SF2A 2021
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STELLAR MAGNETIC ACTIVITY OF SOLAR-LIKE STARS ALONG THEIR EVOLUTION: IMPACT ON EXOPLANET HABITABILITY

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Abstract. Exoplanet search has been at the center of many space missions such as CoRoT, *Kepler*, TESS, and PLATO in a near future. In particular, a special attention is given to exoplanet that could be habitable. While this requires conditions on the planet orbit that depend on the spectral type of the host star, the level of the magnetic activity is key as it would have a non-negligible impact on the development of life, such as sweeping away the planet atmosphere. It is thus important to know how magnetic activity evolves during the lifetime of a star. In this review, I will show what we have learned on the magnetism of solar-like stars on the main sequence up to the red-giant branch. I will mostly focus on stars observed by the *Kepler* mission and for which surface rotation periods have been measured with photometric data. These studies will provide some insights, especially for the PLATO mission.

Keywords: Solar-like stars; Magnetic activity; Stellar evolution; Habitability of exoplanets; NASA *Kepler* mission

1 Introduction

The last decade, the search and discovery of exoplanet has undergone a leap forward with the space missions CoRoT (COnvection, Rotation, Transits Baglin et al. 2006), *Kepler* (Borucki et al. 2010), K2 (Howell et al. 2014), and TESS (Transiting Exoplanet Survey Satellite Ricker et al. 2015). More than 4,000 confirmed exoplanets are known*. However, the search for planets in the habitable zone is still on. While the "goldilock zone" depends on the spectral type of the host star, it is also important to take into account the radiation emitted by the latter. The NASA mission TESS has the goal to look for exoplanets in the habitable zone. Given that M dwarfs are the most numerous stars and that the the habitable zone is closer compared to G dwarfs, more focus is given to M dwarfs (e.g. Kostov et al. 2019; Günther et al. 2019; Bluhm et al. 2020; Gilbert et al. 2020; Van Eylen et al. 2021). Usually, those stars have higher X-ray and UV radiation compared to earlier type stars and the magnetic activity of stars needs to be studied in order to better assess the habitability and development of life on the exoplanets detected around them.

An interesting system is Proxima Centauri, the closest star to our Sun, which is an M dwarf hosting a super-Earth (Anglada-Escudé et al. 2016). The X-ray emission received by the planet is 400 times larger than for Earth but Bolmont et al. (2017) showed that for similar systems, the water loss could still be small enough to allow the planet to be habitable. In the same direction, Abrevaya et al. (2020) led experimental studies of flare impact on micro-organisms survival and measured viable counts that remained above the Level Of Detection up to 600 s after a flare. They found that a small part of a microbial population irradiated during a flare is able to survive.

Knowing the level of magnetic activity of the planet host star is thus important not only for different spectral types but also at different evolutionary stages. For a star like the Sun, stellar magnetic activity results from the interplay between rotation, convection, and magnetic field. Several models have been developed for the Sun that are based on dynamo theory. In one of the most common dynamo theory, called $\alpha\Omega$ dynamo, two different effects are taken into account to explain the changes in the magnetic field geometry: the Ω effect that

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comes from the latitudinal differential rotation on the surface of the star and the α effect that is responsible for local twists of the magnetic field. The different models that have been developed are either 2- or 3-D and can be mean field, thin shell or distributed dynamos (e.g. MacGregor & Charbonneau 1997; Augustson et al. 2013; Brun & Browning 2017; Jouve et al. 2020). While a lot of effort has been undertaken to understand the detailed mechanisms responsible for the magnetic activity of stars, in particular to reproduce what is observed for the Sun, in this review, we will focus on the observations of magnetic activity of stars (from F to M-type) from the main sequence and as a function of age.

2 Proxies for Stellar Magnetic Activity

Stellar magnetic activity can be studied using different indexes. Chromospheric emission can be studied with spectroscopy with lines such as Ca HK or Hα. Other observations include X-ray and UV measurements. Flares and spots (or active regions) can also be studied with photometric data. Finally, it has been shown that magnetic activity of the Sun and solar-like stars affect the properties (frequency and amplitude) of the acoustic modes observed in those stars (e.g. Salabert et al. 2009; García et al. 2010; Kiefer et al. 2017; Santos et al. 2018; García & Ballot 2019). In the following subsections we will show examples of works done for some of those different types of observations.

