

# Hints of enhanced magnetic activity after the intermediate rotation period gap as traced by the chromospheric Ca II infrared triplet

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## ABSTRACT

For low-mass stars ( $M < 1.4 M_{\odot}$ ), the connection between stellar rotation and magnetic activity governs stellar spin-down, shapes the environments of their exoplanets, and provides an age-diagnostic via magneto-gyro-chronology. Recently, unexpected phenomena known as the intermediate rotation period gap and the rotational stalling have been discovered. These are likely due to internal angular momentum redistribution, and mark departures from a smooth spin-down evolution. These rotational features have been shown to cause enhanced magnetic activity on the photosphere, as measured by the photometric index from light curves ( $\langle S_{\text{ph}} \rangle$ ), in both cluster and field stars. However, their influence on other magnetic activity proxies, and particularly in field stars, remains poorly understood. In this work, we study the impact of the intermediate-period gap on chromospheric magnetic activity as traced by the Ca II infrared triplet (IRT) index. We target the stars observed by the *Kepler* mission, as this is the largest and most reliable sample of field stars with measured rotation periods sensitive to the gap. We calculate the Ca II IRT index for the *Kepler* stars using the spectroscopic information from the *Gaia* mission data release three (DR3). We study the rotation-activity relation as a function of location on the Hertzsprung-Russell (HR) diagram and spectral type, finding that K dwarfs are more active than G dwarfs, which in turn are more active than F dwarfs. For main-sequence stars, we find that chromospheric magnetic activity is also enhanced after the intermediate-period gap, mirroring its effect on the photospheric  $\langle S_{\text{ph}} \rangle$  index. Our work reveals that the intermediate-period gap marks a genuine transition in stellar magnetic behavior, not only at the photosphere but also at the chromosphere. This highlights the need to account for its signatures across activity proxies, as well as its impact on exoplanet habitability and the age-rotation-activity relation.

**Key words.** Stars: activity – Stars: chromospheres – Stars: evolution – Stars: late-type – Stars: rotation – binaries: general

## 1. Introduction

Stellar magnetic activity is a fundamental ingredient in how low-mass main-sequence (MS) stars, namely those with masses  $\lesssim 1.4 M_{\odot}$  and convective envelopes, evolve and interact with their surroundings (e.g., Güdel 2007; Stassun et al. 2014; Airapetian et al. 2020). Activity is tightly connected to rotation through dynamo processes operating in their convective envelopes and interiors (e.g., Brun & Browning 2017; Charbonneau 2020). Magnetized stellar winds remove angular momentum and brake the stellar surface (Parker 1958; Schatzman 1962; Weber & Davis 1967; Kawaler 1988), so rotational spin-down links surface magnetic activity to the internal transport of angular momentum and, more generally, to the long-term evolution of stellar rotation (e.g., Denissenkov et al. 2010; Gallet & Bouvier 2013, 2015; van Saders & Pinsonneault 2013).

Along their evolution, stars inhabit different activity and rotation regimes. They are born as rapid rotators in the saturated regime, where magnetic activity is roughly independent of rotation rate (e.g., Vilhu & Walter 1987; Stauffer et al. 1994;

Jeffries et al. 2011). As they age and spin down, stars transition to the unsaturated regime where rotation and activity are closely connected (e.g., Pizzolato et al. 2003; Wright et al. 2011, 2018), virtually forgetting their initial conditions and populating the converged rotational sequence. In this latter regime, both rotation and magnetic activity decay in a broadly systematic way ( $\propto \text{age}^{-1/2}$ ; Skumanich 1972), enabling the use of rotation and activity as age diagnostics through gyro-chronology (e.g., Barnes 2003, 2007; Epstein & Pinsonneault 2014; García et al. 2014a; Angus et al. 2015, 2019; Godoy-Rivera et al. 2021a; Bouma et al. 2023; Stassun & Kounkel 2024; Van-Lane et al. 2025) and magneto-chronology (e.g., Mamajek & Hillenbrand 2008; Gondoin 2018; Lorenzo-Oliveira et al. 2018; Mathur et al. 2023; Ye et al. 2024; Carvalho-Silva et al. 2025).

Beyond stellar physics, magnetic activity sets the conditions in which exoplanets form and evolve, shaping star–planet interactions (e.g., Strugarek 2018; Ahuir et al. 2021; Allan et al. 2026; Pezzotti et al. 2026) and influencing the potential habitability of planetary systems (e.g., Vidotto et al. 2013; Richey-Yowell et al. 2019, 2023; Johnstone et al. 2021; See et al. 2025).

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A detailed understanding of the rotation–activity connection has therefore become central to models of stellar and planetary evolution (e.g., [Matt et al. 2015](#); [Tripathi et al. 2021](#)). The Skumanich-like spin-down picture for low-mass stars described above ( $\propto \text{age}^{-1/2}$ ) has been challenged over the past decade by new photometric and spectroscopic observations (e.g., [Angus et al. 2015](#); [van Saders et al. 2016](#); [Garraffo et al. 2018](#); [Hall et al. 2021](#); [Saunders et al. 2024](#)). Early hints in open clusters suggested that rotational sequences did not always follow the expected smooth age progression (e.g., [Meibom et al. 2011](#); [Agiueros et al. 2018](#)). This behavior was later studied in more detail by [Curtis et al. \(2019\)](#), who showed that the rotational sequences of the open clusters Praesepe and NGC 6811 largely overlap for K dwarfs despite their different ages (0.7 vs. 1.0 Gyr, respectively), revealing a spin-down stalling phase in which stars remain rotating more rapidly than predicted by standard gyro-chronology relations (see also [Curtis et al. 2020](#); [Gruner & Barnes 2020](#); [Dungee et al. 2022](#); [Bernizzoni et al. in preparation](#)). Further departures from Skumanich-like spin-down have been identified in field stars, in the form of a bimodal distribution of rotation periods separated by a sparsely populated gap, hereafter referred to as the intermediate-period gap (e.g., [McQuillan et al. 2014](#); [Reinhold & Hekker 2020](#); [Gordon et al. 2021](#); [Lu et al. 2022](#)).

The physical origin of the intermediate-period gap and the spin-down stalling are still under discussion. Several studies have proposed that the coupling between the radiative core and the convective envelope, or more generally in the internal redistribution of angular momentum, could explain them (e.g., [Spada & Lanzafame 2020, 2026](#); [Lu et al. 2024](#); [Han et al. 2026](#)). From an observational point of view, these phenomena should leave a measurable imprint on stellar magnetic activity. If the surface rotation does not follow the standard spin-down, dynamos are expected to respond, and activity diagnostics should reflect this modified rotational history. Indeed, several investigations of magnetic activity around these features have been published recently (e.g., [Corsaro et al. 2021](#); [See et al. 2021](#); [Chahal et al. 2023](#); [Degott et al. 2025](#)).

Hints of changes in magnetic activity associated with the above were reported by [Santos et al. \(2024\)](#), based on the coronal X-ray luminosities of [Wright et al. \(2011\)](#), in terms of a change in the slope of the rotation-activity relation of field stars around the intermediate-period gap, as well as by [Richey-Yowell et al. \(2022\)](#) in terms of the chromospheric UV flux of cluster K dwarfs showing a prolonged saturation near the age of their spin-down stalling phase. Further evidence has been provided by studying the photospheric spot-filling fractions of cluster stars ([Cao et al. 2023](#)), and the photometric variability of both field and cluster stars ([Mathur et al. 2025](#) and [Santos et al. 2025](#), respectively; see also [Borg et al. in preparation](#)). While these works have encompassed different atmospheric layers and stellar settings, enhanced magnetic activity in the chromosphere as probed by field stars has only been detected in Ca II H&K ([Ye et al. 2025](#)). Expanding such detection to other chromospheric activity diagnostics would provide supporting evidence that intermediate-period gap marks a universal transition in magnetic behavior across the stellar atmosphere and a range of ages.

Chromospheric activity indicators offer a sensitive probe of magnetic fields in the outer atmospheres of cool stars ([Hall 2008](#); [Linsky 2017](#); [Godoy-Rivera et al. in preparation](#)). Among them, the Ca II infrared triplet (IRT) has emerged as a powerful tracer of chromospheric activity in low-mass stars (e.g., [Shine & Linsky 1972](#); [Linsky et al. 1979](#); [Martin et al. 2017](#); [Zills et al. 2024](#)).

**Table 1.** Target list, stellar properties, and activity indices.

Column	Description
KIC	KIC ID
<i>Gaia</i> DR3	<i>Gaia</i> DR3 source ID
$M_{G_0}$	Absolute de-reddened <i>G</i> -band magnitude
$(BP - RP)_0$	De-reddened $(BP - RP)$ color
Summary Flag CMD	Identifies Joint-MS and Joint-Evolved targets
Spectral Type Joint MS	Identifies spectral type of Joint-MS targets
Flag Binary Union	Flags the targets identified as binary candidates
$P_{\text{rot}}$	Rotation period
$\sigma_{P_{\text{rot}}}$	Rotation period error
$\langle S_{\text{ph}} \rangle$	Photometric activity proxy
$\sigma_{\langle S_{\text{ph}} \rangle}$	Photometric activity proxy error
$\delta \log P_{\text{rot}}$	Difference of logarithmic period (star minus gap)
$(\text{Ro}/\text{Ro}_{\odot})$	Rosby number (solar-normalized)
$\log R'_{\text{IRT}}$	Calcium activity index
$\sigma_{\log R'_{\text{IRT}}}$	Calcium activity index error
$P_{\text{orb}}$	Orbital period
$\sigma_{P_{\text{orb}}}$	Orbital period error
$e$	Orbital eccentricity
$\sigma_e$	Orbital eccentricity error

**Notes.** (The full table is available in Sect. “Data availability.”)

This index presents the advantage of being accessible in large modern spectroscopic surveys, being less affected by interstellar absorption than traditional optical lines, and having an intrinsically higher signal-to-noise ratio at longer wavelengths than the widely used Ca II H&K index in cool stars (e.g., [Fritzewski et al. 2021](#); [Lanzafame et al. 2023](#); [Strassmeier et al. 2025](#)). With the goal of building a comprehensive picture between rotational evolution and chromospheric diagnostics, we investigate whether the intermediate-period gap imprints a measurable signature on magnetic activity as traced by the Ca II IRT in low-mass field stars.

This paper is organized as follows. In Sect. 2 we describe the target sample and its photometric rotation and photospheric magnetic activity proxies. In Sect. 3 we present the chromospheric Ca II IRT magnetic activity index. In Sect. 4 we assess the sample overlap between these photospheric and chromospheric activity proxies, and examine their degree of agreement. In Sect. 5 we analyze the relation between rotation and the Ca II IRT index, and its dependence on spectral type, Rossby number, and stellar multiplicity. We conclude in Sect. 6.

## 2. Target list and photometric rotation-activity data

We focused on the stars observed by *Kepler* ([Borucki et al. 2010](#)), a mission that provided long-baseline ( $\sim 4$  years), high-precision photometric light curves. The *Kepler* targets were recently characterized using the third data release (DR3) of the *Gaia* mission ([Gaia Collaboration et al. 2016, 2021, 2023b](#)), allowing a detailed analysis of their color-magnitude diagram (CMD; Sect. 2.1). Combined with the *Kepler* observations, this sample offers the most comprehensive view of photometric activity and rotation for field stars in a regime sensitive to the intermediate-period gap (Sect. 2.2 and 2.3). We report our target list in Table 1, together with the main properties used throughout this work.

