

Rotation and spots in normal A and Am/Fm stars

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ABSTRACT

Frequency analysis of long-term ultraprecise photometry can lead to precise values of rotation frequencies of rotating stars with ‘hump and spike’ features in their periodograms. Using these features, we computed the rotation frequencies and amplitudes. The corresponding equatorial rotational velocity (V_{rot}) and spot size were estimated. On fitting the autocorrelation functions of the light curves with the appropriate model, we determined the star-spot decay time-scale. The V_{rot} agrees well with the projected rotational velocity ($v \sin i$) in the literature. Considering a single circular and black spot, we estimate its radius from the amplitude of the ‘spike’. No evidence for a significant difference in the average ‘spike’ amplitude and spot radius was found for Am/Fm and normal A stars. Indeed, we derived an average value of $\sim 21 \pm 2$ and $\sim 19 \pm 2$ ppm for the photometric amplitude and of 1.01 ± 0.13 and $1.16 \pm 0.12 R_E$ for the spot radius (where R_E is the Earth radius), respectively. We do find a significant difference for the average spot decay time-scale, which amounts to 3.6 ± 0.2 and 1.5 ± 0.2 d for Am/Fm and normal A stars, respectively. In general, spots on normal A stars are similar in size to those on Am/Fm stars, and both are weaker than previously estimated. The existence of the ‘spikes’ in the frequency spectra may not be strongly dependent on the appearance of star-spots on the stellar surface. In comparison with G, K, and M stars, spots in normal A and Am/Fm stars are weak, which may indicate the presence of a weak magnetic field.

Key words: stars: chemically peculiar – stars: general – stars: rotation – starspots.

1 INTRODUCTION

The main-sequence A-type stars are intermediate-mass stars, which show various interesting phenomena such as chemical peculiarities, pulsation, activity and rotation, etc. The chemically peculiar (CP) stars (Preston 1974; Renson 1988; Monier 2019) can be distinguished from the normal A stars (Adelman 1986, 2004) based on the enhancement of the absorption lines in their spectra. The optical spectra of the CP stars are characterized by strong lines of silicon metals and/or rare-Earth elements and weak lines of calcium. The CP stars are dominated by metallic line (Am/Fm) stars and are subdivided into two main groups: the Am/Fm stars (CP1; having an overabundance of iron-group metals and an underabundance of He, Ca, and/or Sc in their atmospheres) and the magnetic Ap stars (CP2; showing photometric and magnetic variability and having abnormally strong lines of Si, Cr, Sr, and rare-Earth elements in their spectra) (Conti 1970; Preston 1974; Fossati et al. 2009).

The atomic diffusion is thought to be the dominant process responsible for the chemical anomalies observed in the CP stars (Michaud 1970; Watson 1970; Khokhlova 1981; Hui-Bon-Hoa

2000; Turcotte 2003; Théado et al. 2011). Due to radiation pressure and gravitational settling, chemical elements undergo an upward/downward drift into/out of the atmosphere. Depending on the ionization state and the atomic properties of the elements and in the absence of mixing, an equilibrium is attained. At equilibrium, the elements are vertically stratified (Ryabchikova et al. 2002; Khalack & LeBlanc 2015) and the abnormal chemical abundances manifest in the atmospheres. In Am/Fm stars, when the magnetic fields are detected, they are ultraweak and relatively uniform (e.g. Aurière et al. 2010; Blazère et al. 2014; Blazère, Neiner & Petit 2016a; Neiner, Wade & Sikora 2017; Cantiello & Braithwaite 2019), which produce evenly distributed abundances in the atmospheres. On the other hand, Ap stars possess strong global magnetic fields of the range 200 G–30 kG (Power et al. 2007; Braithwaite 2014). In these stars, depending on the magnetic field strength that may suppress convection and the inclination of the field lines, patches of different abundances are produced on the surface (Michaud 1970; Mullan 1973).

The atomic diffusion can be counteracted by mixing. The currently known mixing processes include meridional circulation caused by rotation and convection. This implies that the CP stars should be rotating more slowly relative to normal A stars. The majority of Am/Fm stars are indeed slow rotators (Fossati et al. 2008;

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Takeda et al. 2008; Stateva et al. 2009), with $v \sin i < 120 \text{ km s}^{-1}$ (Abt 2009). The slow rotation in Am/Fm stars is attributed to the tidal synchronization in the case of close binaries (Khokhlova 1981; Kunzli & North 1998; Balona et al. 2011). The Am/Fm stars are often components of binaries (Abt 1961; Vauclair 1976; North et al. 1998; Debernardi 2000; Stateva et al. 2009) with orbital periods between 1 and 10 d (Smalley et al. 2014). This makes rotation one of the most important phenomena in stellar physics. The availability of accurate and precise values of rotation periods provides an important platform in understanding other stellar phenomena such as pulsation (Dziembowski, Krolikowska & Kosovichev 1988; Soufi, Goupil & Dziembowski 1998) and overshooting (Browning, Brun & Toomre 2004; Costa et al. 2019) and allows to draw conclusions about the processes that may be linked with the observed chemical abundances in stellar atmospheres of Am/Fm stars (Turcotte 2001; Murphy 2014). The other reported success of the rotationally induced mixing is the ability to explain the origin of the Boesgaard lithium gap (Boesgaard & Tripicco 1986) in F stars (Sills & Deliyannis 2000). Apart from using spectroscopy, where the rotation rate is retrieved from the broadening of the absorption lines (Kaler 1989), stellar rotation period can be determined from seismic splitting (Claverie et al. 1981; Saio 1981), spot induced rotational modulation (Kron 1947; Mosser et al. 2009), and chromospheric activity especially Ca II emission (Noyes et al. 1984).

Due to the availability of high-precision and almost continuous photometric data from space missions like the nominal *Kepler* mission (Borucki et al. 2010), K2 (Howell et al. 2014), and the Transiting Exoplanet Survey Satellite (*TESS*; Ricker et al. 2014), from which precise rotation periods can be obtained, Balona (2013) derived rotation periods of a large number of A-type stars from the original *Kepler* field (Borucki et al. 2010) based on spot induced rotational modulation. Star-spots and flares are claimed to have been discovered in rotationally modulated normal A and Am/Fm stars (Balona 2012, 2013; Balona et al. 2015; Balona, Švanda & Karlický 2016). Balona (2013) obtained a mean rotational modulation amplitude, interpreted as a reflection of the star-spot size, of 875 normal A stars as $541 \pm 86 \text{ ppm}$ and Balona et al. (2015) found $93 \pm 25 \text{ ppm}$ for 10 Am/Fm stars. As star-spots and flares are signatures of a high magnetic field, this would imply a strong magnetic field in these stars. Pedersen et al. (2017) confirmed the presence of flare-like structures in only some stars studied by Balona (2012, 2013). However, after consideration of different possibilities, Pedersen et al. (2017) found that the flare-like structures have a high possibility of originating from cool and unresolved companions.

