

The solar–stellar connection: Magnetic activity of seismic solar analogs

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Abstract

Finding solar-analog stars with fundamental properties as close as possible to the Sun and studying the characteristics of their surface magnetic activity is a very promising way to understand the solar variability and its associated dynamo process. However, the identification of solar-analog stars depends on the accuracy of the estimated stellar parameters. Thanks to the photometric CoRoT and *Kepler* space missions, the addition of asteroseismic data was proven to provide the most accurate fundamental properties that can be derived from stellar modeling today. Here, we present our latest results on the solar–stellar connection by studying 18 solar analogs that we identified among the *Kepler* seismic sample (Salabert et al., 2016a). We measured their magnetic activity properties using the observations collected by the *Kepler* satellite and the ground-based, high-resolution HERMES spectrograph. The photospheric (S_{ph}) and chromospheric (S) magnetic activity proxies of these seismic solar analogs are compared in relation to the solar activity. We show that the activity of the Sun is comparable to the activity of the seismic solar analogs, within the maximum-to-minimum temporal variations of the 11-year solar activity cycle. Furthermore, we report on the discovery of temporal variability in the acoustic frequencies of the young (1 Gyr-old) solar analog KIC 10644253 with a modulation of about 1.5 years, which agrees with the derived photospheric activity S_{ph} (Salabert et al., 2016b). It could be the signature of the short-period modulation, or quasi-biennial oscillation, of its magnetic activity as observed in the Sun and in the 1-Gyr-old solar analog HD 30495. In addition, the lithium abundance and the chromospheric activity estimated from HERMES confirms that KIC 10644253 is a young and more active star than the Sun.

1 Introduction

The Mount Wilson Observatory (MWO) monitoring (Wilson, 1978; Duncan et al., 1991) of chromospheric activity of main-sequence G and K stars has suggested the existence of two distinct branches of cycling stars, the active and inactive (Saar & Baliunas, 1992; Soon et al., 1993), and that the Sun lies squarely between the two, thus appearing as a peculiar outlier (Böhm-Vitense, 2007). Today, whether the solar dynamo and the related surface magnetic activity are typical or peculiar still remains an open question (Metcalfe et al., 2016). Finding solar-analog stars with fundamental properties as close as possible to the Sun and studying the characteristics of their surface magnetic activity is a very promising way to understand solar variability and its associated dynamo (Egeland et al., 2016). Moreover, the study of the magnetic activity of solar analogs is also important for understanding the evolution of the Sun and its environment in relation to other stars and the habitability of their planets. However, the identification of solar-analog stars depends on the accuracy of

the estimated stellar parameters.

The unprecedented quality of the continuous four-year photometric observations collected by the *Kepler* satellite (Borucki et al., 2010) allowed the measurements of acoustic oscillations in hundreds of solar-like stars (Chaplin et al., 2014). Moreover, the length of the *Kepler* dataset provides a unique source of information for detecting magnetic activity and the associated temporal variability in the acoustic oscillations. Indeed, it is well established that in the case of the Sun, acoustic (p) oscillation frequencies are sensitive to changes in the surface magnetic activity (Woodard & Noyes, 1985). Moreover, the p-mode frequencies are the only proxy that can reveal inferences on sub-surface changes with activity that are not detectable at the surface by standard proxies (e.g., Salabert et al., 2009, 2015; Basu et al., 2012).

Cayrel de Strobel (1996) provided a definition of a solar-analog star based on the fundamental parameters, such as mass and effective temperature. Here, we took advantage of the combination of asteroseismology with high-resolution spectroscopy which substantially improves the accuracy of