### 2.1. Target sample

We defined the target sample as the 196,762 stars observed by *Kepler* characterized in [Godoy-Rivera et al. \(2025\)](#) (see also [Mathur et al. 2017](#)). These stars have *Kepler* input catalog (KIC; [Brown et al. 2011](#)) IDs with *Gaia* DR3 counterparts in the

one-to-one Gaia-Kepler.fun<sup>1</sup> crossmatch. They predominantly span apparent magnitudes between  $12 < G < 16$  mag, with a median distance of  $\approx 1.1$  kpc. The middle panel of Fig. 1 shows the absolute and de-reddened CMD of the sample, which includes solar-like stars, upper MS stars, and evolved phases such as the red giant branch (RGB) and red clump (RC).

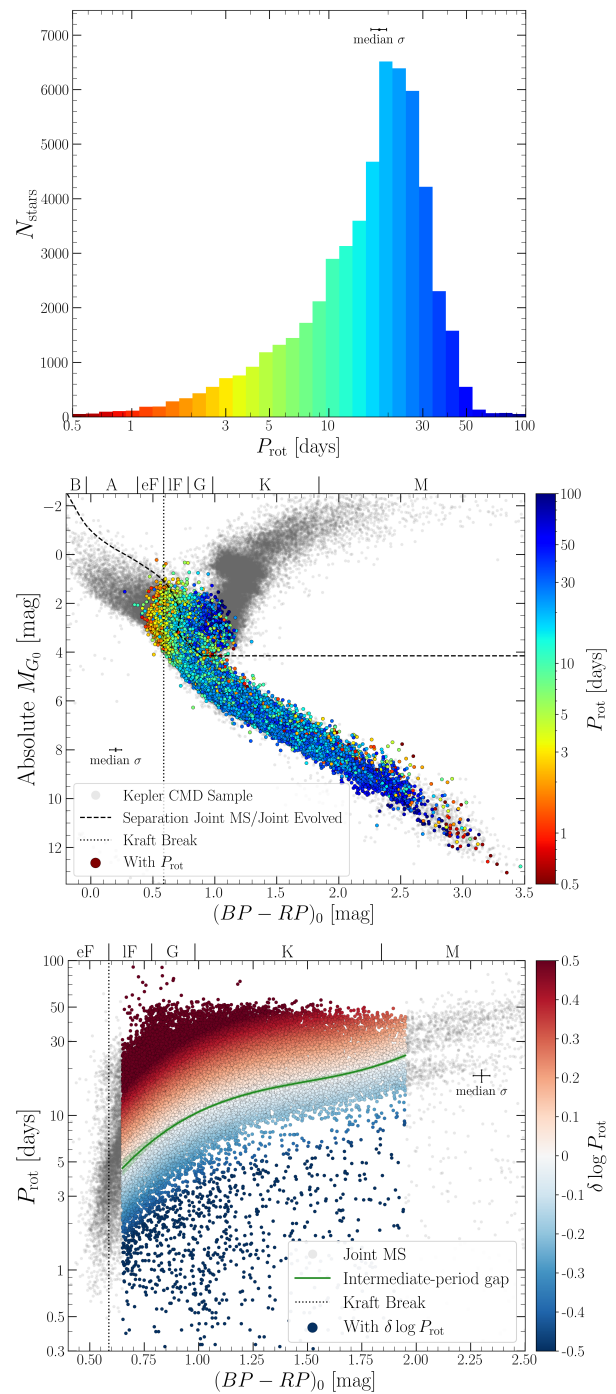
To streamline our analysis, we divided the *Kepler* CMD sample into two broad categories, namely “Joint MS” and “Joint Evolved”. Based on the analysis of Godoy-Rivera et al. (2025), the Joint-MS category comprises the stars located along the MS (specifically their Dwarf, Photometric Binary, Overlap Dwarf/Subgiant, and Uncertain MS regions) and amounts to 131,258 targets (66.7% of the sample), while the Joint-Evolved category comprises post-MS stars (specifically their Subgiant and Giant Branch regions) and amounts to 47,999 targets (24.4% of the sample). This separation provided a straightforward CMD classification<sup>2</sup>, which we illustrate as the dashed line in the middle panel of Fig. 1. We report the resulting classification as the “Summary Flag CMD” column in Table 1.

We note that throughout this work, whenever possible, we chose to characterize our sample in the de-reddened *Gaia* DR3 color and absolute magnitude space. While several literature catalogs report stellar parameters (such as effective temperature and luminosity) for the *Kepler* targets (e.g., Zhang et al. 2025), *Gaia* DR3 is the best current source to ensure a homogeneous, precise, and unbiased characterization for the full sample (Godoy-Rivera et al. 2025).

## 2.2. Rotation periods and photometric magnetic activity

Rotation periods and magnetic activity proxies have been measured for *Kepler* solar-like targets thanks to active regions moving into and out of view as stars rotate (e.g., McQuillan et al. 2014; Sagynbayeva et al. 2025). In this work, we adopted the values of rotation period ( $P_{\text{rot}}$ ) and average photometric activity proxy ( $\langle S_{\text{ph}} \rangle$ ) from Santos et al. (2019) and Santos et al. (2021). These were derived from the long-cadence *Kepler* light curves<sup>3</sup>, calibrated following García et al. (2011), García et al. (2014b), and Pires et al. (2015). From these,  $P_{\text{rot}}$  was obtained from the rotationally modulated variability, and  $\langle S_{\text{ph}} \rangle$  was calculated as the mean of the standard deviations of the light curve measured over segments of length  $5 \times P_{\text{rot}}$  (Mathur et al. 2014a). While other literature catalogs report complementary (or even larger) samples of rotation periods and/or activity proxies for the *Kepler* stars (e.g., Long et al. 2023; Reinhold et al. 2023; Claytor & Tayar 2025; Degott et al. 2025; Kamai & Perets 2025), we prioritized the values by Santos et al. (2019) and Santos et al. (2021). This choice was motivated by their  $P_{\text{rot}}$  and  $\langle S_{\text{ph}} \rangle$  measurements being derived in a homogeneous and self-consistent manner, thus ensuring a uniform treatment across the sample. Importantly, the above definition of  $\langle S_{\text{ph}} \rangle$  ensures its physical interpretation as a proxy for photospheric magnetic activity (Mathur et al. 2014a,b; Salabert et al. 2016, 2017; Kashyap et al. 2026).

We crossmatched our target list (Sect. 2.1) with the Santos et al. (2019) and Santos et al. (2021) catalog, and found



**Fig. 1.** Characterization of the rotating *Kepler* stars. Top: distribution of rotation periods. Middle: CMD with the full *Kepler* sample shown in grey, and the subset with measured rotation periods shown colored by their  $P_{\text{rot}}$  values. The dashed line shows the separation between Joint-MS and Joint-Evolved targets, and the vertical dotted line illustrates the Kraft break. Bottom:  $P_{\text{rot}}$  vs. color diagram for the Joint-MS targets. The intermediate-period gap is shown as the green line (see Table 2). The stars in the color range of the period-gap are color-coded by their  $\delta \log P_{\text{rot}}$  values (see Equation 1). Typical uncertainties are illustrated by the median  $\sigma$  symbol.

<sup>1</sup> <https://gaia-kepler.fun/>

<sup>2</sup> We note that the Joint MS and Joint Evolved categories amount to  $\approx 91.1\%$  of the total *Kepler* sample, with the remaining  $\approx 8.9\%$  being composed of stars that failed the quality cuts for a reliable CMD placement and categorization (see Table 1 in Godoy-Rivera et al. 2025).

<sup>3</sup> Available at MAST via: <https://archive.stsci.edu/doi/resolve/resolve.html?doi=10.17909/t9-mrpw-gc07>.

54,881 targets in common (27.9% of the sample). The resulting  $P_{\text{rot}}$  distribution is shown in the top panel of Fig. 1. The distribution peaks at  $\sim 20$  days and spans a broad range of values (from below 1 up to 100 days), consistent with a field popula-

tion (e.g., van Saders et al. 2019). In the middle panel of Fig. 1, the CMD of this sample is color-coded by  $P_{\text{rot}}$ , which shows the color-dependence of the rotation periods of low-mass stars. This is also illustrated in the bottom panel of Fig. 1. Early-type solar-like stars tend to be faster rotators than later-type stars. This is particularly true for the *Kepler* sample, which is mostly comprised of relatively old stars that have already transitioned into the unsaturated regime and the converged rotational sequence (e.g., Santos et al. 2024). Above the Kraft break (Kraft 1967), corresponding to F5V stars (Beyer & White 2024;  $(BP - RP)_0 \lesssim 0.587$  mag or  $T_{\text{eff}} \gtrsim 6,550$  K from Pecaute & Mamajek 2013), illustrated as the vertical dotted lines in the middle and bottom panels of Fig. 1, stars tend to remain rapid rotators ( $P_{\text{rot}} \lesssim 5$  days) due to an inefficient magnetic braking related to their thin convective layers (e.g., Matt et al. 2015). Below the Kraft break,  $(BP - RP)_0 \gtrsim 0.587$  mag, we see the effects of spin-down due to angular momentum losses in stars with convective envelopes. On the Joint-Evolved zone of the CMD, we see the impact of structural effects (i.e., radius expansion) as stars leave the MS and evolve along the RGB.

### 2.3. Intermediate-period gap

In part of the color range probed by the bottom panel of Fig. 1, the  $P_{\text{rot}}$  distribution of the *Kepler* MS stars is bimodal. This underdensity of stars at intermediate rotation periods is known as the intermediate-period gap (e.g., McQuillan et al. 2013, 2014; Davenport 2017; Davenport & Covey 2018; Santos et al. 2019, 2021). Near this dearth region, stars tend to have lower  $\langle S_{\text{ph}} \rangle$  values than stars with longer periods. This behavior is counter-intuitive, as in the unsaturated regime, faster rotators are generally expected to show higher activity (see Sect. 1). Consequently, in the  $\langle S_{\text{ph}} \rangle - P_{\text{rot}}$  diagram, the gap corresponds to a local minimum in activity (see Fig. B.6 in Santos et al. 2023). This has been used to determine the location of the gap as a function of  $T_{\text{eff}}$  (e.g., Reinhold & Hekker 2020; Santos et al. 2024, 2025).

Throughout this work, we followed the above definition of the intermediate-period gap, namely the  $P_{\text{rot}}$  value at which there is a local minimum in  $\langle S_{\text{ph}} \rangle$ . To maximize homogeneity (see Sect. 2.1), we determined the location of the gap as a function of de-reddened *Gaia* DR3 color instead of effective temperature. We followed the procedure described in Appendix A of Santos et al. (2025), adapted to  $(BP - RP)_0$  colors instead of  $T_{\text{eff}}$ . The resulting parametrization is reported in Table 2 and shown by the green solid line (and shaded region around it) in the bottom panel of Fig. 1. The gap parametrization was done for the range  $0.65 \leq (BP - RP)_0 \leq 1.95$ . Beyond the bluest boundary, the  $P_{\text{rot}}$  distribution is not found to be bimodal, and an activity minimum is difficult to define. Beyond the reddest boundary, the sample sizes become increasingly smaller, which hampers the detection of the local minimum in  $\langle S_{\text{ph}} \rangle$ . These are also reflected in the increasing uncertainty of the gap location towards the bluer and redder extremes. To account for the uncertainties on the rotation periods, de-reddened colors, and local minima identification, we performed bootstrapping by varying the rotation period values, the  $(BP - RP)_0$  values, the size of the  $(BP - RP)_0$  bins, and the size of the  $\log P_{\text{rot}}$  bins. We followed the steps detailed in Santos et al. (2025), with the size of the  $(BP - RP)_0$  bins being randomly selected between 0.01, 0.02, 0.03, 0.04, and 0.05 mag.