The discovery of spot based rotational modulation in normal A and Am/Fm stars was unexpected. They possess a thin subsurface convective envelope, which increases in depth with decreasing effective temperature and decreasing surface gravity (Giampapa & Rosner 1984; Abt 2009). This implies that they lack strong tangled magnetic fields which would be created by the dynamo effect resulting from the convective behaviour of the material with rotation (Brandenburg 2000) like in G, K, and M stars. Aurière et al. (2007) reported that stellar magnetic fields of magnitude below 300 G are not detected. However, ultraweak global magnetic fields have been observed in a number of stars, e.g. normal A-type stars, like Vega ($0.6 \pm 0.3 \text{ G}$; Lignières et al. 2009; 1.0 G and 1.4 G ; Petit et al. 2010; 7.0 G ; Petit et al. 2014) and Am/Fm stars, like Sirius A ($0.2 \pm 0.1 \text{ G}$; Petit et al. 2011), Alhena (around $5 \pm 3 \text{ G}$; Blazère et al. 2016a), β UMa ($1 \pm 0.8 \text{ G}$) and θ Leo ($0.4 \pm 0.3 \text{ G}$; Blazère et al. 2016b), and ρ Pup ($0.29 \pm 0.32 \text{ G}$; Neiner et al. 2017). Cantiello & Braithwaite (2019) theoretically predicted that A stars

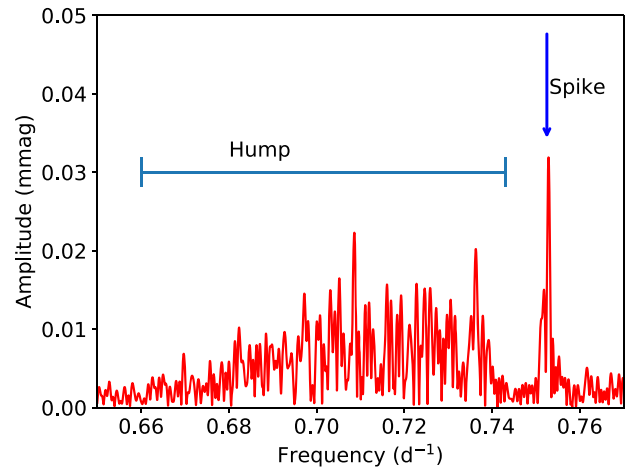


Figure 1. An amplitude spectrum of KIC 6192566 showing a typical hump and a spike. The spike is not strictly sharp.

like Vega, Sirius, β UMa, θ Leo, and Alhena can have magnetic fields of magnitude of 1–10 G generated by dynamo action in the thin He II convective subsurface zone and transported to the surface by magnetic buoyancy. Magnetic fields with such magnitude and the thin convective zone could support, if any, weak star-spots (Blazère et al. 2016a; Neiner et al. 2017; Cantiello & Braithwaite 2019). Therefore, spot sizes in normal A and Am/Fm stars given by Balona (2013) and Balona et al. (2015), respectively, could be overestimated.

In addition, Balona (2013) observed in the frequency spectra of 135 stars of the 875 normal A stars a sharp peak (‘spike’) on the high frequency side of a broad hump of very close frequencies (‘hump’) as shown in Fig. 1. The sharp frequency and the broad hump were seen to have harmonics of lower amplitudes in most cases. Balona et al. (2015) observed the same scenario in some Am/Fm stars. Balona (2014) suspected the sharp peak corresponds to the rotational frequency and its amplitude to be related to the star-spot size, but the hump remained unexplained. Recently, Saio et al. (2018) named these stars ‘hump and spike’ stars. Saio et al. (2018) carefully compared the visibility curves for the global Rossby waves (r modes) (Papaloizou & Pringle 1978) with the frequency spectra of *Kepler* light curves and concluded that the broad humps as observed for these stars are induced by r modes and the spike structures are the rotation frequencies induced by one or more spots.

To search and study the pulsational variabilities in Ap and Am/Fm stars, a dedicated ground-based project the ‘Nainital–Cape Survey’ was initiated between astronomers of India and South Africa. However, with time, astronomers from other institutions in other countries joined this programme making it a multinational collaborative project and a number of results are published (e.g. Ashoka et al. 2000; Martinez et al. 2001; Joshi et al. 2003, 2006, 2009, 2010, 2012, 2016, 2017). The success of the ‘Nainital–Cape Survey’ and the discovery of ‘hump and spike’ features in the frequency spectra (Balona 2013; Balona et al. 2015; Saio et al. 2018) of a number of normal A and Am stars motivated us to initiate another trinational collaborative group among the astronomers from India, Uganda, and Belgium. This paper is the first of the series involving the ‘hump and spike’ stars aiming to present rotation frequencies and velocities, star-spot sizes, and star-spot decay lifetimes based on the ‘hump and spike’ features. Only normal A and Am/Fm stars in the original *Kepler* field with ‘hump

and spike' features in their frequency spectra are investigated. This paper is organized as follows. The adopted target selection criteria and the data reduction are described in Section 2. The results and their discussion are presented in Section 3. The conclusion drawn from our study is given in Section 4.

2 TARGET SELECTION AND DATA REDUCTION

2.1 Selection criteria

The samples in this study were drawn from stars analysed by Balona (2013), Balona et al. (2015), and Gray et al. (2016). Of the 875 rotationally modulated main-sequence normal A stars studied by Balona (2013) and the 15 Am/Fm stars from the nominal *Kepler* mission analysed by Balona et al. (2015), only the normal A and Am/Fm stars with 'hump and spike' features in their frequency spectra were considered. Additional Am/Fm stars with 'hump and spike' features in the frequency spectra were derived from the sources analysed by Gray et al. (2016) under the LAMOST-*Kepler* project (De Cat et al. 2015). A total of 170 'hump and spike' stars were obtained of which 131 are part of the normal A stars reported by Balona (2013), 3 are within the sample studied by Balona et al. (2015) and 36 are from Gray et al. (2016).

2.2 Data reduction

For this study, we used the high-precision and almost continuous photometric data obtained by the *Kepler* mission. The data are available on the Barbara A. Mikulski Archive for Space Telescopes (MAST) website.¹ The stars in the sample were observed in the long-cadence mode with an observation every 29.4 min. A few of the 'hump and spike' stars were also observed in short cadence with a time interval of almost 1 min. Since we are interested in low frequencies, long-cadence data are sufficient to capture long-period variations. The characteristics of long-cadence data are discussed by Jenkins et al. (2010). Within its orbit of 372.5 d, the *Kepler* space craft performs a 90° roll every 3 months to keep its solar panels aligned with the sun. This resulted into quarters named Q₀ upto Q₁₇. The commissioning run (Q₀) only lasted for 10 d, quarters Q₁ and Q₁₇ were only 1 month long. This study uses the data for all the quarters, unlike in Balona (2013) where only the data from quarters Q₀ to Q₁₂ were available.

The light curves are stored in the form of a Flexible Image Transport system (FITS) product, which contain tables with a combination of header key words (Borucki et al. 2010; Koch et al. 2010). Among others, the light curves contain simple aperture photometry (SAP) and pre-search data conditioning (PDC) flux (Thompson et al. 2016). The SAP flux results from the application of the *Kepler* data processing pipeline, which only uses a basic calibration and is affected by errors. The dominant sources of errors include: differential velocity aberration and thermal transients from the reaction wheel desaturation and quarterly rolls (Smith et al. 2012; Stumpe et al. 2014). The PDC module of the data processing pipeline tries to identify and minimize such signal distortions and noise without jeopardizing astrophysical signals (Smith et al. 2012). The most recent version of the pipeline is the multiscale Maximum A Prior (msMAP) pipeline, and this is the one available through MAST. A more detailed description of the characteristics of PDC

flux is found in Stumpe et al. (2012) and Smith et al. (2012). For our purpose, we adopted the PDC flux. The required input for this procedure (barycentric Julian date relative to JD 245 0000.00 and the PDC flux) were extracted from the FITs files. The time was converted to barycentric Julian date relative to JD 245 4950.00 while the PDC flux was converted to millimagnitudes. In different quarters, amplitude variations were observed. To obtain an average amplitude, all the data for all the quarters were stringed together to produce a single light curve. The detailed analysis of the light curves and the corresponding results are discussed in Section 3.

3 RESULTS AND DISCUSSION

3.1 Rotation frequencies

A precise estimate of the rotation frequency of a star results in a reliable rotational velocity provided that the radius is known. Fig. 2 represents some of the *Kepler* light curves that we analysed. These light curves were used to search for amplitude variations. Inspecting the light curves, they seem to be modulated. The modulation mostly comes from the beating of the plethora of r modes. To a lesser extent in such stars, the amplitude modulation could be the result of two or more sinusoids of slightly different frequencies. In addition, we may also not rule out the possibility of having cool backgrounds or close companions responsible for the rotational modulation, though this is expected to be a rare occurrence in our sample. The cooler T_{eff} and greater distance of the background stars would provide weaker total light signal than the study sample. The weaker total light signal would create very small rotational modulation effects which would not always manifest as a measurable effect in our star's light curve. This implies that the observed signal is intrinsic to the star. The majority of the light curves display low amplitudes, which hampers the visibility of the amplitude variations. An appropriate tool to display and quantify amplitude variability is the discrete Fourier transform for the unequally spaced data (Swan 1982).

