estimated using Johnson $V$ and $V_G$. On the other hand, the Bayesian inference method (Grieves et al. 2018) employs the $Y^2$ evolutionary tracks adopting steps of 0.01 $M_\odot$ in mass, 0.05 dex in metallicity, and 0.05 dex in [\textsc{O}/\textsc{Fe}]. Posterior distributions of ages and other evolutionary parameters are estimated through the proper marginalization of the likelihood as a function of $T_{\text{eff}}, [\text{Fe}/H]^{12}, \log g$, Gaia EDR3 parallaxes (already offset by ~15 $\mu$as) and Gaia DR2 $G$ band photometry. We emphasize that we did not use Gaia EDR3 G band in the Bayesian method as there are not yet bolometric corrections (BC) for it. For the brightest stars ($G < 6$ mag), we corrected the Gaia DR2 $G$ band systematics and applied the BC of Casagrande & VandenBerg (2018) to estimate luminosities. The resulting photometric errors are composed by the quadratic propagation of the nominal $G$ band errors reported by Gaia DR2 and a conservative lower limit of 0.01 mag. The likelihood function is evaluated along each possible evolutionary step (within $\pm 10\%$ of the input parameter space) and simultaneously weighted by metallicity and mass inputs, which are based on the solar neighborhood metallicity distribution (Casagrande & VandenBerg 2018) and Salpeter initial mass function, respectively. The values adopted for each one of the evolutionary parameters result from the median (50% percentile) and $1\sigma$ intervals (16-84% percentile) yielded by its posterior cumulative distributions.

The left panel of Figure 5 shows the $q^2$ ages estimated for our sample using spectroscopic stellar parameters and parallaxes as input parameters (hereafter log $g$ & plx) versus the Bayesian inference ages. There is a good agreement between methods with a dispersion of only ~0.48 Gyr. This dispersion is estimated removing the most prominent outlier, which is a star with [Fe/H]$= -0.5$ dex and $M = 0.85 M_\odot$. In the middle panel of Figure 5, we compare the masses and it shows good agreement with a dispersion of only 0.01 $M_\odot$. As the spectroscopic log $g$ is a fundamental observable for estimating isochronal ages, it is important to make a comparison with the trigonometric gravity. It is estimated from the luminosity ($\propto R^2 T_{\text{eff}}^4$)
and gravity ($\propto M/R^2$) relations to arrive to the following expression:

$$\log g(\text{Trig}) = \log \left( \frac{M}{M_\odot} \right) + 4 \log \left( \frac{T_{\text{eff}}}{T_\odot} \right) + 0.4 V + 0.4 BC$$

$$+ 2 \log \left( \frac{\text{plx}}{1000} \right) + 0.104,$$

(Eq. (3)).

where $V$ is the unreddened visual magnitude, $\text{plx}$ the parallax in milliarcsecond, and $BC$ the bolometric correction. The latter is taken from Meléndez et al. (2006). The last term of Eq. (3) is somewhat different from the literature (e.g., Nissen et al. 1997) because we adopted a slightly different absolute bolometric magnitude value for the Sun ($M_{\text{bol,}\odot} = 4.74$; Bessell et al. 1998). As can be seen in the right panel of Figure 5, there is generally good agreement between the spectroscopic and trigonometric $\log g$ (almost within $2\sigma$) with a dispersion of 0.035 dex. Binary stars (represented by yellow triangles) are not considered into the dispersion estimation in all panels of Figure 5. Therefore, with the above results, we can conclude that the ages determined using $q^2$ are as precise as those from the Bayesian inference. This is somewhat expected since the errors derived in this work are small enough to reduce the importance of the prior probability assumptions present in Bayesian models. However, particular attention is paid in this point because age determination techniques must be also tested with other methods as for instance gyrochronology, asteroseismology, chemical clocks, etc. In this paper, we adopted the ages estimated using the $q^2$ since it is shown that this method gives reliable ages as the Bayesian inference. Therefore, the $q^2$ ages will be used in the figures of the next sections. All our age, mass, and radius results using both methods are summarized in Table A2.