For later analysis (see Sect. 5), it is important to know how distant a given star is, in terms of rotation period, from the intermediate-period gap. For this purpose, we followed

**Table 2.** Intermediate-period gap ( $\pm 1\sigma$ ) as a function of de-reddened *Gaia* DR3  $(BP - RP)_0$  color.

$(BP - RP)_0$	$P_{\text{rot,gap-16th}}$	$P_{\text{rot,gap-50th}}$	$P_{\text{rot,gap-84th}}$
0.65	0.608	0.658	0.713
0.70	0.689	0.728	0.772
0.75	0.762	0.792	0.826
0.80	0.826	0.848	0.874
0.85	0.883	0.900	0.919
...	...	...	...

**Notes.** (The full table is available in Sect. ‘‘Data availability.’’)

Santos et al. (2025) and calculated the parameter

$$\delta \log P_{\text{rot}} = \log P_{\text{rot,star}} - \log P_{\text{rot,gap}}, \quad (1)$$

which is the difference between a star’s logarithmic  $P_{\text{rot}}$  minus the logarithmic period of the intermediate-period gap evaluated at the star’s *Gaia* color. In the bottom panel of Fig. 1, the Joint-MS stars within the color range of the intermediate-period gap are color-coded by their  $\delta \log P_{\text{rot}}$  values.

### 3. Calcium infrared index

The Ca II IRT ( $\lambda = 850.03, 854.44, \text{ and } 866.45$  nm) is a well established diagnostic of chromospheric stellar activity (e.g., Shine & Linsky 1972; Linsky et al. 1979; Dempsey et al. 1993; Soderblom et al. 1993; Andretta et al. 2005; Busà et al. 2007; Huang et al. 2024), with strong correlations with other activity indices such as Ca II H&K (Martin et al. 2017). In *Gaia* DR3, a Ca II IRT activity index was reported for  $2 \times 10^6$  stars (Lanzafame et al. 2023), based on medium resolution spectra ( $\lambda/\Delta\lambda \sim 11,500$ ) collected by the radial velocity spectrometer (RVS) between the wavelengths 845 to 872 nm for targets brighter than apparent  $G = 13$  mag (for reference, the *Kepler* targets have a median apparent  $G = 14.6$  mag; Godoy-Rivera et al. 2025). For each target, the observed spectrum was normalized and compared with a template spectrum representing an inactive photosphere. The template spectrum was subtracted from the observed one to isolate the chromospheric contribution, and the activity index was calculated by averaging over the core of the three lines. This is reported as  $\alpha$ , found as the `activityindex_espcs` parameter in the `gaiadr3_astrophysical_parameters` table.

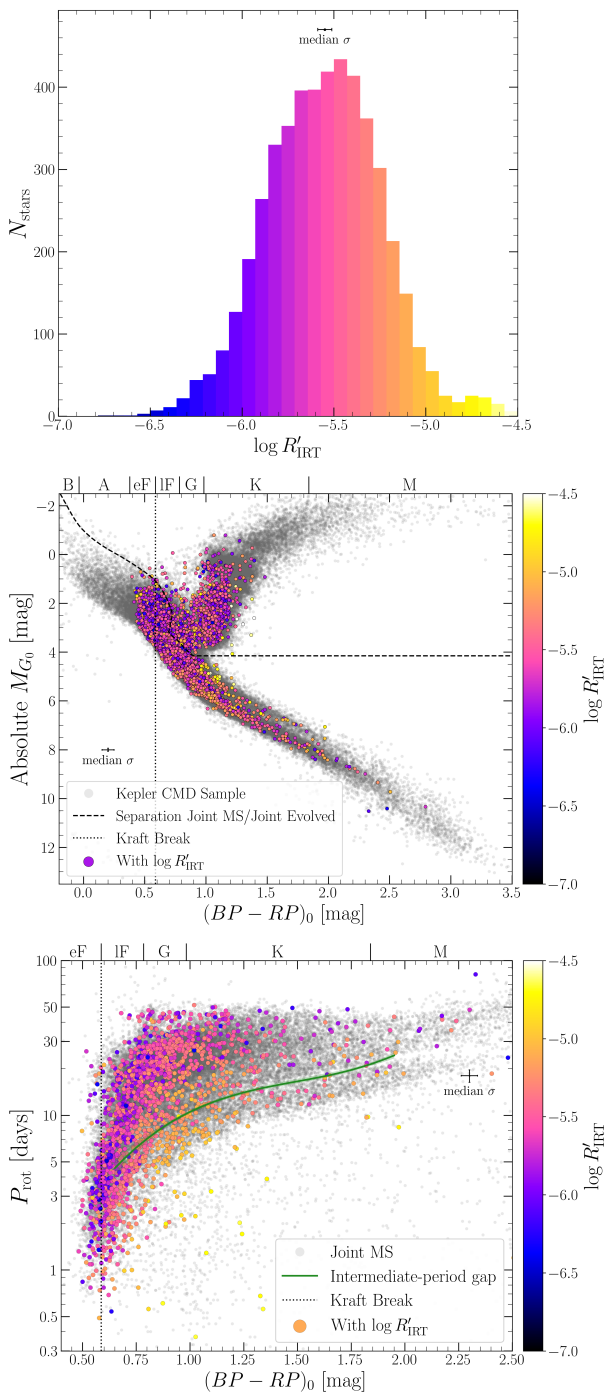
We followed Lanzafame et al. (2023) and converted the  $\alpha$  values to the  $\log R'_{\text{IRT}}$  index as

$$\log R'_{\text{IRT}} = (C_0 + C_1\theta + C_2\theta^2 + C_3\theta^3) + \log \alpha, \quad (2)$$

and propagated uncertainties as

$$\sigma_{\log R'_{\text{IRT}}} = \sqrt{\left[ (C_1 + 2C_2\theta + 3C_3\theta^2) \sigma_\theta \right]^2 + \left[ \frac{\sigma_\alpha}{\alpha \ln(10)} \right]^2}, \quad (3)$$

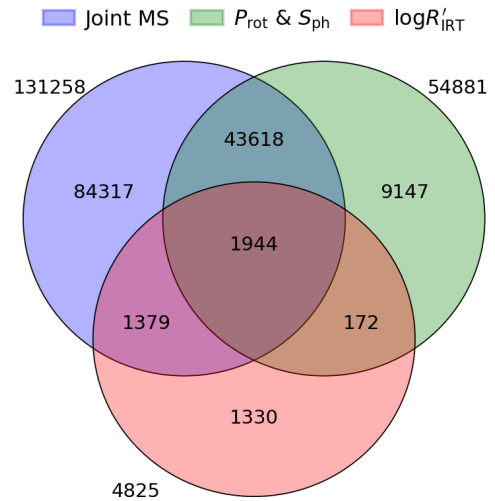
where  $C_{0,1,2,3}$  are the metallicity-dependent coefficients reported in Table 1 of Lanzafame et al. (2023),  $\sigma_\alpha$  is the activity index uncertainty (`activityindex_espcs_uncertainty`),  $\theta = \log T_{\text{eff}}$ , and  $\sigma_\theta = \frac{\sigma_{T_{\text{eff}}}}{\ln(10)T_{\text{eff}}}$ . For this computation, we took the corresponding set of input temperatures, either `gspspec` or `gspphot`, used in the calculation of the template spectrum (reported as `activityindex_espcs_input`). Given that the  $C_{0,1,2,3}$  coefficients are reported in discrete metallicity bins, we interpolated between them and evaluated the coefficients at the corresponding (`gspspec` or `gspphot`) metallicity of each star.



**Fig. 2.** Analogous to Fig. 1, for the Ca II IRT activity index. In all panels the color-coding indicates  $\log R'_{\text{IRT}}$  values.

To ensure reliability on the chromospheric activity index, we followed Breton et al. (2025) and Freund et al. (2025), and applied a  $3\sigma$  quality cut, namely  $\alpha/\sigma_\alpha > 3$ .

All the above produced a set of  $\log R'_{\text{IRT}}$  and  $\sigma_{\log R'_{\text{IRT}}}$  values for 4,825 stars (2.5% of the full sample), which are reported in Table 1. The top panel of Fig. 2 shows the distribution of the Ca II IRT index, which spans the range from  $\log R'_{\text{IRT}} \approx -6.6$  to  $\approx -4.5$ , and peaks at  $\log R'_{\text{IRT}} \approx -5.5$ . Given that star formation occurs predominantly close to the Galactic plane, and *Kepler* observed stars away from it, we did not expect a large population of pre-MS stars or accreting T Tauri stars, which would otherwise occupy the highest activity regime (Lanzafame et al. 2023).



**Fig. 3.** Venn diagram for the subsets of stars classified as Joint MS (purple), with a measured rotation period and photometric activity index (green), and with a measured Ca II IRT index (red).

For further reliability, we tested the significance of the above coefficient-interpolation assumption, as well as the use of different temperature and metallicity values (e.g., compared with the parameters by Berger et al. 2020), on the resulting Ca II IRT index. We found the impact of all these choices to be small, with a median change of  $|\Delta \log R'_{\text{IRT}}| \approx 0.02$ . This value is well below the median index uncertainty of  $\sigma_{\log R'_{\text{IRT}}} \approx 0.04$ . Along the same line, tests showed that the uncertainties  $\sigma_{\log R'_{\text{IRT}}}$  are heavily dominated by the  $\sigma_\alpha$  term, and are only weakly dependent on the temperature and metallicity inputs.

The CMD projection of the Ca II IRT sample is shown in the middle panel of Fig. 2. Despite their rapid rotation, earlier-type MS stars exhibit lower chromospheric activity due to their shallow convective envelopes. For MS stars cooler than the Kraft break, we observe a systematic increase in the  $\log R'_{\text{IRT}}$  index towards later spectral types, consistent with lower-mass stars being more chromospherically active, owing to their deeper convective envelopes. Interestingly, high-activity stars seem to be prominent on the photometric binary sequence, namely the region parallel to the MS at higher luminosities due to unresolved companions. This possibly hints at the role that multiplicity plays in enhancing magnetic activity (see Sect. 5).

The bottom panel of Fig. 2 shows the  $P_{\text{rot}}$  vs. color diagram for the Joint-MS stars, and the subset of them with Ca II IRT values are color-coded by  $\log R'_{\text{IRT}}$ . For stars redder (cooler) than the Kraft break (vertical dotted line), at a fixed *Gaia* color, the slower rotators display lower activity values, in line with expectations of a typical unsaturated-regime rotation-activity relation.

## 4. Characterization

### 4.1. Sample overlap

To understand the degree of overlap among the different data sets, Fig. 3 shows the Venn diagram<sup>4</sup> of the subsets of stars classified as Joint MS, with  $P_{\text{rot}}$  and  $\langle S_{\text{ph}} \rangle$  values, and with Ca II IRT activity index values. Naturally, the Joint-MS sample (purple;  $N = 131,258$ ) is the largest set, as the *Kepler* mission focused on observing Sun-like stars, and most of them have reliable *Gaia* data (Godoy-Rivera et al. 2025). Regarding the rotating sample

<sup>4</sup> Created with `venny4py` (<https://github.com/timberg/venny4py/tree/main>).