For all the stars in our sample, frequencies were calculated from the light curves using the discrete Fourier fitting technique incorporated in the software package PERIOD04 (Lenz & Breger 2005). In Fig. 3, we present typical periodograms for selected stars, whose light curves are shown in Fig. 2. By entirely visual inspection of the periodograms, we identified the frequencies. The features of much interest in the frequency spectra are broad humps of unresolved frequencies coupled with spikes at their slightly higher frequency end. The 'hump and spike' features were found in frequency spectra of 131 normal A and 39 Am/Fm stars. Since it is hard to reliably distinguish between true signals and noise at very low frequencies, the part of the periodogram below 0.05 d⁻¹ was always ignored. In Fig. 3, the panels on the left show the rotation frequencies ($f_{\text{rot, lit}}$) from the literature (Balona 2013; Balona et al. 2015). The $f_{\text{rot, lit}}$ values correspond to the dominant frequencies in a given periodogram. The middle panels show 'hump and spike' features. Features in the right-hand panels correspond to their harmonics. However, in some stars such harmonics are not visible enough, especially for the humps. The presence of harmonics is a characteristic of stellar rotation and the presence of spots. Since the light curve is more of non-sinusoidal shape, the spots create frequency harmonics in the Fourier transform depending on the spot latitude and the inclination angle (Chowdhury et al. 2018).

From the periodograms shown in Fig. 3, spike frequencies were obtained and considered as rotation frequencies (Saio et al. 2018). The results for normal A and Am/Fm stars are depicted in Tables A1 and A2, respectively (available online). The uncertainties in rotation

¹ <http://archive.stsci.edu/>

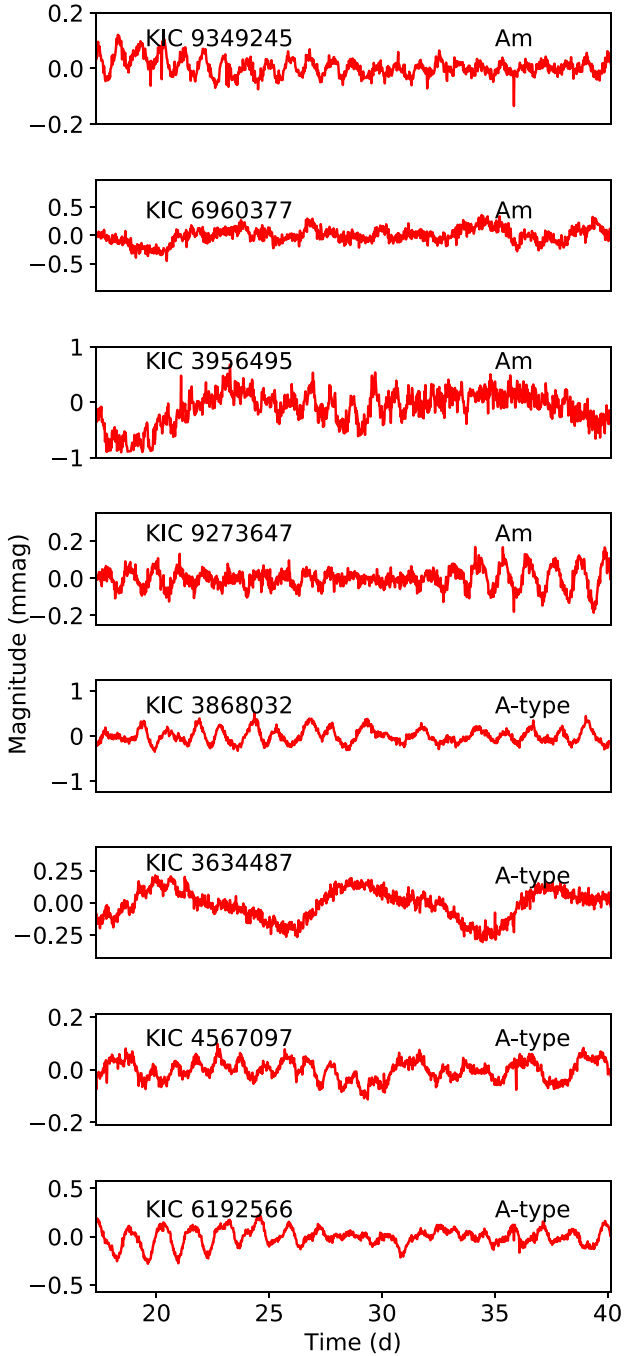


Figure 2. Typical light curves of Am/Fm and normal A stars in the sample of selected stars.

frequencies were computed using the least-squares algorithm and found to be of the order of 10^{-5} d^{-1} . In Fig. 4, we compare our rotation frequencies (f_{rot}) and photometric amplitudes (A_{rot}) with values from previous studies, $f_{\text{rot, lit}}$ and $A_{\text{rot, lit}}$, respectively (Balona 2013; Balona et al. 2015). The full black line is the 1:1 relation, and the dashed lines correspond to harmonics (1:N) and subharmonics (N:1). For the stars that lie along the line with 1:1 relation, the spike corresponds with the frequency of the highest amplitude in a given periodogram. In such cases, our results are in good agreement with the previous values. For the stars where this is not the case, the corresponding values of rotation frequency and amplitude are

different, and the discrepancy increases with increasing N . The residuals in rotation frequencies and amplitudes from the 1:1 lines are represented in panels (b) and (d), respectively. The stars whose rotation frequencies and amplitudes we have entirely corrected lie off the 1:1 line in the panels (a) and (c).

3.2 Rotational velocities

Using the resulting rotation frequencies and stellar radii, rotational velocities were calculated from

$$V_{\text{rot}} = 2\pi R_{\text{eq}} f_{\text{rot}}, \quad (1)$$

where V_{rot} is the equatorial rotational velocity in km s^{-1} , R_{eq} is the equatorial stellar radius in km, and f_{rot} is the rotation frequency in Hz. We used the mean stellar radius (R) that we calculated from

$$\log\left(\frac{R}{R_{\odot}}\right) = 0.5 \log\left(\frac{L}{L_{\odot}}\right) - 2.0 \log(T_{\text{eff}}) + 7.52340473, \quad (2)$$

instead of the R_{eq} . In most cases, R_{eq} is identical to R and the difference does not change the 3σ significance level of the result. We derived the luminosity parameter ($\log(L/L_{\odot})$) from GAIA parallaxes (Gaia Collaboration 2018), reddening from a 3D model (Green 2018; Green et al. 2019), and adopted the effective temperature (T_{eff}) from the revised catalogue of *Kepler* targets for the Q_{1-17} by Mathur et al. (2017). For stars whose parallaxes are unknown, we considered the radius from the revised catalogue of *Kepler* targets by Mathur et al. (2017). The resulting values for luminosity, stellar radius, and rotational velocities for normal A and Am/Fm stars are listed in Tables A1 and A2. In Fig. 5, our derived $\log(L/L_{\odot})$ is compared with that determined by Murphy et al. (2019) for 158 stars that fall on the sample list of the two studies. The two luminosities agree very well with a correlation coefficient, r , of 0.96.

