Stellar Chromospheric Activities Revealed from the LAMOST-K2 Time-domain Survey

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Abstract

By using the LAMOST time-domain survey data, we study stellar activities based on the Hα lines for about 2000 stars in four K2 plates. Two indices, $R_{\alpha}$ and $R_{\alpha}^{\prime}$, are computed from LAMOST spectra, the former of which is derived by excluding the photospheric contributions to the Hα lines, while the latter is derived by further subtracting the non-dynamo-driven chromospheric emission. Meanwhile, the periodicity and variation amplitudes are computed from K2 light curves. Both the $R_{\alpha}$–$R_{\alpha}^{\prime}$ relation and $R_{\alpha}$–$R_{\alpha}^{\prime}$ relation show complicated profiles in the nonsaturated decay region. Hot stars show flatter slopes and a higher activity level than cool stars, and the behavior is more notable in the $R_{\alpha}$–$R_{\alpha}^{\prime}$ relation. This is consistent with recent studies using other activity proxies, including $L_v/L_{bol}$, $R_{HK}$, and amplitudes of optical light curves. This may suggest different kinds of stars follow different power laws in the decay region. Most of our targets have multiple observations, and some of them exhibit significant variability of Hα emissions, which may cause the large scatters shown in the decay region. We find three targets exhibiting positive correlation in a rotational phase, possibly indicating that their optical light curves are dominated by hot faculae rather than cool starspots.

1. Introduction

Stellar magnetic fields are the energy source of stellar activities. According to the dynamo theories, magnetic fields are generated by differential rotation in deep convection zones (Parker 1955a, 1955b; Noyes et al. 1984; Chabrier & Küker 2006) or the interaction of flow turbulence (Durney et al. 1993; Drake et al. 1996). It has been widely accepted that the strength of magnetic fields is positively related to the stellar activity level.

The strength of magnetic activity can be traced by various proxies, including spots, flares, chromospheric emissions, and X-ray and radio emissions. The golden one is the Ca II H and K emission lines, whose cores are extremely sensitive to magnetic fields (Babcock & Babcock 1955; Leighton 1959). Wilson (1978) carried out long-term observations of chromospheric activities for different types of stars. In order to quantify the activity level, Vaughan et al. (1978) introduced the well-known S-index. Later on, Noyes et al. (1984) proposed the $R_{HK}$ value, which can characterize the excess chromospheric emission of Ca II H and K lines.

However, for faint cool stars the Ca II H and K lines are less notable compared to those of hot stars so that they are hard to detect. An alternative proxy of chromospheric activity is the Hα emission. Although such emission could be dominated by photoionization, as the temperature decreases the contribution of collisional excitation would gradually become significant and thus the Hα line can be used as tracer of chromospheric activities (Cincunegui et al. 2007; Linsky 2017).

Chromospheric activity levels are always related to stellar rotation. The well-known activity–rotation relation provides fundamental information on stellar dynamos and angular momentum evolution, and has been comprehensively studied. There are different proxies to trace this relation, including X-ray, Hα line, and Ca II H and K lines. For different tracers, the activity–rotation relation shows a similar trend, e.g., a flat saturated region and a power-law decay region against rotation periods or Rossby numbers (Ro) in the logarithmic scale (e.g., Pizzolato et al. 2003; Wright et al. 2011).

Such a standard relation has been challenged by many recent studies. Pizzocaro et al. (2019) found that instead of continuous decaying, some X-ray emitting Kepler stars with Ro > 0.3 behaved differently in such a relation (see their Figure 8). Lehtinen et al. (2021) argued that such a relation should consist of a broken two-piece power law. Mittag et al. (2018) even divided the relation into four regions after combining the stellar X-ray and Ca II H and K emission. By calculating the photometric variability ($R_{\text{var}}$) for tens of thousands of K2 stars, Reinhold & Hekker (2020) presented the relation between $R_{\text{var}}$ and the rotation periods of different types of stars. Interestingly, a rather flat relation was shown when periods are longer than 20 days. Motivated by these new findings, in this study, we adopted the Hα emission to investigate the relation between magnetic activity and rotation for various types of stars based on the recent LAMOST time resolved sky survey and K2 light curves. An ideal sample to study the connection between different activity proxies and the mechanism of stellar dynamos is also provided. The paper is organized as follows. In Section 2 we introduce the sample and data reduction. Section 3 shows the main results, including relative corrections of equivalent widths (EWs), the calculation of normalized Hα luminosities, and the
estimation of rotation periods and Rossby numbers. We discuss our results in Section 4, including the activity–rotation relation based on \( \text{H}_\alpha \) emission, and the relation between \( \text{H}_\alpha \) emission and K2 brightness in the rotational phase.

2. Source Selection and Data Reduction

2.1. Source Selection

The Kepler mission and its extended K2 mission provided light curves with high photometric precision of more than 200,000 stars. Such a huge and elite sample would open a new era of studying stellar physics (Borucki et al. 2010; Koch et al. 2010). The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (hereafter LAMOST, also named as the Guoshoujing Telescope) is a quasi-meridian Schmidt telescope with a 4 m aperture and a field of view of 5° (LAMOST; Cui et al. 2012). With 4000 fibers on its focus surface, tens of millions of spectra have been gathered with high efficiency.

Since 2012, the LAMOST-Kepler/K2 projects have been carried out, which performed both time-domain and non-time-domain sky surveys of the Kepler field and the K2 campaigns, releasing both the medium-resolution spectral (MRS) and low-resolution spectral (LRS) data for tens of thousands of targets (Fu et al. 2020; Zong et al. 2020). Recently, LAMOST has started the second 5 yr sky survey, which performs both LRS and MRS observations with \( \Delta \lambda/\lambda \sim 1800 \) and \( \sim 7500 \), respectively (Liu et al. 2020; Zong et al. 2020). The MRS observations provide spectra covering the wavelength range from 4950 Å to 5930 Å for the blue arm and from 6300 Å to 6800 Å for the red arm, respectively. Spectra of the LRS observations cover the wavelength range of 3650–9000 Å.