(green;  $N = 54,881$ ), while a fraction of the targets are classified as Joint Evolved, the majority of the Santos et al. (2019, 2021) stars correspond to Joint-MS targets, as rotation is more easily detected for stars with shorter periods and higher photometric activity levels. Regarding the sample with Ca II IRT measurements (red;  $N = 4,825$ ), while the majority of the stars correspond to Joint-MS targets (69%), the *Gaia* RVS magnitude limit (apparent  $G < 13$  mag) resulted in many  $\log R'_{\text{IRT}}$  measurements belonging to the Joint-Evolved regime (31%; see the middle panel of Fig. 2), i.e., targets that are intrinsically more luminous.

For the remainder of this paper, we focus on the intersection of the above samples, namely the subset of Joint-MS stars with measured rotation periods and photometric activity indices, as well as Ca II IRT activity indices. This subset amounts to  $N = 1,944$  targets. Given the additional factors that dictate stellar evolution in evolved stars, we leave a thorough study of the Joint-Evolved targets and their rotation-activity relation (e.g., Dixon et al. 2020, 2025; Lehtinen et al. 2020; Godoy-Rivera et al. 2021b) as future work.

#### 4.2. Photospheric vs. chromospheric magnetic activity

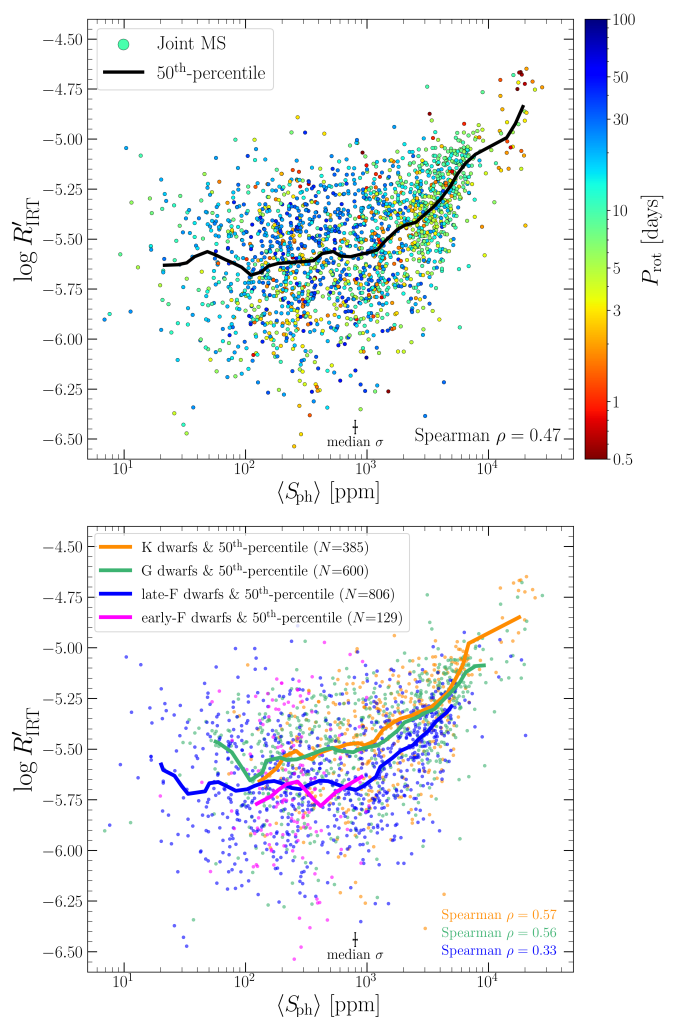
Magnetic activity in solar-like stars gives rise to a variety of phenomena that originate at different depths within the star and its atmosphere. Accordingly, it is interesting to study the degree of correlation between different proxies. The top panel of Fig. 4 shows the comparison of the photospheric index  $\langle S_{\text{ph}} \rangle$  (Sect. 2.2) vs. the chromospheric index  $\log R'_{\text{IRT}}$  (Sect. 3) for the Joint-MS sample. For reference, the solid black line shows the 50<sup>th</sup>-percentile of the  $\log R'_{\text{IRT}}$  distribution in bins of  $\langle S_{\text{ph}} \rangle$ . Further details on the binning procedure are described in Appendix A. There is a clear correlation between both proxies, especially in the regime of higher activity (i.e.,  $\log R'_{\text{IRT}} \gtrsim -5.6$  and  $\langle S_{\text{ph}} \gtrsim 10^3$  ppm). This is supported by a Spearman correlation coefficient (SCC) of  $\rho = 0.47$  with a  $p$ -value of  $8.79 \times 10^{-109}$ , indicating a statistically significant, moderate relationship.

Comparing our results with the literature, we note that they are in good agreement with the sample of *Gaia*/K2 (Howell et al. 2014) stars from Breton et al. (2025) in the high-activity regime (see their Fig. 11). Moreover, our global trend is qualitatively similar to the one seen in Gehan et al. (2024) (see their Fig. 3). While their sample is composed of RGB stars and ours is restricted to MS stars, both Ca II IRT index vs.  $\langle S_{\text{ph}} \rangle$  diagrams show a relation that steepens for  $\langle S_{\text{ph}} \gtrsim 10^3$  ppm.

We note that, at the very low activity levels in the top panel of Fig. 4, stars may be reaching their basal chromospheric flux (e.g., Schrijver 1987; Gondoin 2020; Masseron et al. in preparation), thus impeding the correlation to extend further towards the bottom-left corner of the diagram. In principle, lower values of the Ca II IRT index could have been retrieved from the raw *Gaia* data, specifically in the range of  $-8 \lesssim \log R'_{\text{IRT}} \lesssim -6.5$ . However, these were excluded when applying the  $3\sigma$  quality cut on Sect. 3, which we adopted to ensure reliable measurements.

To expand our analysis, we test possible dependencies of the  $\log R'_{\text{IRT}}$  vs.  $\langle S_{\text{ph}} \rangle$  correlation on rotation period. For this, the points in the top panel of Fig. 4 are color-coded by their  $P_{\text{rot}}$  values. While the steepest part of the correlation ( $\langle S_{\text{ph}} \rangle \sim 3 \times 10^3$  ppm) is mostly populated by moderately rapid rotators ( $P_{\text{rot}} \sim 10$  days), the overall trend holds for a range of rotation periods.

Despite this overall agreement, several factors can naturally introduce deviations between the two proxies. Although both indicators trace magnetic activity, they reflect phenomena occurring in different features and at different layers in



**Fig. 4.** Ca II IRT activity index vs. average photometric activity index for the Joint-MS sample. In the top panel the entire Joint-MS sample is color-coded by  $P_{\text{rot}}$ , whereas in the bottom panel the color-coding reflects spectral type (K dwarfs in orange, G dwarfs in green, late-F dwarfs in blue, and early-F dwarfs in magenta). The solid lines show the respective 50<sup>th</sup>-percentiles, Spearman coefficients are listed in the bottom-right corners, and typical uncertainties are indicated by the median  $\sigma$  symbols. A higher  $\langle S_{\text{ph}} \rangle$  typically means a higher  $\log R'_{\text{IRT}}$ , with later spectral types exhibiting stronger correlations.

the stellar atmosphere. The photometric  $\langle S_{\text{ph}} \rangle$  is mostly sensitive to brightness variations caused by dark spots (Shapiro et al. 2016; Li & Basri 2024), while  $\log R'_{\text{IRT}}$  measures chromospheric emission related to magnetic heating within plage regions (e.g., Shine & Linsky 1972; Linsky et al. 1979; Soderblom et al. 1993; but see also Andretta et al. 2005; Zills et al. 2024).

Furthermore, the observing windows of both activity proxies were not contemporaneous, as *Kepler* observed from 2009 to 2013, while *Gaia* DR3 observed from 2014 to 2017. Since stars also exhibit variability in their magnetic activity levels (e.g., Wilson 1978; Baliunas et al. 1995; Morris et al. 2025), the non-overlapping observations are an additional source of scatter in the top panel of Fig. 4. Indeed, given the temporal offset between the *Kepler* and *Gaia* observations, since more rapidly rotating stars tend to have shorter magnetic activity cycles (e.g., Böhm-Vitense 2007), they are more likely to exhibit the same cycle phase in  $\log R'_{\text{IRT}}$  and  $\langle S_{\text{ph}} \rangle$  compared to slowly rotating stars. As shown by Mathur et al. (2025) based on solar data, this

430 results in additional scatter being added for slowly rotating stars relative to rapidly rotating stars (see their Appendix A). Another contributing factor to the scatter is the possible temporal offset between magnetic activity proxies (e.g., Salabert et al. 2017). In spite of the aforementioned caveats, taken together these results indicate that both proxies trace the same underlying magnetic activity, despite probing different atmospheric layers (e.g., Bjørgen et al. 2018; Zhang et al. 2020).

440 Because the depth of the convective envelope increases towards lower mass stars (e.g., Kippenhahn et al. 2013), and convection plays a central role in generating magnetic activity (e.g., Charbonneau 2014), it is interesting to separate stars by their spectral type (SpT). As described in Appendix B, we split the Joint-MS sample into early-F, late-F, G, K, and M dwarfs. Their respective  $\langle S_{\text{ph}} \rangle$  vs.  $\log R'_{\text{IRT}}$  diagrams are shown in the bottom panel of Fig. 4. This revealed different levels of agreement between the photospheric and chromospheric indices. The correlation between  $\langle S_{\text{ph}} \rangle$  and  $\log R'_{\text{IRT}}$  is strongest for K and G dwarfs (SCC of  $\rho = 0.57$  and  $p$ -value =  $1.09 \times 10^{-34}$ , and SCC of  $\rho = 0.56$  and  $p$ -value =  $1.58 \times 10^{-50}$ , respectively) and weakest for late-F dwarfs (SCC of  $\rho = 0.33$ ;  $p$ -value =  $2.36 \times 10^{-22}$ ). 450 For early-F dwarfs, the correlation is not statistically significant ( $p$ -value of 0.90). M dwarfs were not analyzed, neither here nor in the upcoming diagrams, given their limited sample size ( $< 25$  stars).

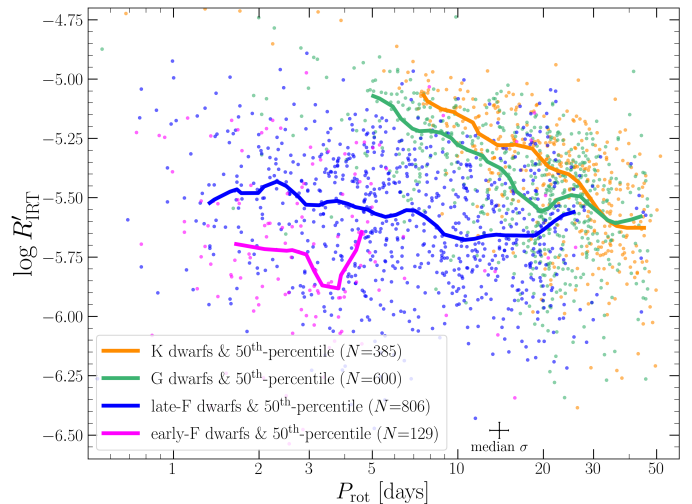
One possible explanation is that magnetic cycle properties, including the cycle period, may depend on spectral type or rotation period (e.g., Baliunas et al. 1995; Soon et al. 1993; Saar & Brandenburg 1999; Reinhold et al. 2017, 2019; Boro Saikia et al. 2018; Kitchatinov et al. 2018; Olsper et al. 460 2018; Willamo et al. 2020). If cycle timescales vary across spectral types, magnetic activity levels may evolve on different timescales, potentially increasing the scatter when comparing non-contemporaneous photospheric and chromospheric measurements.