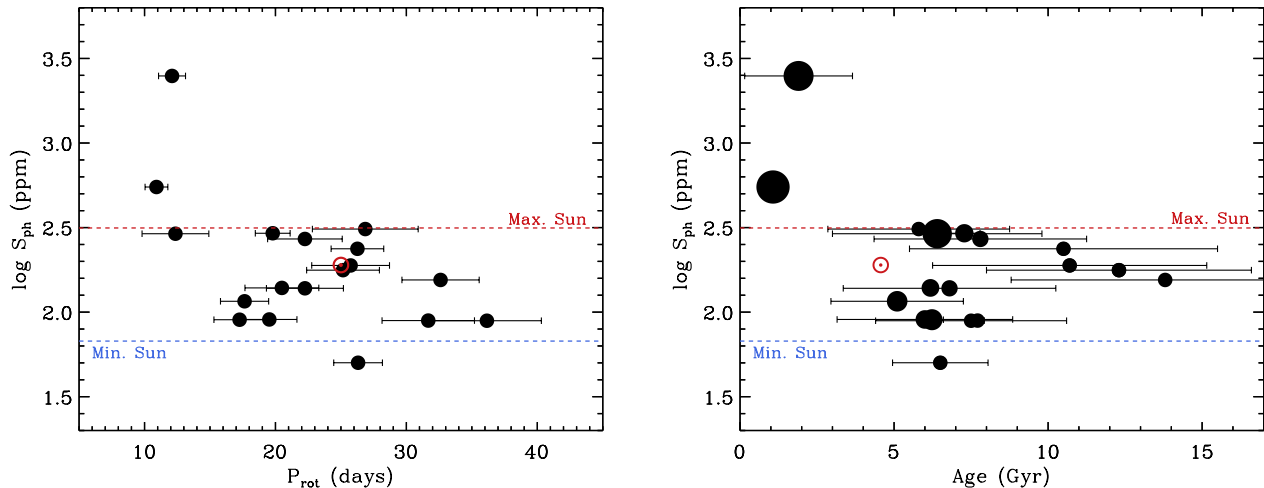


Figure 1: *Left panel:* Photospheric magnetic activity S_{ph} index as a function of the rotational period P_{rot} of the 18 seismic solar analogs identified within the *Kepler* sample of solar-like stars. The mean activity level of the Sun calculated from the VIRGO/SPM observations is represented for a rotation of 25 days with its astronomical symbol (in red), and its mean activity levels at minimum and maximum of the 11-year cycle are represented by the horizontal dashed lines. *Right panel:* Same as the left panel but as a function of the seismic ages. The position of the Sun is also indicated for an age of 4.567 Gyr. The size of the symbols is inversely proportional to the surface rotation P_{rot} . Adapted from Salabert et al. (2016a).

the stellar parameters and reduces their errors (Mathur et al., 2012; Chaplin et al., 2014; Metcalfe et al., 2014; Creevey et al., 2016). Moreover, Mosser et al. (2009) and García et al. (2010) show evidences that the magnetic activity inhibits the amplitudes of solar-like oscillations, what is later on confirmed on a large sample by Chaplin et al. (2011). In the case of the Sun, the amplitudes of the acoustic modes decrease by about 15% between solar minimum and maximum for the low-degree modes (see e.g., Salabert et al., 2003, and references therein), which are the modes detectable in observations of solar-like stars. In consequence, the selection of stars analog to the Sun should include the detection of solar-like oscillations as an additional selection criterium. This is what we called a seismic solar-analog star, thus extending the Cayrel de Strobel (1996)’s definition. Furthermore, we included in the sample only stars with a measured rotation period (García et al., 2014) to ensure the presence of surface magnetic activity. A total of 18 seismic solar analogs were thus identified (Salabert et al., 2016a) from the photometric *Kepler* observations of solar-like oscillators (Chaplin et al., 2014).