Recently, Wang et al. (2021) reported the first results of the LAMOST time-domain survey, covering four K2 plates. There are 10,700 targets in their sample and most of them have multiple observations. For the LRS observations, 767,158 spectra were derived in blue arms and 767,150 spectra in red arms. For the MRS observations, 478,694 spectra were gathered for both the blue and red arms.

Among these targets, over 3000 targets have K2 light curves. In Wang et al. (2021), the Lomb–Scargle method (Lomb 1976; Scargle 1982) was applied for period detection. In brief, a two-step grid searching method was carried out to determine the optimized period (VanderPlas & Ivezic 2015), including searching in a broad grid for a series of period candidates and zooming in on a narrow grid to find the real peak. All the light curves were folded based on the detected periods and the variable types of stars were classified by using light-curve templates (e.g., Kim et al. 2014). These objects are our input sample.

In order to exclude potential binaries, we calculated the radial velocity (RV) for each object based on multiple MRS exposures through the cross-correlation method. The PHOENIX high-resolution synthetic spectra (Husser et al. 2013) were used as templates and were convolved to the MRS resolution \( R = 7500 \). The cross-correlation results were visually checked to exclude double-lined spectroscopic binaries. Meanwhile, targets with RV variation larger than 10 km s\(^{-1}\) were also removed. In addition, we excluded possible pulsating variables...
and other potential types of variables given in Wang et al. (2021). This yielded 2454 stars.

Figure 1 plots the color–magnitude diagram of both the Wang et al. (2021) sample and our targets in blue and red dots, respectively. Our sample contains stars with different spectral types and there are 1856 dwarfs and 593 giants, among which there are 17 A-type stars, 505 F-type stars, 684 G-type stars, 1140 K-type stars, and 103 M-type stars. Stellar parameters, including the effective temperature \( T_{\text{eff}} \), surface gravity \( \log g \), and metallicity \([\text{Fe}/\text{H}]\), of these stars were extracted from the LAMOST DR8 catalog, and were estimated based on the LAMOST stellar parameter pipeline (Luo et al. 2015).

2.2. Equivalent-width Measurements

Only the spectra with a signal-to-noise ratio \((S/N)\) higher than 10 were reserved for our spectral analysis. These spectra were normalized for further EW calculation (Zhang et al. 2020a, 2021). Figure 2 shows an example of H\(\alpha\) emission of target J034241.89+241158.3. Generally, there are two ways to calculate the EWs: integration and Gaussian fitting. Widths of Balmer lines would decrease with effective temperatures (Mihalas 1978). Therefore, the wavelength range for the calculation should be different for each type of star. We followed four steps to test the results by changing the wavelength range. Detailed steps are listed as follows.

1. We divided our sample into several groups according to their effective temperatures. A-type stars are hotter than 7500 K and cooler than 10,000 K. Targets with effective temperatures between 6000 and 7500 K were marked as F-type stars. For G-type and K-type stars, the temperature range was set to be from 5300 K to 6000 K, and from

![Figure 3. Comparison between Gaussian fitting and integration method for calculating the EWs of H\(\alpha\) lines. Panels (a) and (b) are the results of medium-resolution spectral (MRS) observations. Panels (c) and (d) are the results of low-resolution spectral (LRS) observations. Different colors represent different stellar types.](image-url)
4000 K to 5300 K, respectively. Targets with effective temperatures lower than 4000 K were treated as M-type stars.

2. The line centers of H$_\alpha$ were corrected using the RVs derived in Section 2.1.

3. For the integration method we used the formula:

$$EW_{H\alpha} = \int \frac{F_{\alpha} - F_{c}}{F_{c}} d\lambda.$$  

Here $F_c$ is the median value of the pseudocontinua. For all kinds of stars, the range of the pseudocontinua outside the line range on both sides was set to be 10 Å.

4. We tested two sets of the integration ranges: fixed range (20 Å) and variable range. In the latter set, for A-, G-, K-, and M-type stars, the widths of the line around the line center were set to be 50 Å, 20 Å, 20 Å, and 10 Å, respectively. For early-F stars the H$_\alpha$ line is wider than late F stars. Thus we divided F stars into three subsamples using a temperature bin of 500 K. For stars with 7000 K to 7500 K, 6500 K to 7000 K, and 6000 K to 6500 K, the integration ranges of the H$_\alpha$ lines were set to be 40 Å, 30 Å, and 20 Å, respectively. This step leads to two equivalent-width results, named $EW_{\text{integ,20 Å}}$ and $EW_{\text{integ,var}}$.

5. In the Gaussian fitting method, we set the wavelength range as a constant, i.e., 20 Å, for all types of stars. The corresponding EWs were named as $EW_{\text{fit}}$.

The comparisons between different methods are shown in Figure 3. It is clear that for hot stars, $EW_{\text{integ,20 Å}}$ significantly deviate from $EW_{\text{fit}}$ due to the wide H$_\alpha$ profile, while $EW_{\text{integ,var}}$ agree well with $EW_{\text{fit}}$. When the lines are weak, EWs from the integration method are close to zero whereas those from Gaussian fitting would become unreliable, since those lines would deviate from a Gaussian shape and the low S/N would result in poor fittings. Therefore, we preferred to use $EW_{\text{integ,var}}$ (hereafter EW) in following analyses.

We then estimated the errors of the EWs. For each spectrum, 1000 synthetic spectra were simulated by adding Gaussian noise to each wavelength using the flux uncertainty given by LAMOST data. All the EWs of these 1000 spectra were measured and the standard deviation was used as the error of the EW. The results of the EWs from MRS and LRS observations are listed in Tables 1 and 2, respectively.

### 2.3. Correction of EWs

In order to remove photospheric contribution to the H$_\alpha$ lines, for each target, we calculated the $EW_{\text{phot}}$ of H$_\alpha$ using the PHOENIX high-resolution spectra (Husser et al. 2013). Model templates were picked out based on $T_{\text{eff}}, \log g$, and [Fe/H] of our sample. The $EW_{\text{phot}}$ were also calculated in the same wavelength range mentioned in Section 2.2 according to different stellar types.