2.1 Spectroscopic observations

Almost fifty years ago, a large spectroscopic survey was started at the Mount Wilson Observatory in order to study magnetic activity of solar-like stars through the chromospheric emission from the CaHK lines (Wilson 1978). This allowed the follow up of several hundreds of stars during several decades. Later on, more surveys were led such as at the Lowell observatory (e.g. Hall et al. 2007) or the SMARTS telescope (e.g. Metcalfe et al. 2010). HARPS spectra have also been used for more than 4,000 cool stars (Boro Saikia et al. 2018). These observations have shown that different types of variability can be observed with stars showing regular cycles, stars with flat variability, or stars with some variability but no regular patterns (e.g. Baliunas et al. 1995).

A clear relation between the activity cycle and the rotation period was also seen using these observations, where two branches appeared (also called the active and inactive branches). An interesting feature was that the Sun was just in between these branches making it peculiar compared to other solar-like stars (Böhm-Vitense 2007). However that position can be more or less obvious depending on the parameters considered (Brandenburg et al. 2017).

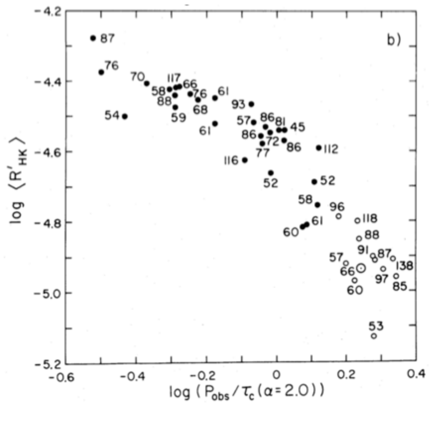

Fig. 1. Chromospheric activity index (R'_{HK}) as a function of the Rossby number for stars observed with the Mount Wilson Observatory. The Sun is represented with the solar symbol. Extracted from Noyes et al. (1984).

One key parameter for magnetic activity and dynamo models is the Rossby number (Ro), which is the ratio between the rotation period and the convective turnover time. There are different ways of computing it (e.g. Noyes et al. 1984; Wright et al. 2011; Brun et al. 2017; Corsaro et al. 2021; Lehtinen et al. 2021) but as shown in Figure 1, in general there is a clear relation between the chromospheric activity index (R'_{HK}) and the Rossby number. When Ro increases the magnetic activity decreases. For stars on the main sequence, the increase of Ro is usually due to the increase of the rotation period, which means that the stars are older as known with age-rotation relations (Skumanich 1972; Barnes 2007). Mamajek & Hillenbrand (2008) looked into the activity-age relations using cluster data, obtaining a precision of ∼0.2 dex for stars younger than the Sun.

2.2 X-ray luminosity and Flares

X-ray luminosity measurements are also an interesting proxy for magnetic activity. X-rays are emitted from stellar coronae that are constituted of magnetic hot plasma. The heating of the corona appears to come from the magnetic activity of the star. Figure 2 shows the X-ray emission of a large sample of stars from M to G dwarfs as a function of Ro (Wright et al. 2018). Two regimes can be noted: the saturated and unsaturated regimes where the knee between the two is at Ro∼0.1. The unsaturated regime follows what is expected with the evolution of magnetic activity with rotation periods. The common explanation for these two regimes is based on the type of dynamo operating in the stars (Barnes 2003). For the low Ro, i.e. fast rotators, this is the "Convective" sequence while for the slower rotators, this is the "Interface" sequence. The fact that fully convective M dwarfs show a similar behavior is quite surprising suggesting that those stars have a similar dynamo to the one of partially convective stars.

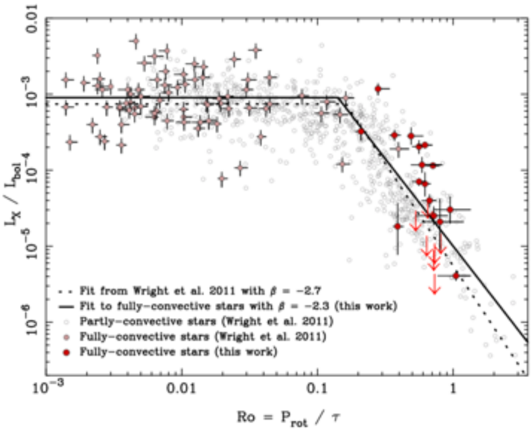

Fig. 2. X-ray luminosity as a function of the Rossby number. Partially convective stars are represented with grey circles and fully convective stars are represented with color symbols.Extracted from (Wright et al. 2018).