2 Magnetic activity of seismic solar analogs

2.1 Photospheric magnetic activity

Based on the rotation period, P_{rot} , of a given star, Mathur et al. (2014b) defined a photospheric proxy of stellar magnetic variability, called S_{ph} , derived from the analysis of the light-curve fluctuations over sub series of length $5 \times P_{\text{rot}}$. Its calculation was adapted from the starspot proxy proposed by García et al. (2010) where they show that the photometric proxy of the F-type HD 49933 observed by the Convection, Rotation, and planetary Transits (CoRoT, Baglin et al., 2006) satellite is correlated with the measured p-mode frequency

shifts and anti-correlated with the mode amplitudes leading them to conclude that the proxy is related to magnetic activity. As the variability in the light curves can have different origins and timescales (magnetic activity, convection, oscillations, companion), the rotation period needs to be taken into account. The S_{ph} proxy was used to estimate the magnetic activity of several *Kepler* targets (Mathur et al., 2014b; García et al., 2014; Salabert et al., 2016a,b; Lund et al., 2016) and CoRoT (Ferreira Lopes et al., 2015) targets, where, for instance, spectral observations used to derive established activity proxies (as the S and R'_{HK} indices) do not exist and are difficult to obtain for a large number of faint stars. We note however that S_{ph} represents a lower limit of the photospheric activity as it depends on the inclination angle of the star’s rotation axis in respect to the line of sight. This is however assuming that the development of the latitudinal distribution of the starspots is comparable to the one observed for the Sun, that is from mid to low latitudes. Other photospheric metrics were developed to study the stellar variability in the *Kepler* data but they do not use the knowledge of the rotation rate in their definition (Basri et al., 2010, 2011; Chaplin et al., 2011; Campante et al., 2014). Here, the photospheric activity S_{ph} index of the 18 identified seismic solar analogs was estimated through the analysis of the *Kepler* long-cadence observations which were calibrated using the *Kepler* Asteroseismic Data Analysis and Calibration Software (KADACS, García et al., 2011).

The left panel of Fig. 1 shows the S_{ph} of the 18 seismic solar analogs as a function of their surface rotation period P_{rot} . The mean value of the solar S_{ph} over cycle 23 calculated from the photometric observations collected by the Variability of Solar Irradiance and Gravity Oscillations (VIRGO; Fröhlich

et al., 1995) instrument onboard the Solar and Heliospheric Observatory (SoHO; Domingo et al., 1995) spacecraft is also indicated, as well as the corresponding values at minimum and maximum of activity. We note that the VIRGO instrument is composed of three Sun photometers (SPM). The photospheric activity of the identified 18 seismic solar analogs is comparable to the Sun, within the range of activity covered over a solar cycle. The right panel of Fig. 1 shows for the same set of 18 stars the measured photospheric activity as a function of their seismic ages (Mathur et al., 2012; Chaplin et al., 2014; Metcalfe et al., 2014) compared to the Sun. We note the large differences in the uncertainties of the age estimates depending on the applied method to derive them (see Metcalfe et al., 2014). It is also worth noticing that stars between 2 and 5 Gyr-old are missing in our sample. Nevertheless, the position of the Sun indicates that its photospheric activity is compatible with older solar analogs. Although the *Kepler* seismic sample contains only few stars younger than the Sun, our results show that the two youngest seismic solar analogs in our sample below 2 Gyr-old are actually the most active, as well as being the fastest rotating stars. Furthermore, the photospheric activity of stars older than the Sun seems to not evolve much with age. Pace (2013) studied the chromospheric activity of field dwarf stars as an age indicator, and shows that it stops decaying for stars older than 2 Gyr-old. The photospheric activity of the solar analogs analyzed here is observed to be comparable to the Sun after 2 Gyr-old within the minimum-to-maximum range of the solar cycle, given the uncertainties on the age estimates and the limited size of our sample. This is also assuming that our sample is not too biased towards stars observed during periods of low activity of their magnetic cycles, or that they are not in an extended cycle. Nevertheless, observations of additional solar analogs younger than the Sun are needed to fill the range of ages below 5 Gyr-old.