5 STELLAR ROTATION WITH KEPLER & TESS

It is well-known that late-type stars inherit part of the original molecular cloud angular momentum as they are born. Therefore, a large spread in their initial rotational velocities is observed among young open cluster and stellar associations (Bouvier et al. 1997). As the stars arrive at the main sequence, it is expected that magnetized stellar winds, powered by stellar dynamo, drive the angular momentum evolution throughout their evolutionary history, gradually forgetting the initial rotational conditions. Therefore, after a given age, late-type stars tend to converge into well-behaved rotational sequence as a function of mass and age, enabling the calibration of empirical rotation-age-mass relations (Skumanich 1972; Barnes 2003). This age-dating technique is known as gyrochronology and establish a precise rotational clock where stellar ages are estimated from rotational period measurements (Barnes 2003; Meibom et al. 2011, 2015).

In the last decade, a new era for astronomy began with the successful Kepler (Borucki et al. 2010), K2 (Howell et al. 2014), and TESS (Ricker et al. 2015) missions. In this paper, we take advantage of the large public database of these surveys to measure rotation periods ($P_{\text{rot}}$) for our sample. We found 31 precise light curves (one in Kepler, two in K2, and 28 in TESS) where several of them belong to the short and long cadence (e.g., 2-minute and 30-minute cadence observation in TESS). To extract TESS and Kepler light curves, we repeated the same procedure adopted in Lorenzo-Oliveira et al. (2020). The light curves were obtained from target pixel files using pixel level decorrelation technique through the lightkurve\textsuperscript{13} python package (Lightkurve Collaboration et al. 2018). For each target, we remove surrounding pixels eventually contaminated by nearby stars. The resulting light curves are cleaned from outliers beyond $\pm 3\sigma$ and in some cases binned in steps of 0.5 h to enhance the signal-to-noise ratio and also mitigate short-term variability (e.g., oscillations, spacecraft pointing jitter).

$P_{\text{rot}}$ were initially measured through Generalized Lomb-Scargle analysis. Since most of our stars shows moderate to low level of activity, we restricted our search for rotational periods within a reasonable window between 1 and 50 days. Detected rotation periods are defined by signals in the periodograms with false alarm probability below 1%. In the cases where aliases of the strongest detection are also present and statistically significant, we choose to report the secondary detection together with the strongest one. For a sanity test, the $P_{\text{rot}}$ were also estimated through Gaussian Process (GP) that uses a kernel developed from a mixture of two harmonic oscillators (for a complete description see Foreman-Mackey et al. 2020). Figure 6 shows the reduced light curve of HIP 17936 with the GP model plotted in black solid line and its $2\sigma$ model prediction in red shaded region. The $P_{\text{rot}}$ estimated with both methods are in a very good agreement and we use the median of them as the adopted rotational period value (see Table A1).

In Figure 7 are displayed the rotational evolution of our sample

\textsuperscript{13} https://docs.lightkurve.org/index.html
Relative Flux [ppm] 

-10 -5 0 5 10 15 20 25 30 

Time [days] 

Figure 6. TESS light curve (filled circles) of the new solar proxy HIP 17936 observed in one sector. The black line represents the GP model, while the red shaded region its 2σ rotation prediction model.

Figure 7. Age-Rotation diagram for our solar twins and proxies using model predictions from Barnes (2010) calibrated to the Sun (green solar standard symbol) and with variations of ±0.05 M\(_0\) (shaded region). The red dashed line represents the rotational evolution of the Sun.