Flares are another manifestation of the magnetic activity of stars. The *Kepler* mission (even more with the very high cadence mode of TESS) has allowed us to study flares in a large number of stars, showing that stellar flares can be much more energetic than solar flares. Yang & Liu (2019) analyzed the *Kepler* providing a large flare catalog. By measuring the flare energy for 3,240 stars with 162,262 flare events, they found that the flare activity behaves very similarly to the X-ray luminosity as a function of the Rossby number. They also looked at differences with spectral types, showing that for hotter stars the flare energy decreases in such way that M dwarfs have more energetic flares.

2.3 Spectropolarimetric observations

Spectropolarimetric observations allow us to measure the magnetic field of stars. The Bcool[†] team has been leading a survey of spectropolarimetric observations at the NARVAL (Aurière 2003) and ESPaDOnS (Donati 2003) spectropolarimeters. By analyzing 170 solar-like stars observed for 7 years they measured the magnetic field from Stokes parameters. They studied the relation with ages, where ages were derived from the $R'_{\rm HK}$ relations. They found that the magnetic field also decreases when the star gets older (Marsden et al. 2014).

3 Recent results from *Kepler* photometric observations

Photometric observations, as done by the *Kepler* mission, not only provide information about transiting exoplanets but allows us to study different types of variability of the stars. With high-precision observations, we

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can study stellar surface rotation thanks to the presence of spots or active regions that come in and out of view.

3.1 Measuring surface rotation and magnetic activity level

When a star is active, we can measure its rotation period through the modulation in the lightcurves. Several techniques can be used to measure that periodicity (Lomb-Scargle periodograms, Auto-correlation function, time-frequency analysis, Gaussian Processes...). With hundreds of thousands of stars observed by the *Kepler* mission, many studies were done to measure the surface rotation of stars (e.g. Reinhold et al. 2013; McQuillan et al. 2014; García et al. 2014; Santos et al. 2019; do Nascimento et al. 2020; Santos et al. 2021).

Since the measurement of a rotation period is related to the presence of magnetic features on the surface of a solar-like star, we can measure a proxy of magnetic activity with the standard deviation in the lightcurve. Several proxies have been used with *Kepler* data such as $R_{\rm var}$ (Basri et al. 2013) or $S_{\rm ph}$ (Mathur et al. 2014).

The most recent catalog of solar-like stars and subgiants contain rotation periods for more than 55,000 stars (Santos et al. 2021), constituting the largest catalog available so far. Rotation periods were obtained from the analysis of more than 160,000 stars observed with *Kepler* for up to 4 years by using a combination of auto-correlation function, wavelet analysis, and machine learning (Mathur et al. 2010; Ceillier et al. 2017; Breton et al. 2021). Figure 3 shows the distribution of the magnetic activity proxy $S_{\rm ph}$ as a function of effective temperature for main-sequence stars (top panel) and subgiants (bottom panel) showing that magnetic activity is higher for low-mass stars.

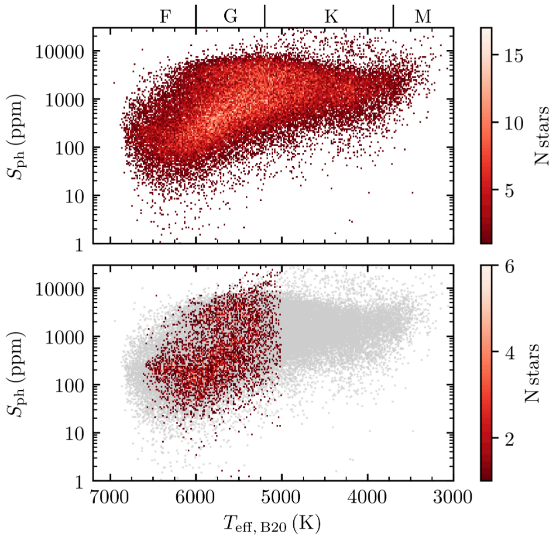

Fig. 3. Magnetic activity proxy $S_{\rm ph}$ vs $T_{\rm eff}$ for the *Kepler* targets with measured rotation periods color-coded with the number of stars: mains-sequence stars (top) and subgiants (bottom panel). Extracted from Santos et al. (2021).

3.2 Evolution of stellar magnetic activity

With such a large sample, we can start to study how the dynamics of solar-like stars evolve with age and as a function of other stellar parameters.

By cross-matching the sample of stars with measured rotation periods and metallicity from spectroscopic surveys, See et al. (2021) studied how the magnetic proxy $R_{\rm var}$ changed with metallicity. They compared their observations with stellar evolution models that included angular momentum transport. They found that the magnetic activity level is higher when the star is more metallic in agreement with the models.