2.2 Chromospheric magnetic activity

In addition, the chromospheric activity S index of these 18 solar analogs was estimated from spectroscopic observations collected with the HERMES spectrograph (Raskin et al., 2011) mounted on the 1.2-m MERCATOR telescope at the Observatorio del Roque de los Muchachos (La Palma, Canary Islands, Spain). A detailed description of the data processing of the HERMES observations can be found in Beck et al. (2016). The S index measures the strength of the plasma emission in the cores of the Ca II H&K lines in the near ultra violet (Wilson, 1978). The result is dependent on the instrumental resolution and on the spectral type of the star. However, as the selected stars were chosen for all having comparable stellar properties to the Sun, the estimated values of the S index can be thus safely compared between each others.

The comparison between the photospheric S_{ph} and the chromospheric S magnetic activity proxies is shown on Fig. 2 for a subset of 13 stars with a signal-to-noise ratio (S/N) in the near ultra violet $S/N(\text{Ca}) > 15$ (see details in Salabert et al., 2016a). We note that the S index was scaled to the MWO system following the HERMES instrumental scaling factor derived by Beck et al. (2016). The mean values at minimum and maximum along the solar cycle of the photospheric (see Section 2.1) and chromospheric (Egeland et al., submitted; Hall & Lockwood, 2004) magnetic activity levels are also represented. The resulting activity box corresponds to the range of change in solar activity along the 11-year magnetic cycle. Although the sample of stars is small, the S_{ph} and S indices

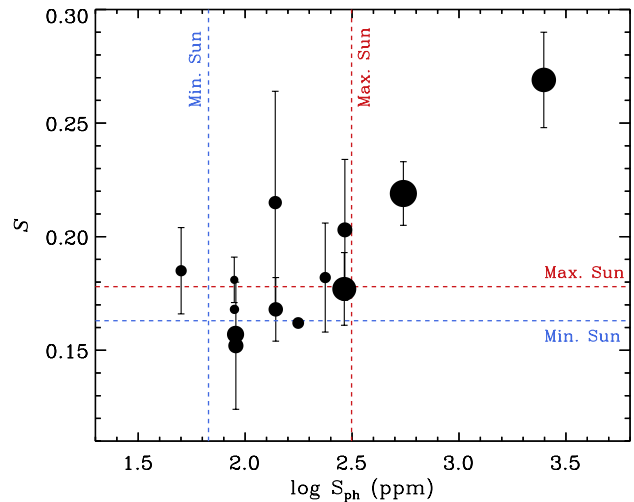


Figure 2: Chromospheric S index derived from HERMES observations and calibrated into the MWO system as a function of the photospheric S_{ph} index. The corresponding activity levels of the Sun at minimum and maximum of its 11-year magnetic cycle are represented by the horizontal and vertical dashed lines. The symbol size is inversely proportional to the rotation period P_{rot} . Adapted from Salabert et al. (2016a).

are observed to be complementary, within the errors. We note also that both proxies were not estimated from contemporaneous *Kepler* and HERMES observations, introducing a dispersion partly related to possible temporal variations in the stellar activity. Nevertheless, it confirms that S_{ph} can complement the classical S index for activity studies. Furthermore, the level of activity of solar analogs observed with the Mount Wilson program (Baliunas et al., 1996; Donahue et al., 1996) is in agreement with our *Kepler* sample, giving additional confidence in our determination of the activity.

3 Comparison with solar magnetic activity

The photospheric activity proxy S_{ph} of the Sun was calculated for sub series of $5 \times P_{\text{rot}} = 125$ days (with $P_{\text{rot}} = 25$ days) over 4720 days of the VIRGO/SPM observations covering the entire solar cycle 23 (1996–2008). The resulting temporal evolution of S_{ph} is compared in Fig. 3 to the some standard solar proxies which were averaged over the same sub series: (1) the total sunspot number¹; (2) the total sunspot area²; (3) the chromospheric Ca II K-line emission³; (4) the 10.7-cm radio flux⁴. We also compared the S_{ph} to the temporal variations of the acoustic low-degree oscillation frequencies extracted over the same sub series of VIRGO/SPM observations following the methodology described in Salabert

¹Source: WDC-SILSO, Royal Observatory of Belgium at <http://www.sidc.be/silso/datafiles>