6 CHROMOSPHERIC ACTIVITY

Thanks to the very good performance of the TS23 spectrograph in the blue part of the spectra, we estimated the activity indices for our sample by measuring the Ca\(\text{II}\) H&K emission line fluxes (3933.664 Å and 3968.470 Å). The normalization of the spectral region bracketing the Ca\(\text{II}\) lines demands a different normalization procedure. In order to ensure the overall consistency of activity measurements, for each star, we performed a differential normalization procedure of the echelle spectral orders that surround the Ca\(\text{II}\) lines. As a template to guide the normalization procedure of a given star, we build a high SNR master spectrum from the large HARPS (\(R = 115000\)) time series and thus degraded the resolving power to match with TS23 observations (\(R = 60000\)). In the cases where no HARPS observations were performed for a given TS23 solar twin candidate, we choose another HARPS star with similar \(T_{\text{eff}}\) and [Fe/H] as a template. The \(S_{\text{HK}}\) index was calculated following the prescription given in Wright et al. (2004). In order to perform a reliable calibration of our \(S_{\text{HK,TS23}}\) indices into the Mount Wilson system (MW), we first selected a subsample of 10 stars whose \(S_{\text{MW}}\) are very well estimated by Lorenzo-Oliveira et al. (2018) and then complemented with 5 new solar-type stars found in the European Southern Observatory (ESO) archive\(^{14}\) also with common observations between HARPS and TS23. This sample of 15 stars is distributed between active and inactive regimes (Table A3). As a result, we obtain the following calibration equation:

\[
S_{\text{MW}} = 0.038(\pm0.015) + 1.048(\pm0.125) \times S_{\text{HK,TS23}},
\]

where the typical standard deviation of the linear fit is 0.0073 (see Figure 8), comparable with calibrations carried out using spectrographs of higher resolving power and stability than TS23 (e.g. HARPS). The converted \(S_{\text{MW}}\) values and their respective errors taking into account photometric and repeatability measurement errors are given in Table A1 for the \(\text{H}\) sample. However, we excluded from our sample stars with \(S_{\text{MW}}\) values estimated in a single patch epoch.

Activity levels were estimated using \(\log R'_{\text{HK}}(T_{\text{eff}})\) index following the procedure given by Lorenzo-Oliveira et al. (2018). We emphasize that \(\log R'_{\text{HK}}(T_{\text{eff}})\) should not be confused with the usual \(\log R'_{\text{HK}}\) based on photometric colors (Noyes et al. 1984). For the most active stars, the difference between both indices is negligible, however substantial differences arise after \(\log R'_{\text{HK}} \sim -4.8\) towards the lowest activity levels. Besides, the updated Ca\(\text{II}\) index \(\log R'_{\text{HK}}(T_{\text{eff}})\) shows improved activity-age correlation for inactive stars. To build this index, Lorenzo-Oliveira et al. (2018) removed the photospheric effect.

\(^{14}\) http://archive.eso.org/wdb/wdb/phase3_spectral/ form?phase3_collection=HARPS
contribution of the $R'_{\text{HK}}$ by using an improved photospheric correction as a function of $T_{\text{eff}}$ (Equation (7) therein) instead of the standard photometric color ($B - V$) (Wright et al. 2004). The uncertainties are estimated through random samples from a Gaussian distribution that takes into account the $\sigma(S_{\text{HK,MW}})$. As a result, we obtained updated chromospheric indices $\log R'_{\text{HK}}(T_{\text{eff}})$ for our sample and they can be also found in Table A1.

In Figure 9 are shown the chromospheric indices versus the ages for our solar proxy sample. The activity-age relation found by Lorenzo-Oliveira et al. (2018) is also plotted as red dashed lines with its $2\sigma$ activity variability prediction band (shaded region). We can clearly see that our new sample of solar twins/proxies also follows this correlation, thereby favouring the chromospheric activity as a useful clock even for stars older than the Sun. However, notice that the activity-age relation in Lorenzo-Oliveira et al. (2018) was derived using high resolving power ($R = 115000$) time-series of Ca II H&K measurements. Besides, the typical $[\text{Fe/H}]$ values of their sample are more narrowed around the solar metallicity ($\pm 0.05$ dex of the solar value) in comparison to our sample. The latter explains the presence of some outliers in our activity-age diagram. The solar analog stars and solar-type stars are not included in Figure 9 as their mass and $[\text{Fe/H}]$ regime are different to the solar proxies.