We calculated the average rotational velocity of Am/Fm and normal A stars as 105 ± 3 and $161 \pm 3 \text{ km s}^{-1}$, respectively. Am/Fm stars rotate slowly relative to normal A stars. This confirms the conclusion from several studies (e.g. Abt & Morrell 1995; Adelman 2004; Stateva et al. 2009; Gebran et al. 2016). For 103 of the ‘hump and spike’ stars in our sample, their projected rotational velocity ($v \sin i$) is available from the LAMOST-*Kepler* project (Frasca et al. 2016) obtained from analysis of low-resolution ($\mathfrak{N} \simeq 1800$) spectra using the code ROTFIT (Frasca et al. 2003, 2006). For KIC 9117875, KIC 11443271, and KIC 9349245, $v \sin i$ determined from high-resolution spectroscopy by Niemczura et al. (2015), Pedersen et al. (2017), and Niemczura et al. (2017), respectively, was adopted. Given the low resolution of LAMOST spectra, a value of $v \sin i$ below 120 km s^{-1} cannot be determined. Therefore, for the stars tagged with ‘< 120’ in column 11 of Tables A1 and A2, we only know that they are rotating slowly in the sense that their $v \sin i$ is below 120 km s^{-1} (Frasca et al. 2016). To validate the V_{rot} determinations, we compared our measurements with the available $v \sin i$ from Niemczura et al. (2015), Frasca et al. (2016), Pedersen et al. (2017) and Niemczura et al. (2017), but ignoring the stars with $v \sin i < 120 \text{ km s}^{-1}$ by Frasca et al. (2016). The results are shown in Fig. 6, where the blue, green, and black dashed lines correspond to $i = 90^\circ$, 60° , and 30° , respectively, and show the direction a star would move if it had a different inclination. Two stars appear slightly above the line $\sin i = 1.0$ (i.e. $i = 90^\circ$). However, based on the lower limit of their error bars they fall in the reality zone. This implies that their $v \sin i$ is slightly lower than what is observed. Generally, this is a promising result, though one would get assurance if i was known and $v \sin i$ from high-resolution spectroscopy was

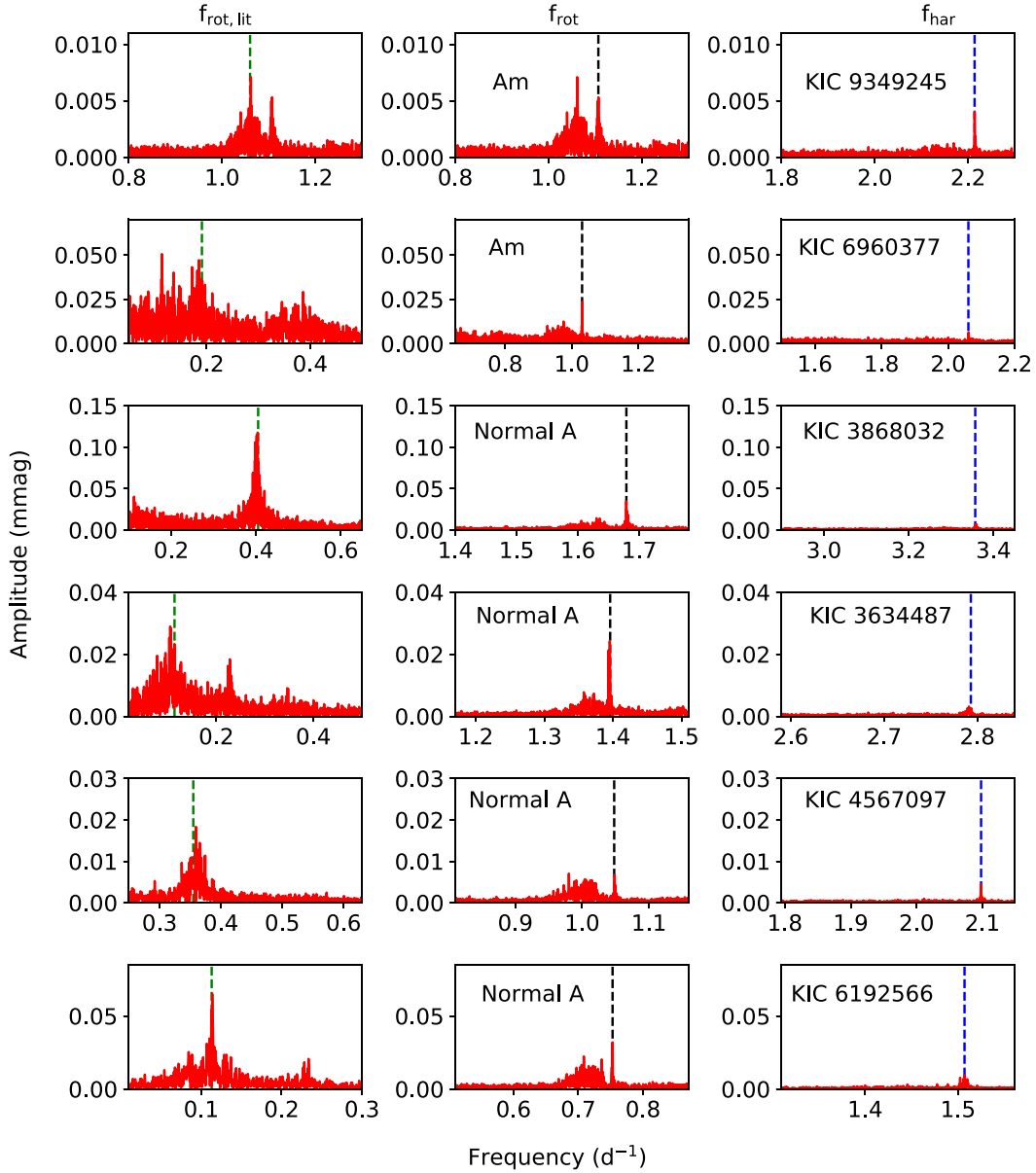


Figure 3. Frequency spectra of selected Am/Fm and normal A stars based on the 4-yr *Kepler* data. The green dashed lines in the panels on the left represent the rotation frequencies ($f_{\text{rot, lit}}$) from the literature (Balona 2013; Balona et al. 2015). Panels in the middle indicate the ‘humps and spikes’ features and those on the right show their first harmonics. The black dashed lines represent the estimated rotation frequencies (f_{rot}) and the blue dashed lines represent the frequency equivalent to $2f_{\text{rot}}$. In the cases where f_{rot} is different from $f_{\text{rot, lit}}$, the spike is not the dominant frequency, a characteristic on which $f_{\text{rot, lit}}$ was based.

available for all the stars in our sample. Unfortunately, the majority of the stars in the sample are too faint ($V \geq 11$ mag) to be able to obtain a high-resolution spectrum with a sufficient quality with small (1–2 m) ground-based telescopes.

Fig. 7 shows the distribution of the derived V_{rot} in this study as compared with the $\nu \sin i$ for the A-type stars studied by Royer, Zorec & Gómez (2007). In their analysis, the authors considered only normal stars of spectral types from B9 to F2. Therefore, for homogeneity, only normal A stars in our sample are included. From Fig. 7, the normal A stars in our sample have a wide range of rotational velocity which is representative of A stars in general when compared with the distribution of $\nu \sin i$ obtained by Royer et al. (2007).