Then the chromospheric emission in the H$_\alpha$ line was defined as:

$$EW' = EW - EW_{\text{phot}}.$$  

It is necessary to treat dwarfs and giants separately. In this work, stars with $\log g \geq 3.5$ were regarded as dwarfs and others were marked as giants. The results are shown in Figure 4.

### 3. Results

#### 3.1. $\chi$ and $R_{H\alpha}'$

Walkowicz et al. (2004) proposed a distance-independent method to calculate the normalized luminosity of H$_\alpha$ lines: $L_{H\alpha}/L_{bol}$, or $R_{H\alpha}'$:

$$R_{H\alpha}' = L_{H\alpha}/L_{bol} = \chi \times EW'.$$  

In this work, $\chi$ was estimated as following:

$$\chi = \frac{f_{6564}}{f_{bol}} = \frac{f_{6564}}{\sigma T_{\text{eff}}}.$$  

The continuum flux $f_{6564}$ was estimated based on the PHOENIX synthetic spectra. We fitted the continuum of these spectra and used the flux at 6564 Å as $f_{6564}$. Figure 5 shows a clear trend of $\chi$ as a function of effective temperature. For each target we calculated a median value of $R_{H\alpha}'$, using multiple

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**Table 1**

| ID  | EW (Å) | BMJD   |
|-----|--------|--------|
| J035106.15-+222205.6 | 1.7 ± 0.08 | 58801.7 |
| J035106.15-+222205.6 | 1.55 ± 0.07 | 58801.72 |
| J035106.15-+222205.6 | 1.72 ± 0.08 | 58801.74 |
| J035106.15-+222205.6 | 1.51 ± 0.09 | 58801.75 |
| J035106.15-+222205.6 | 1.4 ± 0.07 | 58819.62 |
| J035106.15-+222205.6 | 1.67 ± 0.07 | 58819.63 |
| J035106.15-+222205.6 | 1.55 ± 0.07 | 58819.64 |
| J035106.15-+222205.6 | 1.52 ± 0.09 | 58819.65 |
| J035106.15-+222205.6 | 1.59 ± 0.06 | 58819.66 |
| J035106.15-+222205.6 | 1.52 ± 0.07 | 58819.67 |
| J035106.15-+222205.6 | 1.59 ± 0.07 | 58890.45 |
| J035106.15-+222205.6 | 1.66 ± 0.08 | 58890.47 |
| J035106.15-+222205.6 | 1.34 ± 0.1 | 58890.49 |
| J035106.15-+222205.6 | 1.56 ± 0.1 | 58890.5 |

(This table is available in its entirety in machine-readable form.)

**Table 2**

| ID  | EW (Å) | BMJD   |
|-----|--------|--------|
| J035106.15-+222205.6 | 1.5 ± 0.04 | 58784.68 |
| J035106.15-+222205.6 | 1.67 ± 0.04 | 58784.69 |
| J035106.15-+222205.6 | 1.44 ± 0.05 | 58784.7 |
| J035106.15-+222205.6 | 1.64 ± 0.04 | 58784.71 |
| J035106.15-+222205.6 | 1.53 ± 0.06 | 58784.72 |
| J035106.15-+222205.6 | 1.54 ± 0.06 | 58784.73 |
| J035106.15-+222205.6 | 1.63 ± 0.05 | 58784.74 |
| J035106.15-+222205.6 | 1.6 ± 0.03 | 58784.75 |
| J035106.15-+222205.6 | 1.48 ± 0.02 | 58787.72 |
| J035106.15-+222205.6 | 1.68 ± 0.02 | 58787.73 |
| J035106.15-+222205.6 | 1.63 ± 0.02 | 58787.74 |
| J035106.15-+222205.6 | 1.58 ± 0.03 | 58811.65 |
| J035106.15-+222205.6 | 1.61 ± 0.03 | 58811.66 |
| J035106.15-+222205.6 | 1.67 ± 0.04 | 58811.66 |

(This table is available in its entirety in machine-readable form.)
The errors of $R'_{H\alpha}$ were calculated following error propagation and the median value of the errors in multiple observations was used for each target.

The comparisons of $R'_{H\alpha}$ between the MRS and LRS observations are shown in Figure 6. Mostly, the results from the two data sets are in good agreement. Figure 7 shows the distribution of $R'_{H\alpha}$ for different types of stars. These stars share a similar range of emission levels, with $R'_{H\alpha}$ ranging from $-5$ to $-3.5$. M giants tend to have weaker H$\alpha$ emission compared to M dwarfs while the $R'_{H\alpha}$ values are similar for K dwarfs and giants.

### 3.2. Rotation Periods and Rossby Number

As described in Section 2.1, the Lomb–Scargle method was used to determine the period from the K2 data, and the folded light curves were visually checked and the Kepler data integration platform\(^5\) (Yang & Liu 2019) was adopted to improve our efficiency. For A-type stars in our sample, we did not detect a reliable rotation period, while for 36 F-type stars, we detected rotational modulations in their light curves.

\(^5\) http://kepler.bao.ac.cn
Figure 6. Comparisons of $R'_{\text{Ha}}$, derived from medium-resolution spectral (MRS) and low-resolution spectral (LRS) observations for different types of stars.
Rotational modulations have been found in the light curves of many hot stars, which can be explained to be caused by starspots or other corotating structures (e.g., Balona 2011; Balona et al. 2019). However, it is debated that the rotational modulation for early-type stars may have nonmagnetic origins (Lee & Saio 2020; Sikora et al. 2020). For example, the $g$ modes, which are excited by resonant couplings, can be presented in many early-type main-sequence stars. These modes could result in frequencies that are consistent with those of photometric rotational modulations and harmonics (Lee & Saio 2020). In our sample, only nine early-type F stars ($T_{\text{eff}} > 6500$ K) exhibit rotational periods, six of which have $R'_{\text{H}}$ measurements. Performing new observations (such as high-resolution spectroscopic monitoring) capable of detecting or ruling out the presence of starspots for these early-F stars is beyond the scope of this work.