²Source: <http://solarscience.msfc.nasa.gov/greenwch.shtml>

³Source: Sacramento Peak Observatory at <http://nsosp.nso.edu/>

⁴Source: National Geophysical Data Center at <http://www.ngdc.noaa.gov/stp/solar/solardataservices.html>

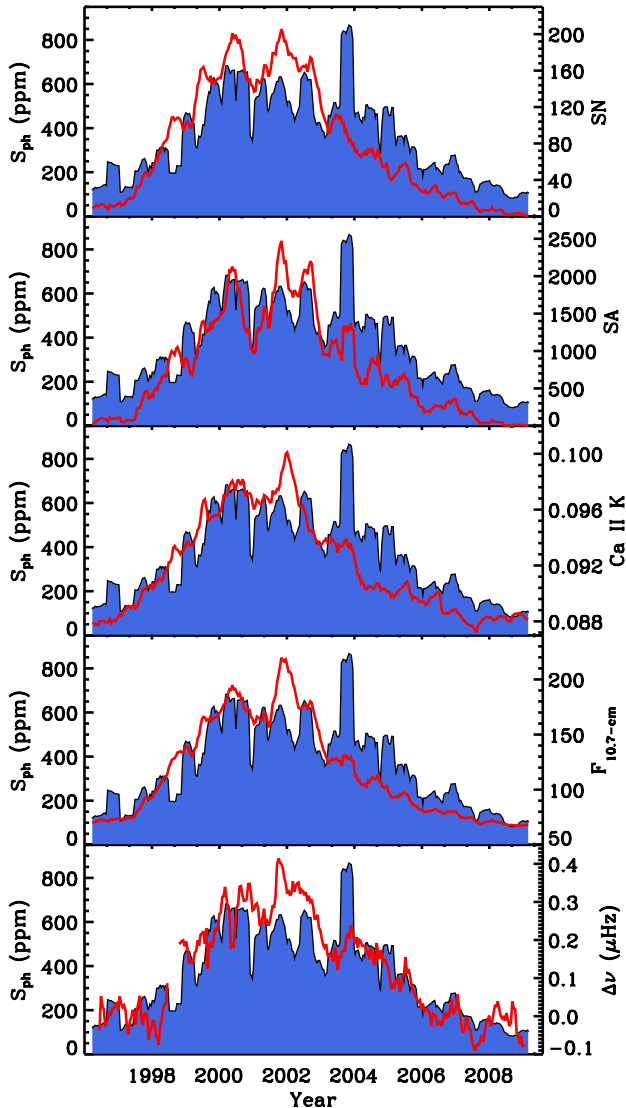


Figure 3: Photospheric activity proxy S_{ph} measured from the photometric VIRGO/SPM observations (blue filled) as a function of time and compared to some standard indices of solar activity (red solid lines). *From top to bottom*: the right-hand y axis corresponds to the sunspot number (SN); the sunspot area (SA); the Ca II K-line emission index in Å; the 10.7-cm radio flux ($F_{10.7\text{-cm}}$) in $10^{-22} \text{ s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1}$; and the frequency shifts $\Delta\nu$ of the acoustic low-degree oscillations in μHz .