3.3 Star-spot size

The star-spot size can give a clue of how strong the magnetic field is on the surface of a star. The knowledge of global magnetic field strength would facilitate giving informative and sound explanations about the development of the chemical peculiarities in intermediate-mass stars since the magnetic field may stabilize against convection which would otherwise hinder atomic diffusion. From the light curves in Fig. 2 and periodograms in Fig. 3, amplitude variations and frequency spikes were observed. The amplitude variations in the light curves and the spikes in the frequency spectra could be due to the presence of one or more star-spots (Balona 2013; Balona et al. 2015; Saio et al. 2018). The star-spot size can be determined

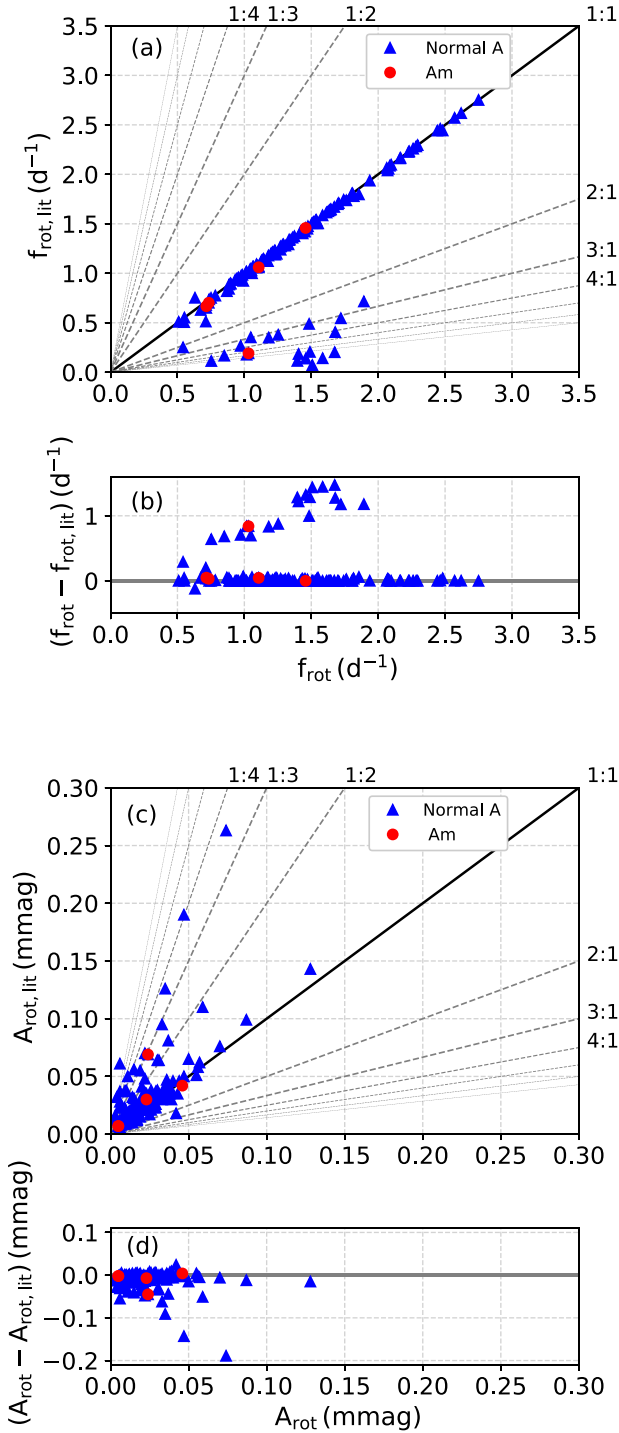


Figure 4. In panel (a), comparison of rotation frequencies (f_{rot}) with values from previous studies ($f_{\text{rot, lit}}$). Panel (b) shows the residuals in the rotation frequencies. In panel (c), photometric amplitudes (A_{rot}) compared with the values ($A_{\text{rot, lit}}$) from the literature (Balona 2013; Balona et al. 2015). Panel (d) represents the residuals in the photometric amplitudes. The full black line is the 1:1 relation, and the dashed lines correspond to harmonics (1:N) and subharmonics (N:1). In panels (a) and (c), the stars that fall off the 1:1 line have rotation frequencies and amplitudes, respectively, which we have completely corrected.

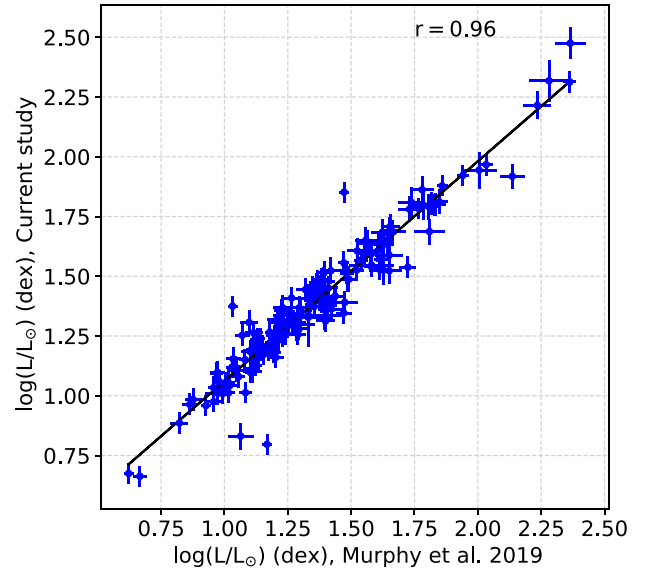


Figure 5. The $\log(L/L_{\odot})$ determined by us compared with that computed by Murphy et al. (2019). The black solid line corresponds to the best fit. The correlation coefficient (r -value) is given in the top right corner.

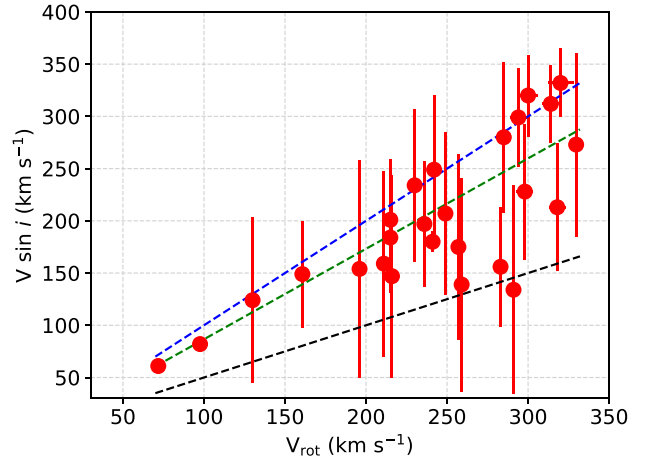


Figure 6. The projected rotational velocity as a function of equatorial rotational velocity. The blue, green, and black dashed lines correspond to $i = 90^\circ$, 60° , and 30° , respectively.

directly from Doppler imaging (Collier Cameron 1995; Barnes, James & Collier Cameron 2002).

However, currently there is no direct method for calculating the star-spot size photometrically. It has been reported that, within a magnetic cycle, the solar photometric variability increases with the activity levels (Krivova et al. 2003). Assuming that the largest active regions dominate the modulation, as a proxy, the photometric amplitude of the rotation frequency can be extrapolated to be representative of the star-spot size (Balona 2013; Giles, Collier Cameron & Haywood 2017). The amplitude may not give the exact magnitude of the star-spot size but gives a good approximation.

From the frequency spectra, we obtained and considered the amplitudes of the spikes to be the photometric amplitudes (A_{rot}) associated with rotation. The uncertainties in amplitude were calculated using Monte Carlo simulations (Lenz & Breger 2005). The

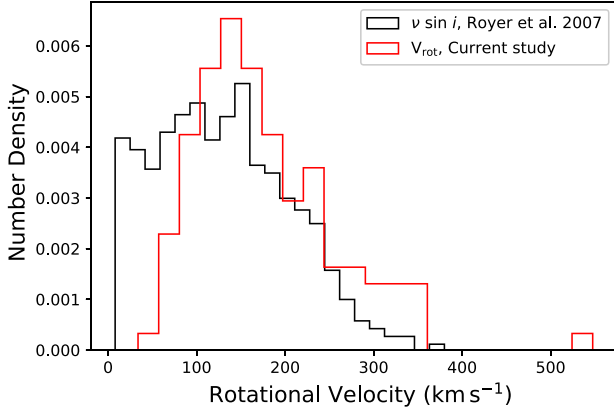


Figure 7. The distribution of the equatorial rotational velocity for the normal A stars in this study and projected rotational velocity, $v \sin i$ for A-type stars analysed by Royer et al. (2007).