In addition, the relative contributions of spots and faculae/plage may also depend on spectral type and activity level. More active, typically late-type stars, are expected to exhibit a larger spot-to-facula/plage ratio than less active, typically early-type stars (e.g., Shapiro et al. 2014). Similarly, rapidly rotating stars are dominated by spots, while slowly rotating stars are dominated by faculae (e.g., Montet et al. 2017; Reinhold et al. 470 2019). These could also contribute to the varying  $\log R'_{\text{IRT}}$  vs.  $\langle S_{\text{ph}} \rangle$  agreement due to the different sensitivity of these magnetic activity proxies, as described above.

## 5. Discussion

### 5.1. Impact of the intermediate-period gap on chromospheric activity across spectral types

480 We now examine how the rotation-activity relation, as probed by the Ca II IRT index, varies across spectral type on the MS (see Sect. 4.2), and how it is influenced by the intermediate-period gap. Figure 5 shows the resulting rotation period vs. Ca II IRT activity index diagram. The different spectral types are indicated by the colors, with the solid lines showing the respective 50<sup>th</sup>-percentile of the  $\log R'_{\text{IRT}}$  distribution in bins of  $P_{\text{rot}}$ . The impact of spectral type on the range of spanned rotation periods is clear: the regime of rapid rotation (e.g.,  $P_{\text{rot}} \lesssim 5$  days) is primarily populated by early-F and late-F dwarfs, while the regime of slow rotation (e.g.,  $P_{\text{rot}} \gtrsim 20$  days) is primarily populated by G and K dwarfs (McQuillan et al. 2014; Santos et al. 2021).



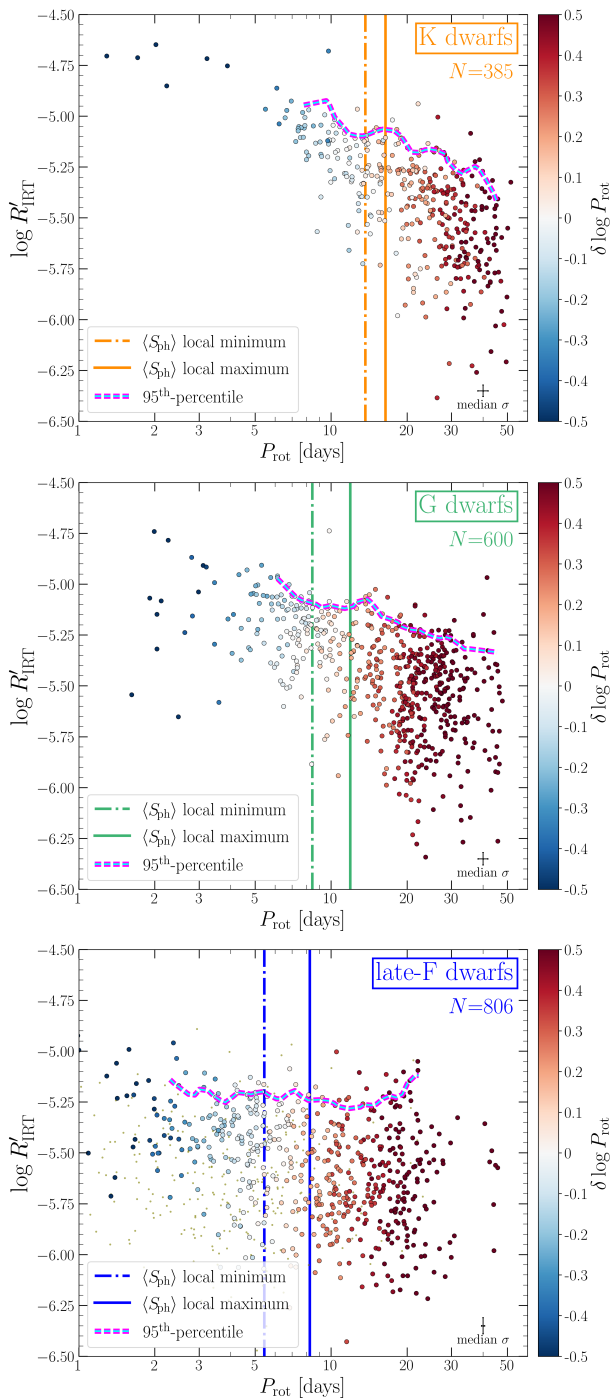
490 **Fig. 5.** Ca II IRT activity index vs. rotation period, as a function of spectral type (K dwarfs in orange, G dwarfs in green, late-F dwarfs in blue, and early-F dwarfs in magenta). Typical uncertainties are illustrated by the median  $\sigma$  symbol. The lines show their respective 50<sup>th</sup>-percentiles, with their slopes getting steeper towards lower stellar masses. At a given rotation period, later spectral types typically have higher activity indices.

Across spectral types, we see an overall negative correlation, with magnetic activity decreasing with increasing  $P_{\text{rot}}$  (i.e., 490 towards slower rotation). The slopes of these correlations, as probed by the median lines, become more pronounced with decreasing stellar mass, likely due to the increasing depth of the convective envelope. They are relatively shallow for the early-F and late-F dwarfs, and are steeper for the G and K dwarfs. Moreover, at fixed rotation period in Fig. 5, later spectral types show higher levels of magnetic activity, in agreement with the literature (e.g., Mathur et al. 2023, 2025). The variations across spectral types can be significant. For example, at a  $P_{\text{rot}} \approx 10$  days, the 500 median activity goes from  $\log R'_{\text{IRT}} \approx -5.65$  for late-F dwarfs, to  $\log R'_{\text{IRT}} \approx -5.15$  for K dwarfs, half an order of magnitude of difference.

To examine the possible impact of the intermediate-period gap on the rotation-activity relation, in Fig. 6 we repeat the  $\log R'_{\text{IRT}}$  vs.  $P_{\text{rot}}$  diagram, showing one spectral type per panel. In this case, the stars are color-coded by their  $\delta \log P_{\text{rot}}$  values<sup>5</sup> (see Sect. 2). Following Santos et al. (2023) and Santos et al. (2025) (see their Appendices B.3 and A, respectively), we quantified the upper envelope of the distribution by computing the 95<sup>th</sup>-percentile of  $\log R'_{\text{IRT}}$  in bins of  $P_{\text{rot}}$ . These upper envelopes are shown as the dashed lines. Figure 6 again shows that the rotation-activity diagram of late-F dwarfs is much flatter compared to those of the G and K dwarfs, as for the latter cases the upper envelope of Ca II IRT activity falls rapidly with increasing rotation period. 510

For reference, the impact of the intermediate-period gap on the photometric magnetic activity proxy  $\langle S_{\text{ph}} \rangle$  was recently studied by Mathur et al. (2025) and Santos et al. (2025). Their results illustrated that, for field stars, the location of the gap coincides with a dip in magnetic activity (local minimum), followed by an enhancement of activity occurring after the gap (local maximum). 520

<sup>5</sup> The early-F dwarfs are not shown as the period gap itself is not defined in that color range (see Fig. 1 and Appendix B). For the same reason, some late-F dwarfs lack  $\delta \log P_{\text{rot}}$  values (and therefore color-coding) in Fig. 6.



**Fig. 6.** Ca II IRT activity index vs. rotation period, separated by spectral type. From top to bottom these are: K dwarfs, G dwarfs, and late-F dwarfs. Stars are color-coded by their  $\delta \log P_{\text{rot}}$  values (if available). In each panel, the dashed line represents the 95<sup>th</sup>-percentile. Typical uncertainties are illustrated by the median  $\sigma$  symbols. The vertical lines (see Table 3) show the  $P_{\text{rot}}$  values of the local minimum of  $\langle S_{\text{ph}} \rangle$  at the intermediate-period gap (dash-dotted), and the local maximum after it (solid). Hints of enhanced Ca II IRT activity after the gap are seen in the K and G dwarfs (and mildly in late-F dwarfs), and these occur at similar  $P_{\text{rot}}$  values as the analogous  $\langle S_{\text{ph}} \rangle$  features.

imum; see their Fig. 7 and 1, respectively). While our sample is significantly smaller than theirs (by a factor of  $\sim 20$ ), due to the stringent brightness selection of the *Gaia* DR3 Ca II IRT data (Sect. 3), it is interesting to compare them and assess whether

**Table 3.** Local minimum and local maximum of the 95<sup>th</sup>-percentile of  $\langle S_{\text{ph}} \rangle$  occurring at the intermediate-period gap (activity dip) and after the intermediate-period gap (activity enhancement), in terms of  $P_{\text{rot}}$  for K, G, and late-F dwarfs (Fig. 6), and in terms of  $(R_0/R_{0\odot})$  for the Joint-MS sample (Fig. 7).

Sample	Variable	$\langle S_{\text{ph}} \rangle$ local minimum	$\langle S_{\text{ph}} \rangle$ local maximum
K dwarfs	$P_{\text{rot}}$	13.6	16.4
G dwarfs	$P_{\text{rot}}$	8.4	11.9
Late-F dwarfs	$P_{\text{rot}}$	5.4	8.2
Joint MS	$(R_0/R_{0\odot})$	0.29	0.38

chromospheric Ca II IRT signatures occur at similar locations as the  $\langle S_{\text{ph}} \rangle$  ones. Thus, for each spectral type, in Fig. 6 the vertical lines indicate the location (in terms of  $P_{\text{rot}}$ ) of the local minimum (dash-dotted) and local maximum (solid) of photospheric activity as probed by the  $\langle S_{\text{ph}} \rangle$  95<sup>th</sup>-percentile around the intermediate-period gap. The values of these minima and maxima were determined following Santos et al. (2023) via bounded minimization (see their Appendix B.3), and are reported in Table 3.

For K dwarfs (top panel of Fig. 6), we observe a close correspondence of the  $\langle S_{\text{ph}} \rangle$  vertical lines with a dip and a peak in the  $\log R'_{\text{IRT}}$  95<sup>th</sup>-percentile. As illustrated by the  $\delta \log P_{\text{rot}}$  color-coding, these happen at the gap (white points) and after it (white-red points), respectively. While the period range between these features is narrow ( $\approx 13$  to 16 days), the fact that both activity proxies show their respective inflections at similar locations supports the idea that they trace a common underlying process. We therefore take this agreement as a hint of the impact of the intermediate-period gap on chromospheric activity.

For G dwarfs (middle panel of Fig. 6), the diagram shows again a decrease in the upper envelope of Ca II IRT activity approximately at the intermediate-period gap ( $P_{\text{rot}} \approx 9$  days; white points in  $\delta \log P_{\text{rot}}$ ), followed by an increase after it ( $P_{\text{rot}} \approx 14$  days; white-red points in  $\delta \log P_{\text{rot}}$ ). This behavior is qualitatively similar to that seen for  $\langle S_{\text{ph}} \rangle$  in K dwarfs, although in this case the comparison with the respective local minimum and maximum shows a lesser degree of agreement, with the activity enhancement after the gap happening at a longer  $P_{\text{rot}}$  than in  $\langle S_{\text{ph}} \rangle$  (see Table 3).