Totally 296 targets with accurate period measurements were picked out. Among them there are 226 targets with measured MRS $R'_{\text{H}}$ and 242 targets with measured LRS $R'_{\text{H}}$, which are marked with $*$ in Tables 3 and 4, respectively. Reinhold & Hekker (2020) also measured rotation periods of K2 targets. To check the accuracy of our results, we compared the rotation periods of common targets between this work and Reinhold & Hekker (2020). Most of the rotation periods are in good agreement (Figure 8). The objects with large deviations mostly have a period ratio being 1/2 or 2, indicating that the period measurements from Reinhold & Hekker (2020) are half or double of the period of our work. In addition, the rotation periods of F-type stars in this work are consistent with those from Reinhold & Hekker (2020).

In this work the grid models of stellar evolution tracks from the Yale–Potsdam Stellar Isochrones (YAPSI) were used to calculate the convective turnover time $\tau_c$ (Spada et al. 2017). We adopted all the subgrids with $Y = 0.28$, which contains solar calibration and includes different metallicity grids of $[\text{Fe/H}]$ of $+0.3$, $0.0$, $-0.5$, $-1.0$, and $-1.5$. We derived the location of each star in the $T_{\text{eff}}$–$\log g$ diagram and compared it with these model evolutionary tracks. The model points located inside the parameter uncertainties were selected to calculate a median value of $\tau_c$. We repeated this step for all metallicity grids and the final $\tau_c$ of each target was estimated through an interpolation of $\tau_c$ among these metallicity grids. Note that none of the early-F stars have $\tau_c$ estimation, suggesting that they will not affect the following analysis on the activity–rotation relation.

Finally the Rossby number was calculated as $\text{Ro} = P_{\text{rot}}/\tau_c$. There are 195 targets with estimations of both Rossby number and MRS $R'_{\text{H}}$, and 203 targets with estimations of both Rossby number and LRS $R'_{\text{H}}$. In Tables 3 and 4 we list all the results.
## Table 3

All the Quantities Calculated from the MRS Data Together with Stellar Parameters

| ID                  | EW′ (Å) | log(R_{Hα}) | Δ(log(R_{Hα})) | EW′ (Å) | log(R_{Hα}) | Δ(log(R_{Hα})) | T_{eff} (K) | log g (dex) | [Fe/H] | log(χ) | τ_c (days) | P_{rot} (days) |
|---------------------|---------|--------------|----------------|---------|--------------|----------------|-------------|-------------|--------|--------|------------|----------------|
| J105250.78+113922.2*| −0.36 ± 0.03 | −4.4 ± 5.47 | 0.07           | −0.94 ± 0.03 | −3.99 ± 5.47  | 0.03           | 6129.21     | 4.36        | −0.16 | −3.96 | 14.85      | 2.7            |
| J105630.42+114349.8 | −0.11 ± 0.16 | −4.95 ± 4.76 | 0.33           | −0.7 ± 0.16 | −4.13 ± 4.76  | 0.1            | 6080.17     | 4.12        | −0.65 | −3.97 | ...        | ...            |
| J105637.75+113841.4 | −1.95 ± 0.09 | −3.74 ± 5.09 | 0.03           | −2.42 ± 0.09 | −3.64 ± 5.09  | 0.02           | 6610.14     | 4.17        | −1.98 | −3.97 | ...        | ...            |
| J035800.88+231205.2*| 0.2 ± 0.02   | −4.67 ± 5.74 | 0.06           | −0.38 ± 0.02 | −4.39 ± 5.74  | 0.04           | 6146.33     | 3.99        | −0.02 | −3.97 | 10.6       | 14.98          |
| J105558.30+105838.5 | 0.07 ± 0.03  | −5.14 ± 5.51 | 0.37           | −0.51 ± 0.03 | −4.26 ± 5.51  | 0.04           | 6146.76     | 4.11        | −0.15 | −3.97 | ...        | ...            |
| J035935.33+231710.4 | −0.65 ± 0.08 | −4.15 ± 5.05 | 0.07           | −1.25 ± 0.08 | −3.86 ± 5.05  | 0.04           | 6029.56     | 4.4         | −0.04 | −3.96 | ...        | ...            |
| J105519.59+111046.1 | 0.11 ± 0.02  | −4.93 ± 5.61 | 0.16           | −0.46 ± 0.02 | −4.29 ± 5.61  | 0.03           | 6204.56     | 4.21        | −0.24 | −3.96 | ...        | ...            |

**Note.** Column (1) ID: target ID. Column (2) EW′: EW of Hα line, excluding the photospheric contribution. Column (3) log(R_{Hα}): logarithmic R_{Hα}. Column (4) Δ(log(R_{Hα})): variability of logarithmic R_{Hα}. Column (5) EW′: EW of Hα line, excluding the photospheric contribution and chromospheric emission that are not related to magnetic activity. Column (6) log(R_{Hα}): logarithmic R_{Hα}. Column (7) T_{eff}: effective temperature. Column (8) log g: surface gravity. Column (9) [Fe/H]: metallicity. Column (10) log(χ): logarithmic χ. Column (11) τ_c: convective turnover time. Column (12) P_{rot}: rotation period.