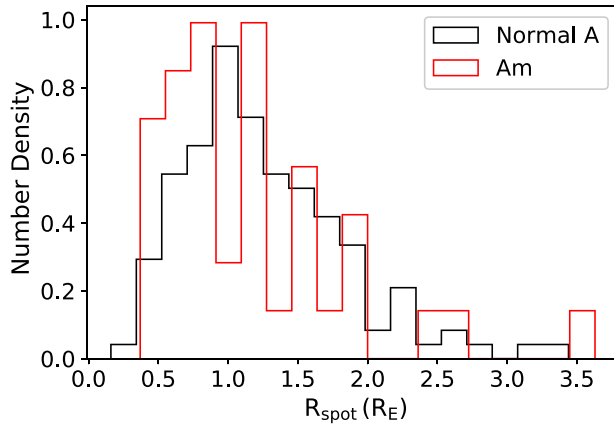


Figure 8. The distribution of the spot size for normal A and Am/Fm stars in our study calculated using equation (4).

results are listed in Tables A1 and A2. The average A_{rot} of Am/Fm and normal A stars was found to be $\sim 21 \pm 2$ and $\sim 19 \pm 2$ ppm, respectively.

For simplicity, we assume a single, circular and black spot to produce the amplitude of the spike and the stars to be spherical. This is identical to determining the size of an exoplanet from a transit. The radius of the spot (R_{spot}) is given by the standard relation

$$R_{\text{spot}} = \sqrt{A_{\text{rot}}} R. \quad (3)$$

We estimated the spot radii using equation (3), the results are given in column 12 of Tables A1 and A2 and their distribution is shown in Fig. 8. Indeed, the spots maybe regions of a lower T_{eff} (Strassmeier 2009) and hence could appear a little darker instead of completely dark. Considering the T_{eff} of the active region (spot) and the photosphere of the star to be T_{spot} and T_{phot} , respectively, equation (3) becomes

$$R_{\text{spot}} = \sqrt{A_{\text{rot}}} R \left(\frac{T_{\text{phot}}}{T_{\text{spot}}} \right)^2. \quad (4)$$

Strassmeier (2009) reported that the spot-to-photosphere temperature ratio ($T_{\text{spot}}/T_{\text{phot}}$) is about 0.8 for active G and K stars and that, on average, the temperature difference appears to be larger for hotter stars. Therefore, we expect $T_{\text{phot}}/T_{\text{spot}} \geq 1.25$, which translates

via equation (4) into star-spot size that is larger by a factor of ≥ 1.56 (Strassmeier 2009). There is a theoretical evidence that spots originating from ultraweak magnetic fields might be hotter with a temperature difference of the order of 10 K, and hence only a very small effect on the star-spot size (Cantiello & Braithwaite 2019). In addition, the calculated R_{spot} is the star-spot group size if there are several spots on the star. The distributions of both normal A and Am/Fm stars are similar and range from 0.2 to about $3.7 R_E$, where R_E is the Earth radius. The derived average spot radius is 1.01 ± 0.13 and $1.16 \pm 0.12 R_E$ for Am/Fm and normal A stars, respectively. Generally, the star-spot size in normal A and Am/Fm stars is smaller than previously estimated by Balona (2013) and Balona et al. (2015) by about 38 percent. This implies that the activity in Am/Fm and normal A stars is weaker than previously suggested by these studies.

3.4 Decay time-scale

The star-spot decay time-scale gives a clue of how long the overall star-spots are sustained on the stellar surface, once they have appeared. The rate of star-spot growth and decay could be linked to the surface magnetic field strength. The star-spot growth and decay contributes to amplitude variations in the light curves. For a better understanding and explanation of various phenomena observed in normal A and Am/Fm stars, good estimates of the decay time-scale are needed. The decay time-scale was determined from fitting autocorrelation functions (ACFs) of the light curves. The ACFs show how similar light curves are to themselves at certain time differences.

For each star, the *Kepler* light curves from all the available quarters were combined together end-to-end and the resultant light curve was cross-correlated with itself at a given time lag to produce ACF (McQuillan, Aigrain & Mazeh 2013; McQuillan, Mazeh & Aigrain 2014). The ACF was normalized on dividing it by the sum of deviations in the flux. For the majority of the stars, the ACFs increase and decrease quasi-sinusoidally depending on the presence of a corotating obstacle in the field of view of the star. At time lags greater than zero, the ACF tends to mimic the displacement of an underdamped simple harmonic oscillator (uSHO; Giles et al. 2017)

$$y(t) = e^{-t/\tau_{\text{DT}}} \left(A \cos \left(\frac{2\pi t}{P_{\text{ACF}}} \right) + B \cos \left(\frac{4\pi t}{P_{\text{ACF}}} \right) + y_0 \right), \quad (5)$$

where

$$t = \Delta T \times n,$$

here t is the time lag in days, ΔT is the median time difference of the light curve, n ascends from 0 to the total number of ACFs, $y(t)$ is the ACF, τ_{DT} is the decay time-scale of the dominant active region, P_{ACF} is the stellar rotation period, and A , B , and y_0 do not represent any physical stellar properties but are constants that are useful in fitting the uSHO equation. All the ACFs were fitted with equation (5) using χ^2 minimization. An example of the ACF for the Am/Fm star KIC 5121064 is given in Fig. 9. The second term in equation (5) is significant for this star, inducing subsequent high and low local maxima in the ACF. Indeed, in Fig. 9, the second local maximum corresponds to the rotation period (P_{ACF}) while a lower local maximum is observed at almost half the rotation period. This smaller peak is catered for by the second term in equation (5). An ACF as the one in Fig. 9 indicates that there is(are) weak star-spot(s) opposite to the stellar face with the dominant star-spot(s). Examples of ACFs where this scenario is not pronounced are shown in Fig. 10. Inspection of the ACFs was done visually. In general,

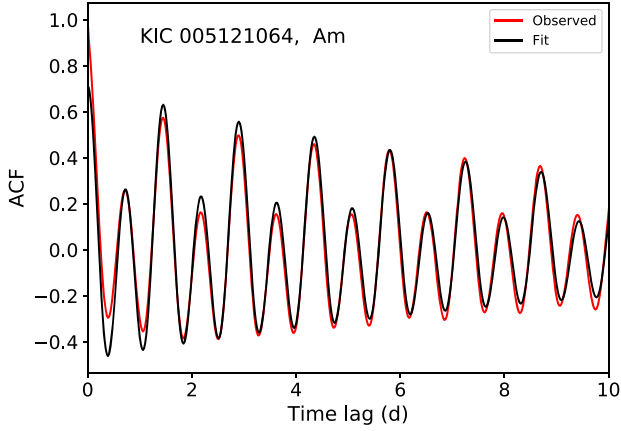


Figure 9. A typical example of autocorrelation function where the second term of equation (5) is manifested.

good quality fits were produced by the least-squares routine (χ^2 minimization).

About 40 per cent of the ACFs do not show any significant peaks. Examples of such ACFs are shown in Fig. 11, where it is observed that generally the ACF decays instantly without significant local maxima. This points towards a short decay time and low amplitudes, so it suggests very weak or the absence of star-spots and corotating structures. However, the ‘hump and spike’ features exist in their frequency spectra. This implies that significantly large star-spots may not be required to produce the existing spikes in the frequency spectra. A similar observation was made by Saio et al. (2018) as very small star-spots were enough to produce spikes in the models. The resulting values of the decay time τ_{DT} and the period P_{ACF} are listed in Tables A1 and A2. The stars without any significant peaks in their ACFs have (*) assigned to their τ_{DT} values in the Tables and they were not considered during the discussion of the decay time-scale. In Fig. 12, rotation periods derived from ACFs (P_{ACF}) are compared with periods from the spikes (P_{Tot}). The black solid and dashed lines represent the 1:1 relation and the harmonics (1:N) and subharmonics (N:1), respectively. The two periods are well in agreement. However, there are two normal A stars (KIC 4557097 and KIC 10068389) for which the periods of both methods do not agree. This implies that the spikes get overshadowed by the dominant frequencies during the ACF analysis. This is because the spikes are not the dominant peaks in their periodograms. This also applies to all the stars that do not perfectly lie along the line 1:1. We also never considered the two stars (KIC 4557097 and KIC 10068389) in the analysis of the decay time-scale of the sample.