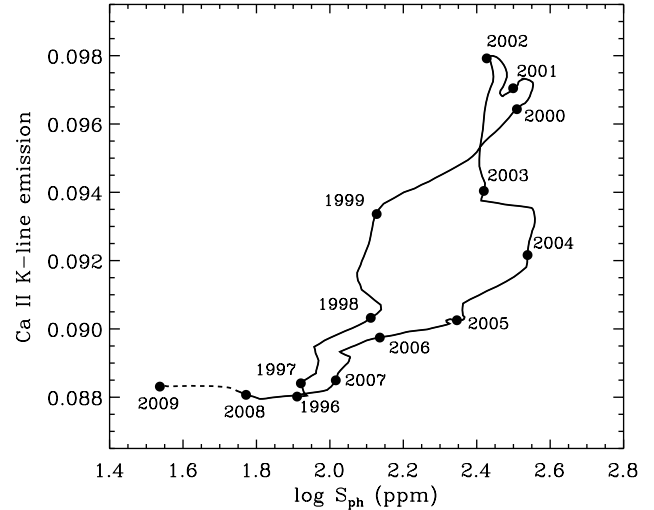


Figure 4: Solar Ca II K-line emission as a function of the photospheric magnetic proxy S_{ph} of the Sun during the solar cycle 23 (1996–2008) and smoothed over one year. The first year of cycle 24 is also represented in dashed line. The start of each year is indicated. Adapted from Salabert et al. (2016a).

et al. (2015). Figure 3 clearly demonstrates that the S_{ph} index is a good photospheric proxy for solar activity.

Furthermore, to better understand the relation between the photospheric and chromospheric magnetic activity of the solar analogs represented in Fig. 2, we directly compared the temporal variations of the photospheric S_{ph} index of the Sun to the Ca II K-line emission index (Fig. 4). As in Fig. 3, the period covered corresponds to the solar cycle 23. For illustrative purpose, the data points in Fig. 4 were smoothed over a period of one year. The start of each year is also indicated. The relationship between the two proxies varies between the rising and falling phases of the solar cycle following an hysteresis pattern. Such hysteresis is observed in a wide range of solar observations between photospheric and chromospheric activity proxies, as well as with the p-mode frequency shifts (e.g., Bachmann & White, 1994; Jiménez-Reyes et al., 1998; Tripathy et al., 2001; Özgüç et al., 2012). Finally, Fig. 4 supports the complementarity between the photospheric S_{ph} and chromospheric S proxies observed for the solar analogs in Fig. 2.

4 Magnetic variability in the young solar analog KIC 10644253

With a rotation period of 10.91 ± 0.87 days (García et al., 2014), the solar analog KIC 10644253 (BD+47 2683, $V = 9.26$) is the youngest solar-like pulsating star observed by *Kepler* with an age of 1.07 ± 0.25 Gyr (Metcalfe et al., 2014) and one of the most active (García et al., 2014). KIC 10644253 is thus an excellent candidate for investigating the magnetic activity of a young Sun with asteroseismic data. In addition to the Sun, temporal variations of p-mode frequencies related to magnetic activity were so far observed in only three stars: the F-type stars HD 49933 (García et al., 2010) and