For late-F dwarfs (bottom panel of Fig. 6), the decrease in Ca II IRT activity with increasing rotation period is shallower, and consequently the 95<sup>th</sup>-percentile shows a much weaker period dependence. A modest dip in  $\log R'_{\text{IRT}}$  is seen at  $P_{\text{rot}} \approx 6$  days (white points in  $\delta \log P_{\text{rot}}$ ), followed by a slight peak at  $P_{\text{rot}} \approx 7$  days (white-red points in  $\delta \log P_{\text{rot}}$ ). The  $\langle S_{\text{ph}} \rangle$  lines lie somewhat close to these features, however, given the flatter activity-rotation relation in this regime, defining these minima and maxima around the gap is more uncertain.

Throughout this analysis of Fig. 6, we have focused on the behavior of the upper envelope of  $\log R'_{\text{IRT}}$  vs.  $P_{\text{rot}}$  as traced by the 95<sup>th</sup>-percentile. The motivation for this choice is that stars located near the upper edge of the activity vs. rotation diagram are observed in more favorable conditions. On the one hand, they are expected to be oriented at inclination angles close to  $\sim 90^\circ$  (i.e., equator-on), such that they maximize the visibility of their active regions (e.g., See et al. 2021; Sowmya et al. 2021), which for the Sun are typically formed within latitudes of  $\sim \pm 30^\circ$ . On the other hand, the stars at the upper edge should be around the maximum of their activity cycles. In this way, by adopting the 95<sup>th</sup>-percentile, we minimize the scatter introduced by stars observed at lower inclination angles and quieter phases of their cycles (e.g., see Sect. 2 and 4 of Mathur et al. 2025).

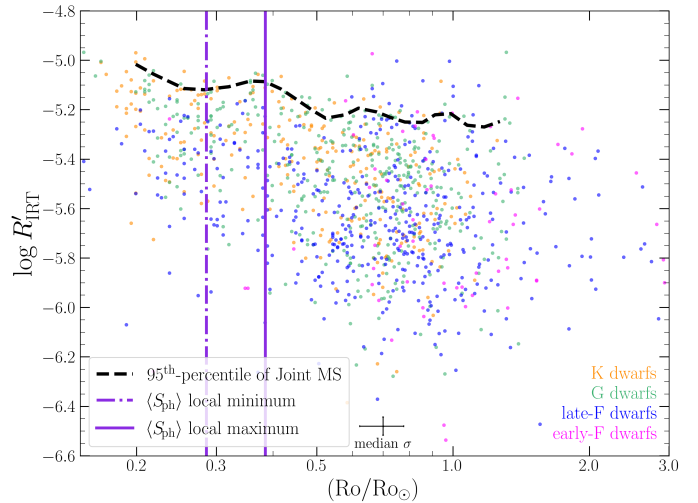
## 5.2. Calcium IRT index vs. Rossby number

580 A common approach to studying the evolution of magnetic activity is through the Rossby number ( $Ro$ ). This parameter is defined as the ratio of the rotation period to the convective overturn timescale ( $\tau_c$ ), i.e.,  $Ro = P_{rot}/\tau_c$ . The timescale  $\tau_c$  depends on the depth of the convective envelope, which in turn increases towards cooler MS stars (e.g., Corsaro et al. 2021; Bonanno et al. 2025). In this way, the Rossby number is a proxy for stellar rotation that accounts for the  $T_{eff}$ -dependence, allowing comparisons among different spectral types.

590 While rotation periods can be measured observationally (in the case of our sample thanks to the *Kepler* photometry), estimates for convective overturn timescale are typically model-dependent. Thus, to study the rotation-activity relation in terms of the Rossby number, we went beyond the *Gaia* DR3 colors and adopted literature stellar properties. Specifically, given the large overlap with our sample, we adopted the  $\tau_c$  values from Mathur et al. (2025), who calculated these using the Yale Rotating Evolution Code (YREC; Pinsonneault et al. 1989; Bahcall et al. 2001; Demarque et al. 2008). By searching for the model that best fitted the observed parameters of the stars ( $T_{eff}$ ,  $L$  or  $\log g$ , and  $[Fe/H]$ ) with the *kiauhoku* optimization tool (Clayton et al. 2020), they obtained  $\tau_c$  and  $Ro$ . For representation purposes, and to allow the comparison between different Rossby number prescriptions, these  $Ro$  values were normalized by the solar value in the YREC models ( $Ro_{\odot} = 2.16$ ). The modelling procedure is further detailed in Mathur et al. (2025).

We note that the temperature and metallicity values used by Mathur et al. (2025) to compute  $Ro$  differ from those we adopted in the  $\log R'_{IRT}$  calculation (Sect. 3). On the one hand, as currently no spectroscopic survey covers the entirety of the *Kepler* field (Godoy-Rivera et al. 2026a), Mathur et al. (2025) used a combination of spectroscopic and photometric inputs, namely: CFOP (*Kepler* Community Follow-up Observation Program; Furlan et al. 2018), APOGEE DR16 (Apache Point Observatory for Galactic Evolution Experiment; Ahumada et al. 2020), LAMOST DR7 (Large Sky Area Multi-Object Fiber Spectroscopic Telescope; Zhao et al. 2012; Zong et al. 2020), and the two latest *Kepler* stellar properties catalogs (Mathur et al. 2017; Berger et al. 2020). On the other hand, to calculate the Ca II IRT magnetic-activity index, we adopted the corresponding *Gaia* DR3 *gspspec* or *gspphot* parameters (see Lanzafame et al. 2023). As discussed in Sect. 3, a different set of stellar properties propagates to only a minor impact on the derived Ca II IRT proxy (Equation 2), which is typically within the uncertainties. Thus, although some heterogeneities are present in our Ca II IRT vs.  $Ro$  analysis below, these do not impact any of the conclusions.

Figure 7 shows  $\log R'_{IRT}$  vs. the normalized Rossby number for the Joint-MS sample, with the different spectral types indicated by the colors. The 95<sup>th</sup>-percentile of the  $\log R'_{IRT}$  distribution in bins of  $(Ro/Ro_{\odot})$  is shown as the black dashed line. 630 Considering the sample as a whole, we observe an overall decrease in the chromospheric activity index with increasing  $Ro$ . Such a behavior is consistent with what has been found for other chromospheric and photospheric magnetic activity indices (e.g., Noyes et al. 1984; Zhang et al. 2020; Reiners et al. 2022; Brown et al. 2022; Cao & Pinsonneault 2022; Mathur et al. 2025; Yang et al. 2025), as well as for the  $\log R'_{IRT}$  itself reported for cluster stars (Fritzewski et al. 2021) and in the field (Freund et al. 2025). This trend is consistent with our targets being located in the aforementioned unsaturated regime, where the activity level is a strong function of  $P_{rot}$  and thus  $Ro$ , in agreement with other rotation-activity studies of the *Kepler* stars



**Fig. 7.** Ca II IRT activity index vs. Rossby number ( $Ro = P_{rot}/\tau$ ), normalized to the solar value ( $Ro/Ro_{\odot}$ ). K dwarfs are shown in orange, G dwarfs in green, late-F dwarfs in blue, and early-F dwarfs in magenta. The dashed line shows the 95<sup>th</sup>-percentile for the combined Joint-MS sample. Typical uncertainties are illustrated by the median  $\sigma$  symbol. A lower Rossby number typically means a higher  $\log R'_{IRT}$ . The vertical lines (see Table 3) show the  $(Ro/Ro_{\odot})$  values of the local minimum of  $\langle S_{ph} \rangle$  at the intermediate-period gap (dash-dotted), and the local maximum after it (solid), which closely align with the analogous features observed in the Ca II IRT index upper envelope.

(e.g., Matt et al. 2015). We note that the saturated regime is only scarcely represented in the *Kepler* sample (e.g., Masuda 2022; Santos et al. 2024), as expected for a predominantly spun-down field-star population.

The  $\log R'_{IRT}$  vs.  $Ro$  diagram of Fig. 7 also probes the impact of the intermediate-period gap on chromospheric activity. In this context, we replicated the comparison between  $\log R'_{IRT}$  and  $\langle S_{ph} \rangle$  in terms of the local minimum and maximum in activity tied to the gap (see Sect. 5.1), but as a function of the Rossby number instead of rotation period. Using the Mathur et al. (2025) sample, we applied the analogous selection criteria (i.e., Joint-MS stars with measured  $\langle S_{ph} \rangle$  and  $Ro$ ) and recomputed the positions of these local minimum and maximum features in terms of  $(Ro/Ro_{\odot})$ . These values are reported in Table 3 and shown as the vertical lines in Fig. 7.

Although again our Ca II IRT sample is significantly smaller than the Mathur et al. (2025) one (by a factor of  $\sim 30$ ), interesting comparisons can be made. As traced by the 95<sup>th</sup>-percentile in  $\log R'_{IRT}$ , the local minimum at the intermediate-period gap appears to be slightly shifted towards a lower  $Ro$  compared to  $\langle S_{ph} \rangle$  ( $Ro/Ro_{\odot} \approx 0.25$ ). However, given our smaller sample size, the agreement is still reasonable. For the local maximum after the gap, the  $\log R'_{IRT}$  behavior shows a strong agreement with  $\langle S_{ph} \rangle$ , coinciding at ( $Ro/Ro_{\odot} \approx 0.38$ ). This comparison further demonstrates that, despite the differences discussed above (Sect. 4 and 5.1), both  $\log R'_{IRT}$  and  $\langle S_{ph} \rangle$  trace the same underlying phenomena, with their local minimum at the intermediate-period gap and local maximum after it appearing at similar values of the Rossby number.

The above analyses are in broad agreement with Ye et al. (2025), who studied the impact of the rotational stalling (see Sect. 1) in open clusters on chromospheric magnetic activity as probed by the Ca II H&K index. Specifically, our results of the Ca II IRT index resemble those of Ye et al. (2025) for K-dwarf stars, with the intermediate-period gap and the stalling coincid-

ing with a dip in chromospheric activity followed by an enhancement (see their Fig. 8c). While their comparison was focused on the location of the stalling in regards to K dwarfs, hints of the analogous behavior may be seen for their G dwarfs too. The comparison with their F-dwarf stars is not as straightforward, as while we decided to split between early-F and late-F dwarfs, Ye et al. (2025) combined them together into a single category.

All in all, the agreement across several magnetic activity proxies that span the photosphere and chromosphere paints a consistent picture: activity decreases at the intermediate-period gap, and increases after it. While Reinhold et al. (2019) and Reinhold & Hekker (2020) interpreted the photometric activity decrease at the gap as the cancellation between dark spots and bright faculae, the persistence of the activity dip and enhancement across photospheric and chromospheric diagnostics disfavor this hypothesis as an explanation to account for all the observables. Instead, with the existing data sets, the core-envelope coupling scenario appears as a more likely cause (e.g., Spada & Lanzafame 2020; Lu et al. 2024).