(This table is available in its entirety in machine-readable form.)
Table 4
All the Quantities Calculated from the LRS Data Together with Stellar Parameters

| ID                | $EW^\alpha$ (Å) | $\log(R^\alpha_{\text{ls}})$ | $\Delta(\log(R^\alpha_{\text{ls}}))$ | $EW^\alpha$ (Å) | $\log(R^\beta_{\text{ls}})$ | $\Delta(\log(R^\beta_{\text{ls}}))$ | $\text{T}_{\text{eff}}$ (K) | $\text{log }g$ (dex) | $\text{[Fe/H]}$ | $\text{log}(\chi)$ | $\tau_c$ (days) | $P_{\text{rot}}$ (days) |
|------------------|------------------|-----------------------------|-------------------------------------------|------------------|-----------------------------|-------------------------------------------|-----------------------------|---------------------|-------------------|------------------|---------------------|---------------------|
| J105250.78+113922.2* | −0.43 ± 0.01     | −4.33 ± −6.16               | 0.09                                      | −1.04 ± 0.01     | −3.94 ± −6.16               | 0.04                                      | 6129.21                     | 4.36                | −0.16             | −3.96            | 14.85               | 2.7                 |
| J105630.42+114349.8 | −0.08 ± 0.12     | −5.08 ± −4.9                | 0.58                                      | −0.7 ± 0.12      | −4.13 ± −4.9                | 0.21                                      | 6080.17                     | 4.12                | −0.65             | −3.97            | ...                | ...                 |
| J105637.75+113841.4 | −1.88 ± 0.05     | −3.75 ± −5.34               | 0.04                                      | −2.42 ± 0.05     | −3.64 ± −5.34               | 0.03                                      | 6610.14                     | 4.17                | −1.98             | −4.03            | ...                | ...                 |
| J105613.73+111240.5 | −0.22 ± 0.1      | −4.6 ± −4.93                | 0.12                                      | −0.84 ± 0.1      | −4.02 ± −4.93               | 0.28                                      | 6079.54                     | 4.24                | −0.15             | −3.95            | ...                | ...                 |
| J035800.88+231205.2* | 0.05 ± 0.0       | −5.27 ± −6.36               | 0.4                                       | −0.56 ± 0.0      | −4.22 ± −6.36               | 0.05                                      | 6146.33                     | 3.99                | −0.02             | −3.97            | 10.6                | 14.98               |
| J105558.30+105838.5 | −0.04 ± 0.01     | −5.38 ± −6.13               | 0.39                                      | −0.65 ± 0.01     | −4.15 ± −6.13               | 0.03                                      | 6146.76                     | 4.11                | −0.15             | −3.97            | ...                | ...                 |
| J035935.33+231710.4 | −0.78 ± 0.04     | −4.07 ± −5.4                | 0.07                                      | −1.41 ± 0.04     | −3.81 ± −5.4                | 0.04                                      | 6029.56                     | 4.4                 | −0.04             | −3.96            | ...                | ...                 |

Note. Column (1) ID: target ID. Column (2) $EW^\alpha$: EW of $\text{H}_\alpha$ line, excluding the photospheric contribution. Column (3) $\log(R^\alpha_{\text{ls}})$: logarithmic $R^\alpha_{\text{ls}}$. Column (4) $\Delta(\log(R^\alpha_{\text{ls}}))$: variability of logarithmic $R^\alpha_{\text{ls}}$. Column (5) $EW^\alpha$: EW of $\text{H}_\alpha$ line, excluding the photospheric contribution and chromospheric emission that are not related to magnetic activity. Column (6) $\log(R^\beta_{\text{ls}})$: logarithmic $R^\beta_{\text{ls}}$. Column (7) $\Delta(\log(R^\beta_{\text{ls}}))$: variability of logarithmic $R^\beta_{\text{ls}}$. Column (8) $\text{T}_{\text{eff}}$: effective temperature. Column (9) $\text{log }g$: surface gravity. Column (10) $\text{[Fe/H]}$: metallicity. Column (11) $\text{log}(\chi)$: logarithmic $\chi$. Column (12) $\tau_c$: convective turnover time. Column (13) $P_{\text{rot}}$: rotation period.

(This table is available in its entirety in machine-readable form.)
of our samples, including the median values of EW and $R'_{\text{H\alpha}}$, the stellar parameters ($T_{\text{eff}}$, $\log g$ and $[\text{Fe}/\text{H}]$), rotational period ($P_{\text{rot}}$), and Rossby number ($R_o$), etc.

4. Discussion

4.1. $R'_{\text{H\alpha}}$ and Rossby Number

Stellar rotation plays a key role in generating magnetic fields. The relations between different activity proxies and rotation have been extensively investigated (e.g., Pizzolato et al. 2003; Wright et al. 2011; Douglas et al. 2014; Newton et al. 2017). The activity–rotation relation is usually suggested to consist of two distinct sequences: the saturated region for rapidly rotating stars, in which the activity level is constant, and the power-law decay region for slowly rotating stars, where the activity level is rotation-dependent.

However, some basic issues on this relation are still under debate: (1) Whether the activity level in the saturation region keeps increasing or is constant when rotation velocity increases? (2) Where does the transition from the saturation to the nonsaturation region occur? (3) Whether the nonsaturation region follows a single power law?

Some previous studies have suggested a slight slope of the activity–rotation relation in the saturated region, indicating a remaining dependence of the activity levels on rotation periods even for active, fast-rotating stars (e.g., Mamajek & Hillenbrand 2008; Reiners et al. 2014). By using the dwarfs observed by both Kepler and XMM-Newton, Pizzocaro et al. (2019) found that some objects, especially F-type stars, clearly deviate from the standard decay power-law relation. In addition, Mittag et al. (2018) revised the relation based on different activity indicators including X-ray, Ca II H and K, and H$\alpha$ emissions. They divided the relation into four regions: a saturated region, a fast decay region, and two slowly decay regions with different power-law shapes. The results of these studies are quite different from the standard picture (Pizzolato et al. 2003; Wright et al. 2011).