7 SUMMARY AND CONCLUSIONS

Thanks to the Gaia mission, we found a large sample of solar twins candidates through constraints on color (using Tycho, 2MASS and Gaia EDR3 catalogs) and absolute magnitude (employing Gaia EDR3 parallaxes). As our sample is within 100 pc from Earth, reddening corrections are negligible. The definitive color constraints used for our solar twin hunting program are shown in Table 1 and were established following the spectroscopic solar twin definition given by Ramírez et al. (2014). However, this definition does not consider the evolutionary state of the star, thus introducing a slight bias in the mass distribution in the sample of known solar twins (see Ramírez et al. 2014; Spina et al. 2018). Although the selection criteria of Ramírez et al. (2009) is useful for obtaining precise chemical abundances differentially to the Sun (due to a narrow range in stellar parameters relative to the Sun), that criteria hampers studies dedicated to understand the rotational and magnetic evolution of the Sun. To address this issue for future works, we propose a new class of star like the Sun: solar proxy, whose definition is based not only on stellar parameters constraints, but also on its evolutionary track during the main sequence. In this new definition, the metallicity and the mass define whether a star is a solar proxy or not. These parameters are constrained to be within $\pm 0.15$ dex and 5% to the solar values, thereby assuring that the star follows a similar evolution as the Sun. The log $g$ is assumed to be from ~4.1 to 4.6 dex since this constraint is used only to verify if the star is on the main sequence. As is shown in Figure 4, the $T_{\text{eff}}$ of solar proxies can take values ranging from ~5310–6050 K, however, for precise abundances, it is recommended to work with stars with $T_{\text{eff}}$ within 150–200 K of the solar value in order to avoid 3D and non-LTE effects. Note that the solar proxy limits are not defined by an irregular polygon region, but instead by evolutionary tracks.

Applying all the definitions discussed above, we identified 70 solar proxies, 46 solar analogs and 13 solar-like stars. Their stellar parameters were estimated through the differential analysis and the spectroscopic equilibrium technique. As a result, we obtained a high internal precision ($\sigma(T_{\text{eff}}) = 15$ K, $\sigma(\log g) = 0.03$ dex, $\sigma([\text{Fe/H}]) = 0.01$ dex, and $\sigma(v_t) = 0.03$ km s$^{-1}$). We also search the close solar twin within our Gaia sample by narrowing down the mass, $T_{\text{eff}}$, log $g$, and $[\text{Fe/H}]$ values to 0.03 M$_\odot$, 50 K, 0.05 dex, and 0.05 dex relative to the solar values, respectively. We found 9 potential candidates that meet these rigorous criteria. However, further studies should be performed to confirm these stars as close solar twins (e.g., chemical composition, Li abundances, etc).

Isochronal ages were estimated trough the Yonsei-Yale isochrones models (Yi et al. 2001) and employing two algorithms that use spectroscopic stellar parameters and precise Gaia EDR3 parallaxes as
input parameters. The ages and masses show a good agreement between the methods within the uncertainties. We also estimated the trigonometric gravity to compare with the spectroscopic gravity and we found relatively good agreement between them, thus validating our age results. However, this is not the case for some binary stars, and it is necessary to use other age determinations such as gyrochronology, astroseismology, chromospheric-age relations, etc., in order to evaluate the reliability of the results. We also determine a precise Mount Wilson system calibration for the activity indices ($S_{HK,T23}$) taken with the TS23 spectrograph at McDonald Observatory (see Eq. 4 and Figure 8). With this new calibration, we obtained improved chromospheric indices ($\log R'_{HK}/T_{eff}$): Lorenzo-Oliveira et al. (2018).