That sample includes a subsample of stars with detection of acoustic modes (García et al. 2014) for which precise ages can be derived with asteroseismology. By comparing the observed rotation periods with *Kepler* with models including classical process for the angular momentum transport, van Saders et al. (2016) showed that the models predicted longer rotation periods than the observed ones, suggesting that the magnetic braking stops near the age of the Sun and that the Sun could be in a transition phase. Later, Metcalfe & van Saders

(2017) linked that transition to the peculiar position of the Sun in the activity cycle period as a function of rotation period where stars could go from one branch to the other during its evolution as shown by the dash lines in Figure 4. This theory assumes that the magnetic activity of the Sun will undergo a drastic decrease while the rotation period will remain unchanged for some time.

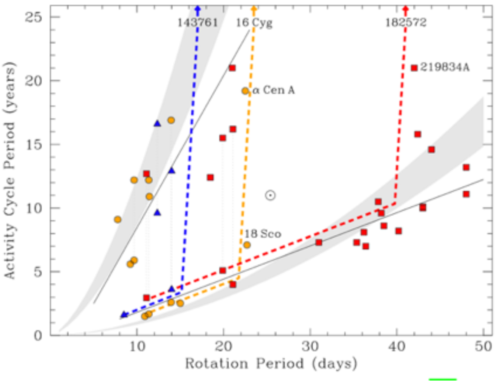

Fig. 4. Magnetic activity cycle period as a function of rotation period for different spectral types: K (blue triangles), G (yellow circles), and F (red squares). The Sun is represented with the solar symbol. The dash lines represent assumed evolutionary path of the stars. Extracted from Metcalfe & van Saders (2017) .

Finally, for red giants, rotation periods have been measured with the *Kepler* data for around 300 stars (Ceillier et al. 2017; Tayar et al. 2017). While some slow rotators are present, there are some fast rotators ($P_{\rm rot} < 50$ days) and they still need to be taken cautiously as there could still be some contamination from a nearby star. However, magnetic fields for red giants have also been measured from spectropolarimetric observations (e.g. Aurière et al. 2008; Konstantinova-Antova et al. 2012) showing that these stars could still be magnetically active.

4 Conclusions

From different indexes for stellar magnetic activity, we saw that there is a saturation for low Ro (younger) stars and a decrease of magnetic activity after a given Ro value. There is also a dependence of the magnetic activity on spectral type: low-mass stars are more active. A metallicity dependence has also been seen where metal-rich stars have higher magnetic activity level.

From the analysis of the photometric data of *Kepler*, it seems that the magnetic braking is stalled after a given Rossby number. One question that remains unanswered is the following: is the Sun in transition?

The knowledge of the level of magnetic activity of planet-host stars is crucial to better define the habitability zone. While it starts to be taken into account, understanding the stellar magnetic activity of stars will have a direct impact on habitability (e.g. Gallet et al. 2017; Johnstone et al. 2021).

S. M. acknowledges support by the Spanish Ministry of Science and Innovation with the Ramon y Cajal fellowship number RYC-2015-17697 and the grant number PID2019-107187GB-I00.

References

Abrevaya, X. C., Leitzinger, M., Oppezzo, O. J., et al. 2020, MNRAS, 494, L69

Anglada-Escudé, G., Amado, P. J., Barnes, J., et al. 2016, Nature, 536, 437

Augustson, K. C., Brun, A. S., & Toomre, J. 2013, ApJ, 777, 153

Aurière, M. 2003, in EAS Publications Series, Vol. 9, EAS Publications Series, ed. J. Arnaud & N. Meunier, 105

Aurière, M., Konstantinova-Antova, R., Petit, P., et al. 2008, A&A, 491, 499

Baglin, A., Auvergne, M., Boisnard, L., et al. 2006, in COSPAR, Plenary Meeting, Vol. 36, 36th COSPAR Scientific Assembly, 3749

Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, ApJ, 438, 269

Barnes, S. A. 2003, ApJ, 586, 464

Barnes, S. A. 2007, ApJ, 669, 1167

Basri, G., Walkowicz, L. M., & Reiners, A. 2013, ApJ, 769, 37

Bluhm, P., Luque, R., Espinoza, N., et al. 2020, A&A, 639, A132

Böhm-Vitense, E. 2007, ApJ, 657, 486

Bolmont, E., Selsis, F., Owen, J. E., et al. 2017, MNRAS, 464, 3728

Boro Saikia, S., Marvin, C. J., Jeffers, S. V., et al. 2018, A&A, 616, A108

Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977

Brandenburg, A., Mathur, S., & Metcalfe, T. S. 2017, ApJ, 845, 79

Breton, S. N., Santos, A. R. G., Bugnet, L., et al. 2021, A&A, 647, A125

Brun, A. S. & Browning, M. K. 2017, Living Reviews in Solar Physics, 14, 4

Brun, A. S., Strugarek, A., Varela, J., et al. 2017, ApJ, 836, 192

Ceillier, T., Tayar, J., Mathur, S., et al. 2017, A&A, 605, A111

Corsaro, E., Bonanno, A., Mathur, S., et al. 2021, A&A, 652, L2

do Nascimento, J. D., J., de Almeida, L., Velloso, E. N., et al. 2020, ApJ, 898, 173