Figure 9. $R'_{\text{H\alpha}}$–$R_o$ relations for medium-resolution spectral (MRS) and low-resolution spectral (LRS) observations. In panels (a) and (c) the relations are in linear-log scale while in panels (b) and (d) they are in log–log scale. Points with different colors represent different effective temperatures. Errors are shown in gray lines. Dashed magenta and black lines are the activity–rotation relations from Douglas et al. (2014) and Newton et al. (2017), respectively. Both the relations were shifted by $R_o/3$. Histograms along the $R_o$ axis are also presented.
Figure 9 displays the $R_{\alpha}\text{-}R_o$ relations for both the MRS and LRS data. No giant star is plotted since there are only five giants with a well-defined Rossby number in our sample. Our results suggest a complicated profile for the activity–rotation relation. In the saturated region, our targets agree with the standard model from previous literature (Figure 9), suggesting that as the Rossby number decreases, the activity level would keep the same. However, only a few targets in our sample lie in this region, more sources are required to confirm whether there is a slight slope (e.g., Mamajek & Hillenbrand 2008; Reiners et al. 2014).

The knee points seem to be varying among different types of stars (Figure 10). In previous studies, the knee point that separates the saturated and nonsaturated regions is at $R_o = 0.13$ (Wright et al. 2011). Alternatively, Mittag et al. (2018) argued that the activity level would keep unchanged only when $R_o < 0.021$, while Newton et al. (2017) showed that the break occurs near $R_o = 0.2$. Note that for these studies, Ro values were calculated from the classical empirical estimation of $\tau$, which is about one-third of the theoretical values of $\tau_c$ in our work (Lehtinen et al. 2020; Wang et al. 2020). It seems that there is more than one knee point in the activity–rotation relation, or different types of stars may have different knee points (Figure 10). However, due to the limited number of targets in the saturated region, we cannot give an accurate estimation of the positions of knee points.

Our results suggested that the fast decay region clearly cannot be fit by a single power law. Stars with different spectral types exhibit different slopes (Figure 10), and a mix of them would lead to a messy relation in the decay region (Figure 9). For example, the slope of F-type stars is gentler than that of cooler stars. In the same range of $R_o$, hot stars (e.g., F stars) seem to be more active in H$_\alpha$ emission than cool stars (e.g., M stars). A similar phenomenon has been found in activity–rotation relations constructed by different activity proxies. As the temperature increases, the slope of the decay region gradually changes, indicating that such a tendency is universal (Pizzocaro et al. 2019; Reinhold & Hekker 2020).

Figure 10. Activity–rotation relations of different kinds of stars. From top to bottom corresponds to F-, G-, K-, and M-type stars. Panel (a) shows the results of medium-resolution spectral (MRS) data and panel (b) displays the results of low-resolution spectral (LRS) data. Again the dashed magenta and black lines are the shifted relation of Douglas et al. (2014) and Newton et al. (2017), respectively. Histograms along the $R_{\alpha}$ are also shown.
4.2. Basal Flux and $R_{\text{H}\alpha}^+$

Schrijver (1987) pointed out that the basal fluxes of chromospheric lines (e.g., Ca II H and K) represent the nonradiative heating in the outer atmosphere, which is unrelated to magnetic activity. The dynamo-driven magnetic activity can be calculated as the excess flux above the baseline, which can be constructed with inactive stars. Here we further studied the impact of such a baseline on stellar activity.

The baseline was fitted based on the most inactive stars in our sample (Figure 4). Then the pure chromospheric emission due to the magnetic activity of the H$\alpha$ line was defined as the chromospheric flux excess following Mittag et al. (2013, 2018):

$$ \text{EW}^+ = \text{EW}' - \text{EW}_{\text{basal}} $$

$$ = \text{EW} - \text{EW}_{\text{phot}} - \text{EW}_{\text{basal}}. \quad (5) $$

Then $\text{EW}^+$ was converted to $R_{\text{H}\alpha}^+$ with the $\chi$ following

$$ R_{\text{H}\alpha}^+ = \frac{L_{\text{H}\alpha}}{L_{\text{bol}}} = \chi \times \text{EW}^+. \quad (6) $$

All the $\text{EW}^+$ and $R_{\text{H}\alpha}^+$ values are listed in Tables 3 and 4.

The $R_{\text{H}\alpha}^+-R_{\odot}$ relations (Figures 11 and 12) show some differences compared to the $R_{\text{H}\alpha}^+-R_{\odot}$ relations. The subtraction of basal flux increases the activity levels of all stars. Now the hot stars and cool stars seem to be divided into two separated groups. Hot stars show a much flatter slope and higher activity in the decay region. The $R_{\text{H}\alpha}^+-R_{\odot}$ relations of F- and G-type stars significantly deviate from the relations of Douglas et al. (2014) and Newton et al. (2017). This again indicates the complex profile of the decay region, and it cannot be fitted by a single power law.

Although the relations from Newton et al. (2017) and Douglas et al. (2014) were constructed from M stars, the deviation of hot stars is still worth being investigated in detail. As the temperature increases, the decay slope also gradually becomes flat. Meanwhile, the activity levels of hot stars increase more after the subtraction of the basal flux. It is hard to tell whether this behavior is real or fake due to the poor fitting of the basal flux. However, as shown in a previous study, hot stars do exhibit a higher X-ray
activity level than cool stars, although their differences are small (Pizzocaro et al. 2019).

One possible origin of the large scatters of stellar activity in the decay region (shown in Figures 10 and 12) may be the variation of the magnetic activity. As shown in Wang et al. (2020), the variation of stellar X-ray activity is universal and significant. Figure 13 displays clear variability of Hα emissions for our sample stars, suggesting notable stellar chromospheric activity variations.

4.3. $R'_{H\alpha}$ and Light Curves

Amplitudes of light curves could be modulated by (cool) starspots or (hot) faculae. The photometric activity proxy $R'_{eff}$, which is used to quantify the sinusoidal modulation of light curves, is proportional to the classical chromospheric proxy $R'_{HK}$ (Zhang et al. 2020b). It is known that large solar plages are spatially associated with sunspots (Mandal et al. 2017). Some previous studies also showed that there was an anticorrelation in the rotational phase between the chromospheric activity proxies (e.g., Ca II H and K, Hα) and light curves: the line emission was stronger when the amplitude of the light curve was near minimum (Dorren & Guinan 1982; Berdyugina et al. 1999; Fang et al. 2010, 2020). This indicates that the plages are located in the outer chromosphere overlying the starspots in the visible photosphere.