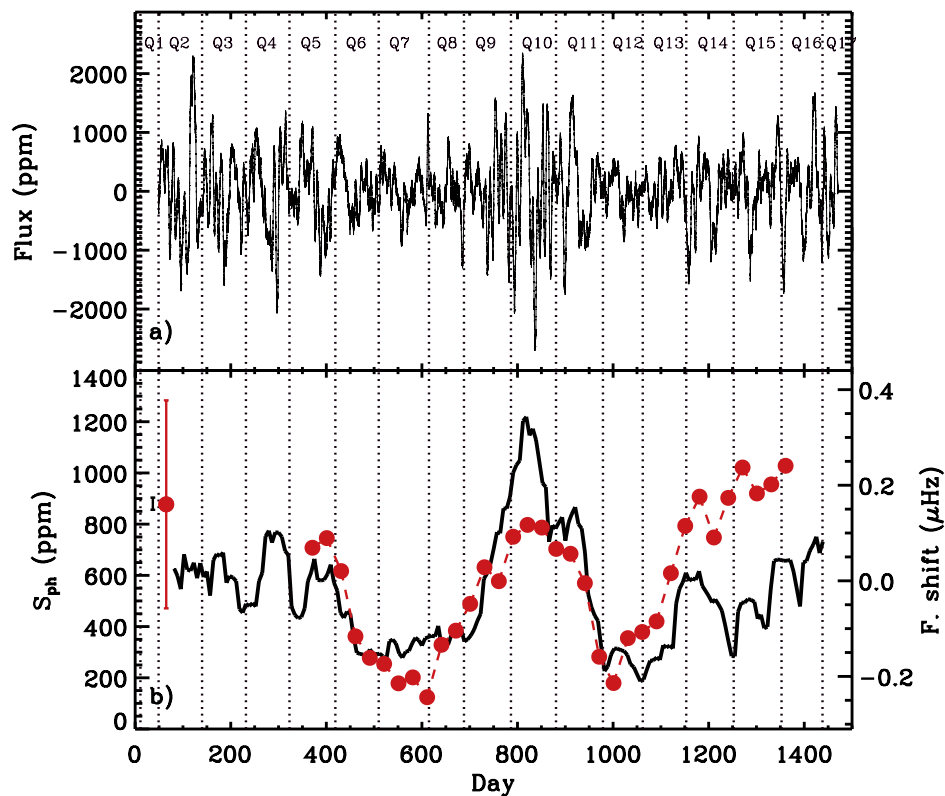


Figure 5: *Top panel*: Photometric long-cadence observations of KIC 10644253 collected over 1411 days by the *Kepler* satellite as a function of time. *Bottom panel*: Photospheric activity S_{ph} index (black) of KIC 10644253 as a function of time compared to the frequency shifts obtained from the cross-correlation analysis (red circles). The frequency shifts were extracted from the continuous short-cadence observations from Q5 to Q17. The associated mean uncertainties are illustrated in the upper left-hand corner using the same color code. In the two panels, the vertical dotted lines represent the observational length of each *Kepler* quarter from Q1 to Q17. Adapted from Salabert et al. (2016b).

KIC 3733735 (Régulo et al., 2016), and the solar-analog G-type KIC 10644253 (Salabert et al., 2016b).

To study the temporal variations of the low-degree, p-mode oscillation frequencies observed in KIC 10644253, the *Kepler* short-cadence dataset was split into contiguous 180-day-long sub series. The associated power spectra were analyzed using both peak-fitting (Ballot et al., 2011; Salabert et al., 2011) and cross-correlation (Régulo et al., 2016) independent methods and the corresponding frequency shifts $\Delta\nu$ extracted (Salabert et al., 2016b). In addition, the light curve was analyzed to estimate the S_{ph} over sub series of $5 \times P_{\text{rot}} = 54.55$ days. Figure 5 shows that both the photospheric S_{ph} and the frequency shifts $\Delta\nu$ present the signature of magnetic activity with a significant temporal variability. A modulation of about 1.5 years is measured in both observables of about 900 ppm for S_{ph} and 0.5 μHz for the frequency shifts. It could be the signature of the short-period modulation, or quasi-biennial oscillation, of its magnetic activity as observed in the Sun (see, e.g., Fletcher et al., 2010). The variations found in KIC 10644253 at a rotation period of about 11 days is analogous to what is found by Egeland et al. (2015) from the study of the temporal variations of the Mount Wilson S index in the solar analog HD30495 falling on the inactive branch (Böhm-Vitense, 2007). Moreover, the comparison between magnitude and frequency dependence of the frequency shifts measured for KIC 10644253 with the ones obtained for the Sun indicates that the same physical mechanisms are involved in the sub-surface layers in both stars.

The analysis of the spectroscopic observations collected by the HERMES instrument shows that KIC 10644253 is about 18% chromospherically more active than the Sun with a S index of 0.213 ± 0.008 . Its high lithium abundance of 2.74 ± 0.03 dex and its effective temperature of 6006 ± 100 K mean that the lithium at the surface has not been depleted yet by internal processes (Ramírez et al., 2012). This is thus validating its young age estimated from seismology and in agreement with a rotation of about 11 days from gyrochronology (Meibom et al., 2011; van Saders et al., 2016). When comparing the measured lithium abundance with its theoretical evolution, Beck et al. (submitted) found a good consensus with the age and mass derived from asteroseismology. Furthermore, among the 18 solar analogs in this sample, KIC 10644253 has the highest lithium abundance. See also Beck et al. in these proceedings.