The majority of the stars have decay time-scales of a few days or less, as shown in Fig. 13(e₁)–(e₃). The average decay time in Am and normal A stars is 3.6 ± 0.2 and 1.5 ± 0.2 d, respectively. The difference may not be associated with the difference in the rotation velocities between the two groups of stars (discussed in Section 3.2), as we observed no correlation between the two parameters. However, the difference could be attributed to the difference in effective temperature. The Am/Fm stars are, in general, cooler than normal A stars in our sample as shown in Fig. 14. The thin convective subsurface layer reduces as the effective temperature increases, which affects the decay lifetime of the available spots. The decay time-scales in Am and normal A indicate that spots in these stars are short lived compared with those in G, K, and M stars. Spots of similar emergence and disappearance time of only a few

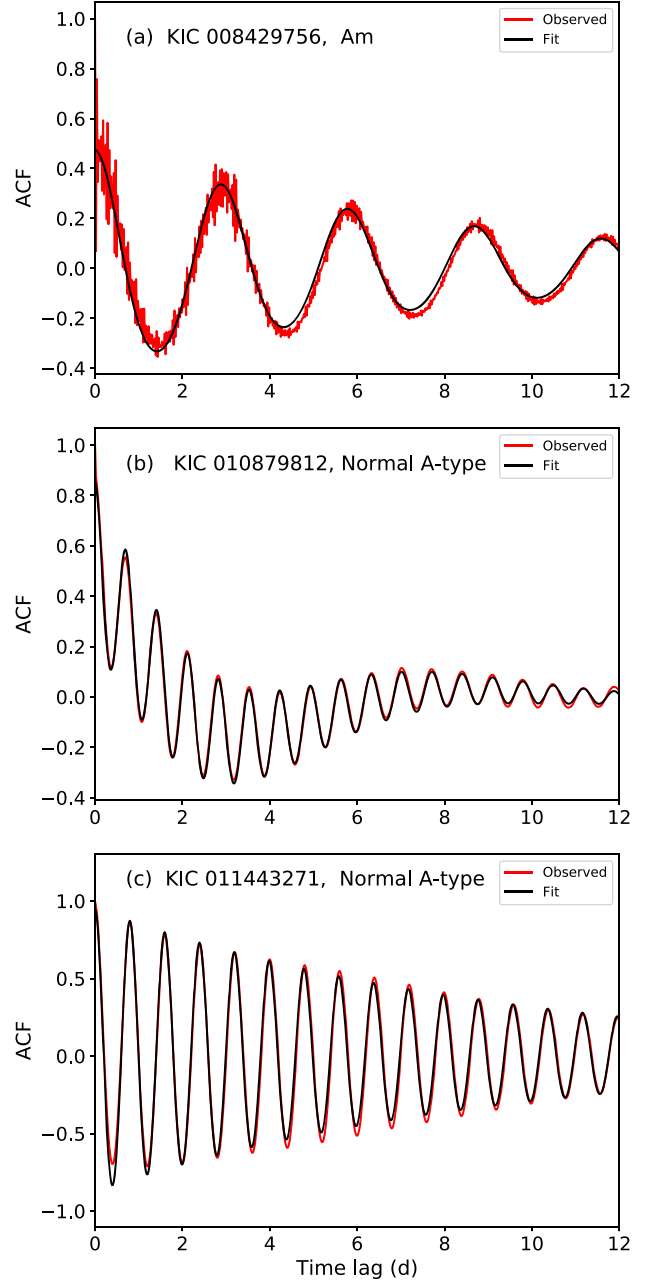


Figure 10. Examples of ACFs plots where the spot(s) is(are) dominant on only one side of the star and so the second term of equation (5) is overshadowed. The first peak corresponds to a time lag equivalent to the rotation period.

days were observed in Vega by Petit et al. (2017). The spots in G, K, and M stars can stay on the surface for as long as 400 d (Giles et al. 2017). Giles et al. (2017) observed that big star-spots live longer on any given star. In Fig. 15, there is a weak positive correlation between spot radius (R_{spot}) and the decay time-scale (τ_{DT}) for the stars in our sample. This implies that the τ_{DT} values weakly depend on the spot size in these stars, and a significantly large sample is required to confirm the observation. Giles et al. (2017) also report that star-spots decay more slowly on cooler stars. Normal A and Am/Fm stars are hotter than G, K, and M stars, which verifies the observations of short decay time-scale. The observed spot sizes and

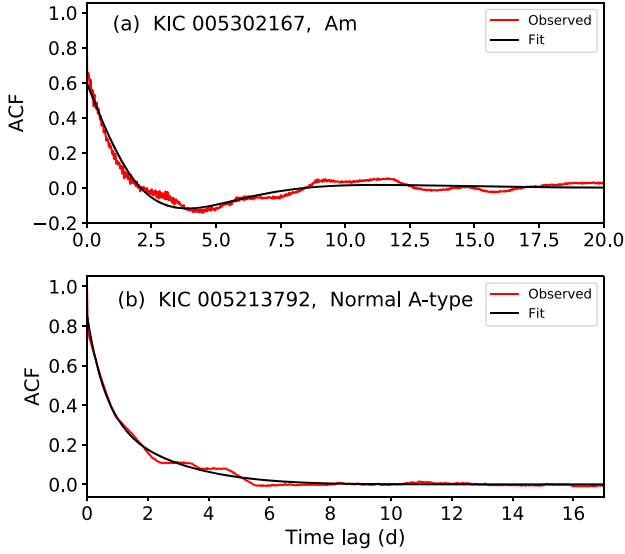


Figure 11. Examples of ACFs which do not show any significant peaks.

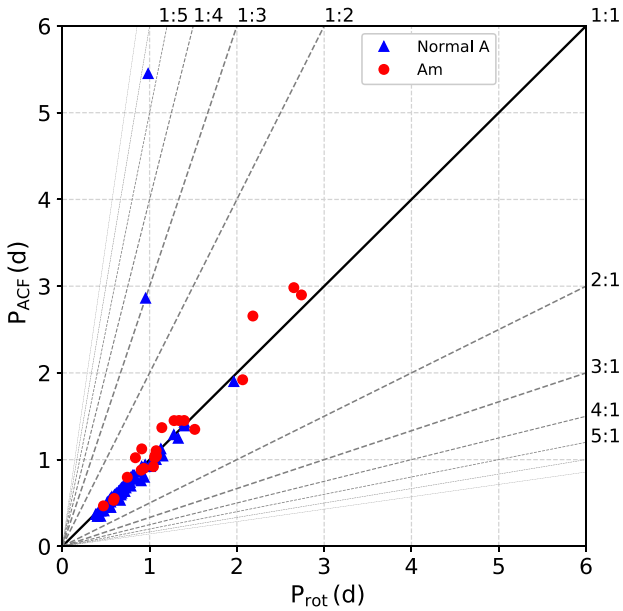


Figure 12. Comparison of rotation periods derived by different methods. The black solid line represents 1:1 relation, while the dashed lines indicate the harmonics (1:N) and subharmonics (N:1). There are two normal A stars with periods that differ a factor of 3 or more.

decay time-scales suggest the presence of a weak magnetic field in the stars of our sample. The magnetic fields could be in the similar range as observed for Vega (Lignières et al. 2009), Sirius (Petit et al. 2011), β UMa and θ Leo (Blazère et al. 2014), HD 188774 (Neiner & Lampens 2015), Alhena (Blazère et al. 2016a), and ρ Pup (Neiner et al. 2017). Cantiello & Braithwaite (2019) reported a similar suggestion that, except for the Ap stars, the other main-sequence A-type stars can have magnetic fields of a few Gauss. Some studies show that such magnetic field can support weak star-spots (e.g. Blazère et al. 2016a; Neiner et al. 2017; Cantiello & Braithwaite 2019). Nevertheless, we may not rule out the possibility

of the observed spots having an origin other than the magnetic fields that is still unknown.