By using the LAMOST time-domain spectra and K2 light curves, we also investigated relations between $R'_{H\alpha}$ and the rotational phase of light curves. For targets with well-detected rotation periods, both the light curves and $R'_{H\alpha}$ values of multiple observations were folded by their rotation periods. We found that for the vast majority of targets, $R'_{H\alpha}$ and optical light curves have no obvious correlation. Only three targets show a possible correlation (Figure 14), J034825.21+233810.6 (EPIC 211041648), J034050.43+232506.3 (EPIC 211028209), and J035102.31+250319.6 (EPIC 211129308); their $R'_{H\alpha}$ series correlates well with the light curve. Meanwhile, the same targets would remain after changing the $R'_{H\alpha}$ to $a_{H\alpha}$.

The positive correlation between the Hα emission and photospheric variability suggests that the later is mainly dominated by faculae instead of starspots. It is possible since Shapiro et al. (2017) presented that the contribution of faculae to the variability of total solar irradiance is comparable to that of spots at timescales from 2 to 7 days. Reinhold & Hekker (2020) showed a gap (mainly around 10–20 days) in the rotation period
distribution and interpreted it as a cancellation between bright faculae and dark spots. The gap is consistent with the period range of 15–25 days, which implies a transition from spot-dominated to faculae-dominated activity (Montet et al. 2017).

The correlation between $R'_{\text{net}}$ and optical light curves may be coincidental, since their observations are not simultaneous. The evolution timescale of starspots or faculae may be extremely shorter than the spectroscopic and photometric observation timescale.
intervals. These may explain why no clear correlation was found for most targets. However, we found that the folded light curves of some targets change slightly during the 4 yr observation, indicating that the active regions evolve slowly. The three objects also show stable light curves (Figure 14), suggesting that the light curves can be used to compare with the LAMOST observations, even if the photometric and spectroscopic observations were not simultaneous. Future simultaneous photometric and spectroscopic observations for more targets could shed more light on this issue.

5. Summary

In this work, we systematically studied the statistical properties of Hα lines based on the LAMOST time-domain spectra. The chromospheric emission was estimated through two steps: (1) Subtracting the photospheric contribution from the observed Hα lines, i.e., $EW' = EW - EW_{\text{phot}}$. An index of $R_{\text{Hα}}$ was calculated from $EW'$. (2) Besides the photospheric part, a baseline, which was thought to be unrelated to chromospheric heating, was fitted from inactive stars and further subtracted, i.e., $EW^+ = EW - EW_{\text{phot}} - EW_{\text{basal}}$. This leads to an estimation of another index $R_{\text{Hα}}$

Both the $R_{\text{Hα}} - R$ relation and $R_{\text{Hα}} - R_{\text{H}}$ relation were investigated. Besides the typical divided saturation region and nonsaturation region, they both show complicated profiles in the latter decay regime. Hot stars show flatter slopes and a higher activity level than cool stars. Such a phenomenon is more notable after the baseline line was subtracted. This suggests that different stars may follow different power laws in the decay region. Alternatively, this may be caused by the larger variability of Hα emission, which was revealed by multiple observations. In addition, the differences between the $R_{\text{Hα}} - R$ relation and $R_{\text{Hα}} - R_{\text{H}}$ relation tells the sensitivity of these indices to the selection of the basal flux. The fitting and subtraction of the baseline strongly affects the distribution of activity levels and the activity–rotation relations of different types of stars, which should be carefully studied for the chromospheric activity proxies.

By using the time-domain photometric and spectroscopic data, we also investigated the phased variations of Hα emission and optical light curves. Only three targets exhibit positive correlations, indicating their light curves are dominated by hot faculae. Further simultaneous photometric and spectroscopic observations will be key to studying this correlation.

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Appendix

Calculating the EWs with a Fixed and Narrow Wavelength Range

In order to test whether the chromospheric activities would mainly contribute to the line core of Hα, which is similar to the situation of Ca II H and K lines, we repeated the calculation processes but the EWs of Hα lines were computed with a fixed integration interval (i.e., 10 Å) for all kinds of stars. Such a narrow integration interval could also avoid the contamination coming from possible blending lines.

Same as Figure 4, in Figure A1 we plot the EWs against effective temperatures. Panels (a) and (b) show the results for dwarf stars and giants, respectively. Different colors represent different kinds of stars. Meanwhile, black dots represent photospheric contribution to Hα lines, which were also derived based on the PHOENIX synthetic spectra (Husser et al. 2013). But this time, the wavelength interval for the integration was also 10 Å.

Then the EWs were corrected using Equation (2) and further converted to normalized luminosity $R_{\text{Hα}}$ based on Equation (3), in which the $\chi$ were from Section 3.1. We compared the newly derived $R_{\text{Hα}}$, named $R_{\text{Hα}, 10\text{Å}}$, and those calculated from various

![Figure A1](image-url)
integration intervals. Obviously, for most of the targets $R'_{\text{H} \alpha, 10 \text{Å}}$ agree well with the $R'_{\text{H} \alpha}$ (Figure A2).

Meanwhile, the activity–rotation relations were then renewed based on $R'_{\text{H} \alpha, 10 \text{Å}}$. Same as Figure 9, we plot the relation in different scales, i.e., linear-log scale in panel (a) and log–log scale in panel (b) of Figure A3. Dashed black and magenta lines are relations from Douglas et al. (2014) and Newton et al. (2017), respectively, which were also shifted by $R_0/3$. Apparently, the $R'_{\text{H} \alpha, 10 \text{Å}}$–$R_0$ relation is similar to the $R'_{\text{H} \alpha}$–$R_0$ relation. In the nonsaturated region the relation cannot be described by a simple power law. Different stars exhibit different slopes in the decay region.