5 Conclusions

The characteristics of the surface magnetic activity of solar analogs can provide useful new constraints to better understand the variability of the Sun and its underlying dynamo. Here, we analyzed the sample of main-sequence stars observed by the *Kepler* satellite for which solar-like oscillations were detected (Chaplin et al., 2014) and rotational periods measured (García et al., 2014). We identified 18 seismic solar analogs (Salabert et al., 2016a) from the asteroseismic stellar properties found in the literature (Mathur et al., 2012; Chaplin et al., 2014; Metcalfe et al., 2014). We then studied the properties of the photospheric and chromospheric magnetic activity of these stars in relation of the Sun (Salabert et al., 2016a). The photospheric activity proxy S_{ph} was derived by means of the analysis of the *Kepler* observations, while the chromospheric activity proxy S was measured with follow-up, ground-based spectroscopic observations collected

by HERMES spectrograph.

We showed that the magnetic activity of the Sun is comparable to the activity of the seismic solar analogs studied here, within the maximum-to-minimum activity variations of the Sun during the 11-year cycle. As expected, the youngest and fastest rotating stars are observed to actually be the most active of our sample. The comparison of the photospheric S_{ph} with the well-established chromospheric S shows that the S_{ph} index can be used to provide a suitable magnetic activity proxy. Moreover, the S_{ph} can be easily estimated for a large number of stars with known surface rotation observed simultaneously with photometric space missions, while the estimation of the associated S index would be highly difficult to achieve as it would require a lot of time of ground-based telescopes to collect enough spectroscopic data for each individual target. Further, these photometric targets are rather faint for spectroscopy observations.

The properties of the young (1 Gyr-old) solar analog KIC 10644253 make this star an excellent candidate for investigating the solar–stellar connection by studying the temporal variability of the magnetic activity of a young Sun with asteroseismic data (Salabert et al., 2016b). Indeed, we showed the existence of a modulation of about 1.5 years which is measured in both the low-degree, p-mode frequency shifts $\Delta\nu$ and in the photospheric activity S_{ph} index. This modulation could be the signature of the short-period modulation of its magnetic activity as observed in the Sun (see, e.g., Fletcher et al., 2010) and in the 1-Gyr-old Mount Wilson solar analog HD 30495 (Egeland et al., 2015) which falls on the inactive branch (Böhm-Vitense, 2007). In addition, the lithium abundance and the chromospheric activity estimated from HERMES confirms that KIC 10644253 is a young and more active star than the Sun.

Acknowledgments

The authors wish to thank the entire *Kepler* team, without whom these results would not be possible. Funding for this Discovery mission is provided by NASA’s Science Mission Directorate. The ground-based observations are based on spectroscopy made with the Mercator Telescope, operated on the island of La Palma by the Flemish Community, at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. This work utilizes data from the National Solar Observatory/Sacramento Peak CaII K-line Monitoring Program, managed by the National Solar Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under a cooperative agreement with the National Science Foundation. The research leading to these results has received funding from the European Community’s Seventh Framework Programme ([FP7/2007-2013]) under grant agreement no. 312844 (SPACEINN). The research leading to these results has also been supported by grant AYA2012-39346-C02-02 of the Spanish Secretary of State for R&D&i (MINECO). DS and RAG acknowledge the financial support from the CNES GOLF and PLATO grants. PGB acknowledges the ANR (Agence Nationale de la Recherche, France) program IDEE (no. ANR-12-BS05-0008) "Interaction Des Etoiles et des Exoplanètes". JDNJr acknowledges support from CNPq PQ 308830/2012-1 CNPq PDE Harvard grant. RE is supported by the Newkirk Fellowship at the High Altitude Observatory. SM acknowledges support from the NASA grant

NNX12AE17G and NNX15AF13G. TM acknowledges support from the NASA grant NNX15AF13G. DS acknowledges the Observatoire de la Côte d'Azur for support during his stays. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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