Our new sample of solar twins/proxies also follow the activity-age correlation, thereby reinforcing the scenario where stars older than the Sun continue to decrease their chromospheric activity (see Figure 9). Rotational periods were estimated using precise TESS, Kepler, and K2 light curves after applying the Generalized Lomb-Scargle and Gaussian Process methods.

In this work, we provide to the community precise stellar parameters, ages, chromospheric indices and rotational periods (albeit we were not able to detect rotational periods in stars older than the Sun; Figure 7). Finally, the Ínůi survey is ideal for exoplanet searches around stars like the Sun (e.g., Bedell et al., 2015), in the quest for Solar System analogs.

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*Facilities:* McDonald Observatory: Harlam J. Smith 2.7-meter Telescope, TS23 spectrograph. Apache Point Observatory: Astrophysical Research Consortium 3.5-meter Telescope, ARCES spectrograph. SOAR Telescope at Cerro Pachon: The Southern Astrophysical Research (SOAR) 4.1-meter Telescope, Goodman High Throughput Spectrograph.

*Softwares:* numpy (van der Walt et al. 2011), matplotlib (Hunter 2007), pandas (McKinney 2010), astroquery (Ginsburg et al. 2019), IRAF (Tody 1986), iSpec (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019), Kapteyn Package (Terlouw & Vogelaar 2015), MOOG (Sneden 1973), q2 (Ramírez et al. 2014), CERES (Brahm et al. 2017), SP_ACE (Boeche & Grebel 2016).

**DATA AVAILABILITY**

The Ínůi survey is available through MNRAS in its online supplementary material, and its spectra can be shared on request to the corresponding author.

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APPENDIX A: TABLES
Table A1. Solar parameters for the 3rd survey. This table is available in its entirety in machine-readable format at the CDS.

| Identifier | log(Teff) (K) | log(g) (cgs) | log([Fe/H]) (dex) | log(v_t) (km/s) | log(R_*/R_Sun) | Remarks |
|------------|---------------|-------------|-------------------|----------------|---------------|---------|
| HD168069   | 5722.8        | 4.380       | 0.03              | -0.046          | -0.007        |         |
| HD94125    | 5727.9        | 4.466       | 0.03              | -0.016          | -0.008        |         |
| HD94125    | 5727.9        | 4.466       | 0.03              | -0.016          | -0.008        |         |
| HD168069   | 5722.8        | 4.380       | 0.03              | -0.046          | -0.007        |         |
| HD94125    | 5727.9        | 4.466       | 0.03              | -0.016          | -0.008        |         |