Furthermore, $R'_{\text{H} \alpha, 10 \text{Å}}$ were converted to $R^+_{\text{H} \alpha, 10 \text{Å}}$ through subtracting the basal fluxes and the $R^+_{\text{H} \alpha, 10 \text{Å}}$–$R_0$ relation is given in Figure A4. It is clear that hot stars then tend to exhibit higher activity levels compared to cool stars. The F- and G-type stars deviate significantly from the relations given by Newton et al. (2017) and Douglas et al. (2014), suggesting that the selection of basal flux could strongly affect the activity relations.
References

Babcock, H. W., & Babcock, H. D. 1955, ApJ, 121, 349
Balona, L. A. 2011, MNRAS, 415, 1691
Balona, L. A., Handler, G., Chowdhury, S., et al. 2019, MNRAS, 485, 3457
Berdyugina, S. V., Ilyin, I., & Tuominen, I. 1999, A&A, 349, 863
Borucki, W. J., Koch, D., Basri, G., et al. 2010, Sci, 327, 977
Chabrier, G., & Küker, M. 2006, A&A, 446, 1027
Cincunegui, C., Díaz, R. F., & Mauas, P. J. D. 2007, A&A, 469, 309
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, RAA, 12, 1197
Dorren, J. D., & Guinan, E. F. 1982, AJ, 87, 1546
Douglas, S. T., Agüeros, M. A., Covey, K. R., et al. 2014, ApJ, 795, 161
Drake, J. J., Stern, R. A., Stringfellow, G., et al. 1996, ApJ, 469, 828
Dunney, B. R., De Young, D. S., & Roxburgh, I. W., 1993, SoPh, 145, 207
Fang, X.-S., Binlin, C. M., Zhao, G., Zhang, L.-Y., & Bharat Kumar, Y. 2020, MNRAS, 495, 2949
Fang, X.-S., Gu, S.-H., Cheung, S.-L., et al. 2010, RAA, 10, 253
Fu, J.-N., Cat, P. D., Zong, W., et al. 2020, RAA, 20, 167
Husser, T. O., Wende-von Berg, S., Dreizler, S., et al. 2013, A&A, 553, A6
Kim, D.-W., Protopapas, P., Bailer-Jones, C. A. L., et al. 2014, A&A, 566, A43
Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, ApJL, 713, L79
Lee, U., & Saio, H. 2020, MNRAS, 497, 4117
Lehtinen, J. J., Käpylä, M. J., Olsert, N., & Spada, F. 2021, ApJ, 910, 110
Lehtinen, J. J., Spada, F., Käpylä, M. J., Olsert, N., & Käpylä, P. J. 2020, NatAs, 4, 658
Leighton, R. B. 1959, ApJ, 130, 366
Linsky, J. L. 2017, ARA&A, 55, 159
Liu, C., Fu, J., Shi, J., et al. 2020, arXiv:2005.07210
Lomb, N. R. 1976, ApSS, 39, 447
Luo, A.-L., Zhao, Y.-H., Zhao, G., et al. 2015, RAA, 15, 1095
Mamajek, E. E., & Hillenbrand, L. A. 2008, ApJ, 687, 1264
Mandal, S., Chatterjee, S., & Banerjee, D. 2017, ApJ, 835, 158
Mihalas, D. 1978, Stellar Atmospheres (2nd ed.; San Francisco, CA: WH Freeman)
Mittag, M., Schmitt, J. H. M. M., & Schröder, K. P. 2013, A&A, 549, A117
Mittag, M., Schmitt, J. H. M. M., & Schröder, K. P. 2018, A&A, 618, A48
Montet, B. T., Tovar, G., & Foreman-Mackey, D. 2017, ApJ, 851, 116
Newton, E. R., Irwin, J., Charbonneau, D., et al. 2017, ApJ, 834, 85
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Parker, E. N. 1982, ApJ, 263, 835
Schrijver, C. J. 1987, A&A, 172, 111
Shapiro, A. I., Solanki, S. K., Krivova, N. A., et al. 2017, NatAs, 1, 612
Spada, F., DeMarque, P., Kim, Y. C., Boyajian, T. S., & Brewer, J. M. 2017, ApJ, 838, 161
VanderPlas, J. T., & Ivezić, Ž. 2015, ApJ, 812, 18
Vaughan, A. H., Preston, G. W., & Wilson, O. C. 1978, PASP, 90, 267
Walkowicz, L. M., Hawley, S. L., & West, A. A. 2004, PASP, 116, 1105
Wang, S., Bai, Y., He, L., & Liu, J. 2020, ApJ, 902, 111
Wang, S., Zhang, H.-T., Bai, Z.-R., et al. 2020, MNRAS, 498, 2456
Spada, F., Demarque, P., Kim, Y. C., Boyajian, T. S., & Brewer, J. M. 2017, ApJ, 838, 161
VanderPlas, J. T., & Ivezić, Ž. 2015, ApJ, 812, 18
Vaughan, A. H., Preston, G. W., & Wilson, O. C. 1978, PASP, 90, 267
Walkowicz, L. M., Hawley, S. L., & West, A. A. 2004, PASP, 116, 1105
Wang, S., Bai, Y., He, L., & Liu, J. 2020, ApJ, 902, 114
Wang, S., Zhang, H.-T., Bai, Z.-R., et al. 2021, RAA, 21, 292
Wilson, O. C. 1978, ApJ, 226, 379
Wright, N. J., Drake, J. J., Mamajek, E. E., & Henry, G. W. 2011, ApJ, 743, 48
Yang, H., & Liu, J. 2019, ApJS, 241, 29
Zhang, B., Li, J., Yang, F., et al. 2021, ApJS, 256, 14
Zhang, B., Liu, C., & Deng, L.-C. 2020a, ApJS, 246, 9
Zhang, J., Bi, S., Li, Y., et al. 2020b, ApJS, 247, 9
Zong, W., Fu, J.-N., De Cat, P., et al. 2020, ApJS, 251, 15

Figure A4. Same as Figure 9 but for $R_{\text{He}, 10 \AA}$.