Finally, at larger values of the Rossby number ( $Ro/Ro_{\odot} \sim 0.7$  to  $1.0$ ), Fig. 7 shows a slight overdensity of stars. This could correspond to the pile-up found in the rotating *Kepler* sample, linked to the weakened magnetic braking phenomenon (e.g., David et al. 2022; Metcalfe et al. 2023). Beyond the solar value ( $Ro/Ro_{\odot} > 1.0$ ), the analysis of photometric and spectroscopic activity proxies from *Kepler* and *K2* data has suggested enhanced magnetic activity in G-type stars (Mathur et al. 2025 and Brandenburg & Giampapa 2018, respectively). This behavior may be related to anti-solar differential rotation according to magneto-hydrodynamical simulations (Karak et al. 2020; Brun et al. 2022; Noraz et al. 2022). While hints of a flattening in the Ca II IRT index beyond  $Ro_{\odot}$  might be present in Fig. 7, unfortunately this regime of the diagram is too scarcely populated to draw any firm conclusions.

### 5.3. The influence of multiplicity

As a final piece of the analysis, we examine the impact of multiplicity on magnetic activity. Binary and higher-order systems are fundamental astrophysical laboratories (e.g., Duchêne & Kraus 2013; Beck et al. 2026). They are common in solar-like stars (Duquennoy & Mayor 1991; Raghavan et al. 2010), and thus assessing their influence is key for our understanding of the rotation-activity relation (Schrijver & Zwaan 1991; Poppenhaeger 2017; Long et al. 2025). This is particularly relevant in the regime where close companions can modify the rotational evolution of stars (e.g., Kounkel et al. 2022, 2023; Godoy-Rivera & Chanamé 2018; Silva-Beyer et al. 2023; Gruner et al. 2023a,b; Beck 2026), yielding populations of rapid rotators in the field (e.g., Lurie et al. 2017; Simonian et al. 2019; Angus et al. 2020; Ding et al. 2024; Patton et al. 2024). A first hint of the impact of multiplicity on activity in our sample was shown on the CMD of Fig. 2, where several targets that populate the photometric binary region have high-activity levels ( $\log R'_{\text{IRT}} \gtrsim -5.5$ ).

More broadly, a thorough search for candidate binary systems was carried out for the *Kepler* stars by Godoy-Rivera et al. (2025) using astrometric, photometric, and spectroscopic diagnostics on the *Gaia* data in combination with literature catalogs (see their Sect. 4 for details). For this work, we used their “Flag Binary Union” column as our binarity indicator, which we repeat in Table 1 for simplicity. The targets not flagged by this column were taken to be single stars. We nonetheless note that, even with the high precision of current surveys, the observed binary

fraction recovered from such data sets (e.g., Beck et al. 2024) remains lower than the expected value from population studies (e.g., Offner et al. 2023; Espinoza-Rojas et al. 2025). Therefore, future data releases (e.g., *Gaia* DR4; Brown 2024) will in all likelihood reveal additional multiple systems.

In the top panels of Fig. 8, we show the rotation-activity relation for our Joint-MS targets probed by  $\log R'_{\text{IRT}}$  (left column) and  $\langle S_{\text{ph}} \rangle$  (right column), splitting the sample into singles (brown) and binaries (violet). For reference, the 95<sup>th</sup>-percentiles of their activity distributions in bins of  $P_{\text{rot}}$  are shown as the dashed lines. For chromospheric activity, while at rotation periods longer than  $\gtrsim 5$  days both populations show similar distributions, for  $P_{\text{rot}} \lesssim 4$  days binary systems stand out with a higher upper envelope of  $\log R'_{\text{IRT}}$  values than single stars at a given rotation period. A similar trend is seen for photospheric activity, where binaries display a higher upper envelope of  $\langle S_{\text{ph}} \rangle$  values than single stars for  $P_{\text{rot}} \lesssim 10$  days. This is also reflected in the individual data points, with the majority of targets more active than  $\log R'_{\text{IRT}} \gtrsim -5.0$  and  $\langle S_{\text{ph}} \rangle \gtrsim 10^4$  ppm being flagged as binaries. Still, MS binaries with short rotation periods span a range of activity values (e.g., Fig. 15 of Beck et al. 2024).

Caveats of the above Ca II IRT vs.  $\langle S_{\text{ph}} \rangle$  comparison are that, on the one hand, the chromospheric activity index is available for a significantly smaller sample than the photospheric one (factor of  $\sim 20$ ). On the other hand, the sample with  $\log R'_{\text{IRT}}$  values is significantly brighter than its counterpart with  $\langle S_{\text{ph}} \rangle$  values (median apparent  $G \approx 11.9$  mag and  $G \approx 14.7$ , respectively, or a flux ratio of  $\approx 13$ ), implying a higher completeness of the binary diagnostics for the former than the latter (e.g., see Fig. 7 of Godoy-Rivera et al. 2025). In spite of these, both proxies exhibit comparable qualitative behaviors.

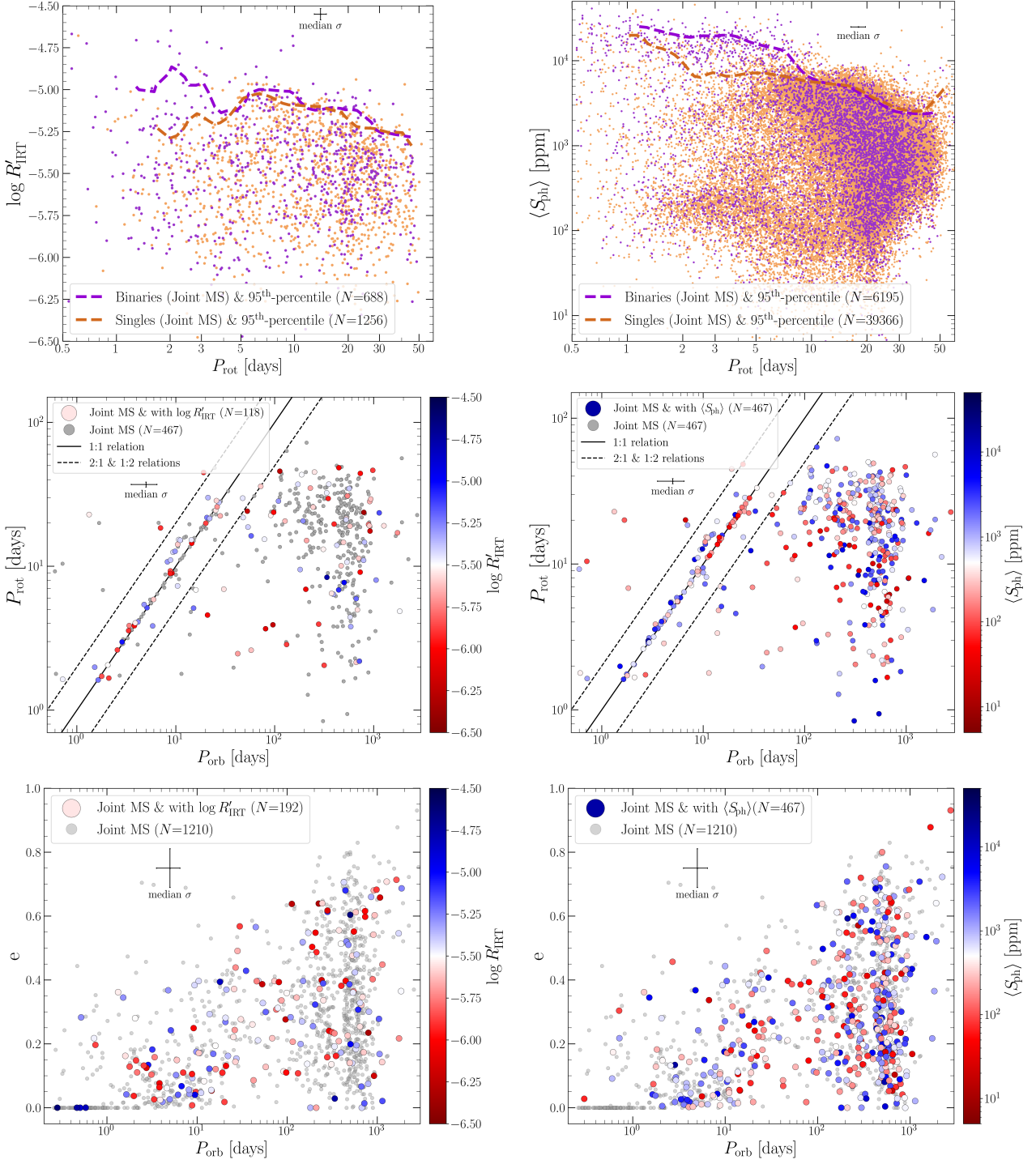
These results show that the influence of multiplicity on enhancing magnetic activity relative to single stars is most prominent among fast rotators, in line with recent findings of chromospheric and photospheric activity proxies for MS and evolved targets (e.g., Gaulme et al. 2020; Gehan et al. 2022, 2024; Beck et al. 2024; Shi et al. 2025; Godoy-Rivera et al. 2026b). Indeed, the range of periods ( $\lesssim 10$  days) of the enhanced activity upper envelopes in the top panels of Fig. 8 falls within the regime where tidal effects become significant (e.g., Lurie et al. 2017). Such strong tidal interactions drive binaries toward circularization and synchronization (e.g., Zahn 2013; Offner et al. 2023), which can lead to strong magnetic activity as well as suppression of oscillation modes (Gaulme et al. 2014, 2020; Beck et al. 2018; Mathur et al. 2019; Benbakoura et al. 2021; Gehan et al. 2024).

To further explore this, we searched for orbital information in the *Gaia* DR3 non-single star two-body orbit catalog (NSS TBO; Gaia Collaboration et al. 2023b,a) and the eXtended Catalogue of Spectroscopic Binary Orbits (SBX; Merle et al. 2026). We found a total of 2,012 systems<sup>6</sup> with orbital periods ( $P_{\text{orb}}$ ), 58 coming from the SBX and 1,954 coming from the NSS TBO<sup>7</sup>. The majority of these (2,008 out of 2,012) also had values for the eccentricity (e). These orbital parameters are reported in Table 1.

The middle panels of Fig. 8 show the  $P_{\text{rot}}$  vs.  $P_{\text{orb}}$  diagram, with the subset of targets with measured activity indices color-coded by  $\log R'_{\text{IRT}}$  and  $\langle S_{\text{ph}} \rangle$  (left and right columns, respectively). Below  $P_{\text{orb}} \lesssim 30$  days, binaries predominantly populate

<sup>6</sup> Of these systems, 4 were found in both catalogs, showing good agreement between their solutions. For these, we adopted their SBX values.

<sup>7</sup> A subset of 30 targets had two solutions in the NSS TBO. For these, we picked the `nss_solution_type` with the shortest orbital period, typically being an SB1 over an Orbital solution.