Donati, J.-F. 2003, in Astronomical Society of the Pacific Conference Series, Vol. 307, Astronomical Society of the Pacific Conference Series, ed. J. Trujillo-Bueno & J. Sanchez Almeida, 41

Gallet, F., Charbonnel, C., Amard, L., et al. 2017, A&A, 597, A14

García, R. A. & Ballot, J. 2019, Living Reviews in Solar Physics, 16, 4

García, R. A., Ceillier, T., Salabert, D., et al. 2014, A&A, 572, A34

García, R. A., Mathur, S., Salabert, D., et al. 2010, Science, 329, 1032

Gilbert, E. A., Barclay, T., Schlieder, J. E., et al. 2020, AJ, 160, 116

Günther, M. N., Pozuelos, F. J., Dittmann, J. A., et al. 2019, Nature Astronomy, 3, 1099

Hall, J. C., Lockwood, G. W., & Skiff, B. A. 2007, AJ, 133, 862

Howell, S. B., Sobeck, C., Haas, M., et al. 2014, PASP, 126, 398

Johnstone, C. P., Bartel, M., & Güdel, M. 2021, A&A, 649, A96

Jouve, L., Lignières, F., & Gaurat, M. 2020, A&A, 641, A13

Kiefer, R., Schad, A., Davies, G., & Roth, M. 2017, A&A, 598, A77

Konstantinova-Antova, R., Aurière, M., Petit, P., et al. 2012, A&A, 541, A44

Kostov, V. B., Schlieder, J. E., Barclay, T., et al. 2019, AJ, 158, 32

Lehtinen, J. J., Käpylä, M. J., Olspert, N., & Spada, F. 2021, ApJ, 910, 110

MacGregor, K. B. & Charbonneau, P. 1997, ApJ, 486, 484

Mamajek, E. E. & Hillenbrand, L. A. 2008, ApJ, 687, 1264

Marsden, S. C., Petit, P., Jeffers, S. V., et al. 2014, MNRAS, 444, 3517

Mathur, S., García, R. A., Régulo, C., et al. 2010, A&A, 511, A46

Mathur, S., Salabert, D., García, R. A., & Ceillier, T. 2014, Journal of Space Weather and Space Climate, 4, A15

McQuillan, A., Mazeh, T., & Aigrain, S. 2014, ApJS, 211, 24

Metcalfe, T. S., Basu, S., Henry, T. J., et al. 2010, ApJ, 723, L213

Metcalfe, T. S. & van Saders, J. 2017, Sol. Phys., 292, 126

Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763

Reinhold, T., Reiners, A., & Basri, G. 2013, A&A, 560, A4

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003

Salabert, D., García, R. A., Pallé, P. L., & Jiménez-Reyes, S. J. 2009, A&A, 504, L1

Santos, A. R. G., Breton, S. N., Mathur, S., & García, R. A. 2021, ApJS, 255, 17

Santos, A. R. G., Campante, T. L., Chaplin, W. J., et al. 2018, ApJS, 237, 17

Santos, A. R. G., García, R. A., Mathur, S., et al. 2019, ApJS, 244, 21

See, V., Roquette, J., Amard, L., & Matt, S. P. 2021, ApJ, 912, 127

Skumanich, A. 1972, ApJ, 171, 565

Tayar, J., Somers, G., Pinsonneault, M. H., et al. 2017, ApJ, 840, 17

Van Eylen, V., Astudillo-Defru, N., Bonfils, X., et al. 2021, arXiv e-prints, arXiv:2101.01593

van Saders, J. L., Ceillier, T., Metcalfe, T. S., et al. 2016, Nature, 529, 181

Wilson, O. C. 1978, ApJ, 226, 379

Wright, N. J., Drake, J. J., Mamajek, E. E., & Henry, G. W. 2011, ApJ, 743, 48

Wright, N. J., Newton, E. R., Williams, P. K. G., Drake, J. J., & Yadav, R. K. 2018, MNRAS, 479, 2351

Yang, H. & Liu, J. 2019, ApJS, 241, 29