Notes. (1) Solar twins, (2) Solar prototypes, (3) Solar anologs, (4) Solar-type stars, (5) Binary star.
| Identifier      | Age (Gyr)  | Mass (M_☉)  | Radius (R_☉)  | Age (Gyr)  | Mass (M_☉)  | Radius (R_☉)  | Remarks |
|-----------------|------------|-------------|---------------|------------|-------------|---------------|---------|
| TYC3130-2191-1  | 8.10 (+0.52) | 0.960 (+0.014) | 1.060 (+0.004) | 8.60 (+0.40) | 0.940 (+0.001) | 1.045 (+0.001) | 1       |
| HIP8522         | 0.70 (+0.97) | 0.999 (+0.004) | 0.902 (+0.004) | 0.60 (+0.50) | 0.998 (+0.008) | 0.893 (+0.008) | 1       |
| HD168069        | 2.20 (+0.10) | 1.050 (+0.008) | 1.100 (+0.009) | 2.20 (+0.50) | 1.050 (+0.010) | 0.993 (+0.001) | 1       |
| HIP103005       | 6.30 (+0.82) | 1.020 (+0.009) | 1.130 (+0.009) | 7.10 (+0.30) | 1.000 (+0.008) | 1.123 (+0.001) | 1       |
| HIP94980        | 2.80 (+1.14) | 1.100 (+0.014) | 1.130 (+0.009) | 7.10 (+0.30) | 1.000 (+0.008) | 1.055 (+0.008) | 1       |
| HIP69709        | 6.90 (+0.91) | 1.030 (+0.009) | 1.130 (+0.009) | 6.90 (+0.91) | 1.030 (+0.009) | 1.130 (+0.009) | 1       |
| HD21374073      | 3.20 (+0.79) | 1.010 (+0.009) | 1.130 (+0.009) | 3.20 (+0.79) | 1.010 (+0.009) | 1.130 (+0.009) | 1       |
| HD148482        | 8.10 (+0.84) | 1.090 (+0.009) | 1.200 (+0.009) | 8.10 (+0.84) | 1.090 (+0.009) | 1.130 (+0.009) | 1       |
| HD181730        | 1.20 (+0.99) | 1.100 (+0.014) | 1.130 (+0.009) | 1.20 (+0.99) | 1.100 (+0.014) | 1.130 (+0.009) | 1       |
| HD235929        | 0.90 (+1.26) | 0.990 (+0.018) | 0.960 (+0.008) | 0.90 (+1.26) | 0.990 (+0.018) | 1.095 (+0.008) | 1       |
| HD235929A       | 4.50 (+1.07) | 1.000 (+0.008) | 1.000 (+0.008) | 4.50 (+1.07) | 1.000 (+0.008) | 1.000 (+0.008) | 1       |
| HIP71989        | 7.40 (+1.04) | 1.000 (+0.008) | 1.130 (+0.014) | 7.40 (+1.04) | 1.000 (+0.008) | 1.130 (+0.014) | 1       |

Notes: (1) Solar twins, (2) Solar proxies, (3) Solar analogs, (4) Solar-type stars, (†) Binary star.
Table A3. Solar twin stars used to calibrated our $S_{HK,TS23}$ indices into the Mount Wilson system (MW).

| ID      | $S_{HK,TS23}$ | $\sigma(S_{HK,TS23})$ | $S_{MW}$ | $\sigma(S_{MW})$ | Reference |
|---------|---------------|----------------------|----------|------------------|-----------|
| HIP7585 | 0.128         | 0.003                | 0.177    | 0.004            | (★)       |
| HIP49756| 0.118         | 0.002                | 0.163    | 0.002            | (★)       |
| HIP79672| 0.125         | 0.001                | 0.167    | 0.004            | (★)       |
| HIP95962| 0.113         | 0.001                | 0.163    | 0.002            | (★)       |
| HIP8507 | 0.129         | 0.005                | 0.174    | 0.005            | (★)       |
| HIP77052| 0.143         | 0.000                | 0.214    | 0.015            | (★)       |
| HIP28066| 0.117         | 0.001                | 0.158    | 0.001            | (★)       |
| HIP85042| 0.112         | 0.001                | 0.158    | 0.004            | (★)       |
| HIP118115| 0.111        | 0.001                | 0.157    | 0.001            | (★)       |
| HIP102040| 0.129        | 0.000                | 0.176    | 0.005            | (★)       |
| HIP113357| 0.109        | 0.004                | 0.154    | 0.001            | (†)       |
| HIP8102 | 0.127         | 0.001                | 0.171    | 0.001            | (†)       |
| HIP1499 | 0.113         | 0.002                | 0.157    | 0.002            | (†)       |
| HIP59532| 0.109         | 0.005                | 0.158    | 0.002            | (†)       |
| HIP106006| 0.114        | 0.001                | 0.158    | 0.003            | (†)       |

Notes. (★) Lorenzo-Oliveira et al. (2018); (†) this work.

Table A4. Spectroscopic binary stars.

| Gaia EDR3 | Identifier |
|-----------|------------|
| 3985360665753530112 | HIP 54191 |
| 1438813773578253312 | TYC 4202-561-1 |
| 2642456024453117056 | HD 224033 |
| 302429645407269120 | TYC 1762-1034-1 |

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