**Fig. 8.** Impact of multiplicity on the magnetic activity of MS targets as probed by the chromospheric Ca II IRT (left column) and the photospheric  $\langle S_{\text{ph}} \rangle$  (right column). Top: activity index vs. rotation period, as a function of stellar multiplicity (singles in brown and binaries in violet). The dashed lines show the 95<sup>th</sup>-percentile of each distribution. In the regime of rapid rotators ( $P_{\text{rot}} \lesssim 5 - 10$  days), binary systems have a higher activity upper envelope than single stars at a given rotation period. Middle: rotation period vs. orbital period color-coded by activity index (if available). The solid lines illustrate the 1:1 relation, while the dashed lines illustrate the 2:1 and 1:2 relations. Along the  $P_{\text{rot}} = P_{\text{orb}}$  line, especially for  $\langle S_{\text{ph}} \rangle$ , enhanced activity can be seen for periods  $\lesssim 10$  days. Bottom: orbital period vs. eccentricity color-coded by activity index (if available). Systems with  $P_{\text{orb}} \lesssim 10$  days and near circular orbits ( $e \lesssim 0.05$ ) often display high activity values. Typical uncertainties are illustrated by the median  $\sigma$  symbols.

the  $P_{\text{rot}} = P_{\text{orb}}$  line. Along this synchronization line, a trend of increased  $\langle S_{\text{ph}} \rangle$  values can be seen for  $P_{\text{orb}} \lesssim 10$  days. For  $\log R'_{\text{IRT}}$  there is no such clear trend, although we note that the sample size is smaller (factor of  $\sim 4$ ). Comparing with the literature, activity enhancements have been seen for close binaries with respect to

wide binaries on the MS (e.g., Yu et al. 2025), as well as for red giant binaries in spin-orbit resonances (e.g., Gaulme et al. 2014; Benbakoura et al. 2021; Gehan et al. 2024).

The bottom panels of Fig. 8 show the analogous eccentricity vs. orbital period diagram, color-coded by magnetic activity

when available. Here, the  $\log R'_{\text{IRT}}$  index does show its highest values for the short-period circularized systems ( $P_{\text{orb}} < 1$  day and  $e \approx 0$ ), with the  $1 \text{ day} < P_{\text{orb}} < 10$  days regime showing both low- and high-activity systems. For  $\langle S_{\text{ph}} \rangle$ , the regime of  $P_{\text{orb}} \lesssim 10$  days is again predominantly populated by high-activity targets in near-circular orbits. These trends are in broad agreement with the literature (e.g., Dixon et al. 2025).

## 6. Conclusions

Stellar magnetic activity indicators are key probes of the rotation-activity connection and of angular momentum evolution. In this paper, we studied chromospheric magnetic activity as probed by the Ca II IRT index provided by *Gaia* DR3 for the *Kepler* field stars. The resulting catalog is reported in Table 1.

We combined our chromospheric  $\log R'_{\text{IRT}}$  indices with literature rotation periods and photospheric activity proxy  $\langle S_{\text{ph}} \rangle$ , to obtain a coherent view of the magnetic properties of low-mass stars across the Hertzsprung-Russell diagram (Fig. 2). We compared both indices with each other, and found a statistically significant correlation (Fig. 4). This reinforces the view that these proxies trace the same underlying dynamo-driven magnetic processes, despite probing different atmospheric layers and temporal windows, which mitigate their correspondence.

Our analysis shows that the intermediate-period gap leaves an imprint on the chromospheric activity level of MS stars that have recently experienced this phase. This is reflected as hints of an activity dip at the gap, followed by an enhancement after it in the  $\log R'_{\text{IRT}}$  index vs.  $P_{\text{rot}}$  diagram (Fig. 6). The locations of these dip and enhancement closely track similar features previously identified in the literature using the photospheric  $\langle S_{\text{ph}} \rangle$  index instead. This alignment is seen not only in terms of  $P_{\text{rot}}$ , but also in the Rossby number (Fig. 7).

This agreement between photospheric and chromospheric diagnostics supports the interpretation of the intermediate-period gap as a genuine transition in stellar magnetic behavior, rather than an artifact limited to a particular activity proxy. Overall, the unsaturated regime probed by the Ca II IRT proxy vs. Rossby number diagram confirms the presence of subtle structures associated with changes in braking efficiency. Moreover, although scarcely populated, our sample possibly hints at the possible weakened magnetic braking phenomenon around and beyond the solar Rossby number.

In terms of the impact of spectral type on the chromospheric  $\log R'_{\text{IRT}}$  index, later-type stars are found to display higher activity levels at a given rotation period (i.e., with K dwarfs being systematically more active than G dwarfs, which in turn are more active than F dwarfs; Fig. 5). The amplitude of these differences can reach half an order of magnitude in Ca II IRT at fixed  $P_{\text{rot}}$ , which has direct implications for the environments of exoplanets around K-type stars.

Multiplicity emerges as an additional ingredient in shaping chromospheric magnetic activity. Binary systems, especially in the regime of rapid rotators ( $P_{\text{rot}} < 5 - 10$  days), systematically show a higher upper envelope of Ca II IRT and  $\langle S_{\text{ph}} \rangle$  values than single stars at a given rotation period (Fig. 8), consistent with tidal interactions maintaining or enhancing rotation and magnetic activity. This highlights the important role of stellar architecture in shaping rotation-activity relations and age diagnostics.

All in all, this work sheds light on the impact of the intermediate-period gap on chromospheric magnetic activity. It represents a homogeneous reference data set for future studies of stellar magnetism, and opens the door to extending this

type of analysis with complementary samples. These will benefit from the wide availability of the *Gaia* chromospheric index in current and upcoming data releases (Lanzafame et al. 2023), together with rotational measurements from ground- and space-based photometry such as the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015), the Zwicky Transient Facility (ZTF; Bellm et al. 2019), and the All Sky Automated Survey for SuperNovae (ASAS-SN; Shappee et al. 2014), as well as the upcoming Planetary Transits and Oscillations of Stars (PLATO; Rauer et al. 2025), the Earth 2.0 mission (ET; Ge et al. 2024), and the Rubin Observatory (Ivezić et al. 2019). All of the above will enable a better understanding of the age-rotation-activity relations, the transition between different braking regimes, and the magnetic environments of exoplanetary systems.

## Data availability

Table 1 and Table 2 are available in electronic form on Zenodo ([https://zenodo.org/records/\[????\]](https://zenodo.org/records/[????])) and at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](https://cdsarc.u-strasbg.fr) ([????]) or via [http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/\[????\]](http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/[????]).

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## Appendix A: Binning Procedure

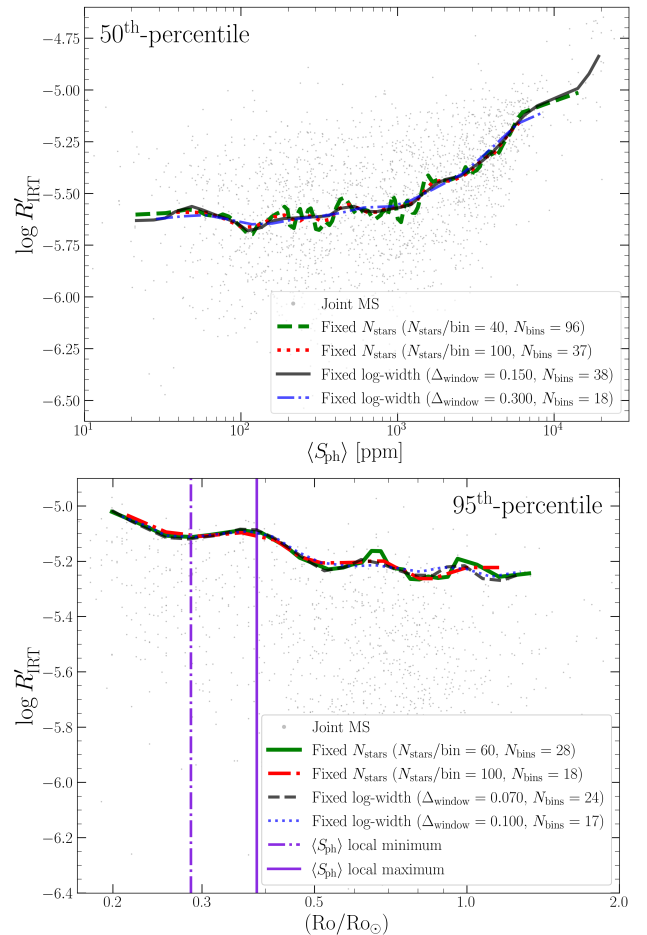
Part of the analysis presented throughout this paper is based on the trends obtained from percentiles of the distribution of  $\log R'_{\text{IRT}}$  in bins of  $\langle S_{\text{ph}} \rangle$ ,  $P_{\text{rot}}$ , and  $\text{Ro}$ . Here, we described the binning procedure used to obtain these percentiles.

The top panel of Fig. A.1 illustrates this in the  $\log R'_{\text{IRT}}$  vs.  $\langle S_{\text{ph}} \rangle$  diagram (see the top panel of Fig. 4). From the scatter plot, we took two approaches to bin the data. In the first one, the stars were sorted by their  $\langle S_{\text{ph}} \rangle$  values, and were binned by a fixed number of stars per bin ( $N_{\text{stars}}/\text{bin}$ ). Within each bin, the 50<sup>th</sup>-percentile of the  $\log R'_{\text{IRT}}$  distribution was calculated, and the resulting trend was smoothed using a 1-D Gaussian convolution kernel. Two examples of this fixed  $N_{\text{stars}}$  approach are shown as the green and red lines. In the second approach, the data were binned by a fixed logarithmic  $\langle S_{\text{ph}} \rangle$  width (of size  $\Delta_{\text{window}}$ ), and again the 50<sup>th</sup>-percentile of the  $\log R'_{\text{IRT}}$  distribution was calculated and the aforementioned smoothing was applied. Two examples of this fixed log-width approach are shown as the black and blue lines. The bottom panel of Fig. A.1 shows the analogous exercise for the  $\log R'_{\text{IRT}}$  vs.  $\text{Ro}$  diagram (see Fig. 7), where the 95<sup>th</sup>-percentile of the  $\log R'_{\text{IRT}}$  distribution was calculated as a function of the different binning approaches.

Figure A.1 shows that, regardless of the binning approach taken, or the specific parameters used, the same overall trends are seen in the diagrams. Throughout this paper, we chose the fixed logarithmic width approach (picking the parameters to account for the varying sample sizes and ranges covered), as it generally yielded smoother percentiles. All in all, the resulting trends are virtually insensitive to the choice of binning method.

## Appendix B: Classification of the Joint-MS sample into spectral types

To separate the Joint-MS sample into spectral types, we used the de-reddened *Gaia* DR3 colors (Sect. 2) and the color-SpT table from Pecaut & Mamajek (2013), classifying the stars as: early-F dwarfs for  $0.377 \leq (BP - RP)_0 < 0.587$  mag, late-F dwarfs for  $0.587 \leq (BP - RP)_0 < 0.784$  mag, G dwarfs for  $0.784 \leq (BP - RP)_0 < 0.983$  mag, K dwarfs for  $0.983 \leq (BP - RP)_0 < 1.840$  mag, and M dwarfs for  $1.840 \leq (BP - RP)_0 < 4.780$  mag. The distinction between early- and late-F dwarfs was taken as the SpT closest to the Kraft break location reported by Beyer & White (2024), corresponding to F5V (see also Wang et al. 2026). The assigned SpTs are reported as the ‘‘Spectral Type’’ column in Table 1.



**Fig. A.1.** Impact of the binning procedure on the resulting  $\log R'_{\text{IRT}}$  trends and percentiles. Top: example with the 50<sup>th</sup>-percentile of  $\log R'_{\text{IRT}}$  vs.  $\langle S_{\text{ph}} \rangle$  (from the top panel of Fig. 4). Bottom: example with the 95<sup>th</sup>-percentile of  $\log R'_{\text{IRT}}$  vs.  $\text{Ro}$  (from Fig. 7). The two methods are fixed  $N_{\text{stars}}$  (green and red lines), and fixed logarithmic width (black and blue lines). Overall, the obtained trends are mostly insensitive to the specific binning method.