3.5 Correlation of rotation and spot properties with other parameters

This study presents a detailed analysis of the rotation properties of ‘hump and spike’ stars. We analysed *Kepler* photometric data of 170 stars. The distribution of the rotation properties of our sources over the temperature (T_{eff}), surface gravity ($\log g$), and luminosity ($\log(L/L_{\odot})$) domains is represented in Fig. 13. Panels (a_{1–3}), (b_{1–3}), (c_{1–3}), (d_{1–3}), and (e_{1–3}) of Fig. 13 show how f_{rot} , V_{rot} , A_{rot} , R_{spot} , and τ_{DT} , respectively, vary with the T_{eff} , $\log g$, and $\log(L/L_{\odot})$ of the studied stars. From panels (a₁) and (b₁), rotation frequency and velocity are moderately correlated with effective temperature. The A_{rot} (panel c₁) and spot radius (panel d₁) have no significant relation with T_{eff} for these stars. A weak dependence of τ_{DT} on T_{eff} is observed in panel (e₁). A similar observation is reported by Giles et al. (2017) for the G, K, and M stars. From the panels in the middle, the rotation and spot properties are independent of $\log g$ for these stars. Based on the r -values in panels (a₃) and (d₃), the rotation frequency and the spot size weakly depend on luminosity. Panel (b₃) indicates a moderately strong relation between V_{rot} and $\log(L/L_{\odot})$. There is no dependence of A_{rot} and τ_{DT} on $\log(L/L_{\odot})$ for these stars. From panels (c_{1–3}), (d_{1–3}), and (e_{1–3}), we conclude that in general, the photometric amplitudes, spot radii, and spot decay time-scales of normal A and Am/Fm stars are on average 0.025 mmag, 1.61 R_E , and 3.3 d, respectively.

Fig. 16 shows distribution of the rotation and spot properties in the Hertzsprung–Russell diagram. The majority of the stars are beyond the blue edge of the theoretical δ Scuti instability strip calculated by Dupret et al. (2004). In Figs 16(a) and (b), the rotation frequency and velocity increase with towards the more massive stars, while the spot radius, in panel (d), seem to increase as stars move off the zero-age main sequence. There are no observable patterns for photometric amplitude and decay time-scale in panels (c) and (e), respectively. The observations will be confirmed when a significantly large number of stars is used. Efforts are being made to search for ‘hump and spike’ stars in the K2 and *TESS* archives.

The magnetic field in all the stars in the sample is presumed ultraweak and magnetic braking may not explain the observed trend of rotation properties. As we ascend the main sequence the effective temperature, luminosity, and mass increase. The more massive stars rotate faster because they have higher initial angular momenta (Bouvier 2013).

4 CONCLUSION

The rotation frequencies of both normal A and Am/Fm stars were obtained from their frequency spectra using ‘hump and spike’ features. Rotation frequency and velocity are found to depend moderately on T_{eff} . A good agreement between the rotational velocities and the available $v \sin i$ from the literature was observed. However, a comparison of the two velocities would be more feasible if $v \sin i$ from high-resolution spectroscopy was available and i was known. The photometric amplitudes were determined and used as proxies for the size of the star-spots. The average photometric amplitude of Am/Fm and normal A stars was found to be $\sim 21 \pm 2$ and $\sim 19 \pm 2$ ppm, respectively. After assuming a single, circular and black spot to produce the amplitude of the spike, the average spot radius was found to be 1.01 ± 0.13 and $1.16 \pm 0.12 R_E$ for

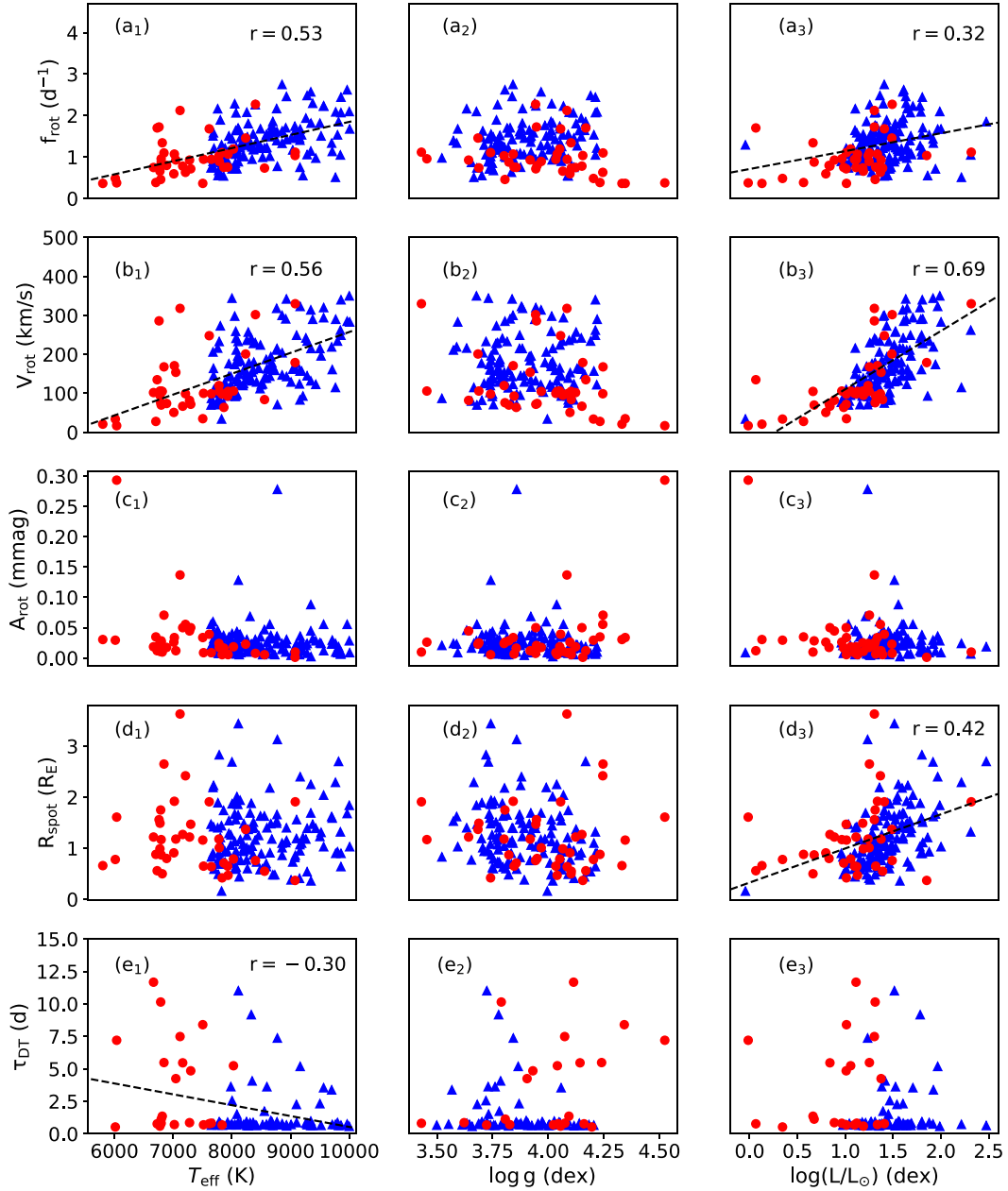


Figure 13. The rotation frequency (a_{1–3}), rotational velocity (b_{1–3}), photometric amplitude (c_{1–3}), spot radius (d_{1–3}), and star-spot decay lifetime (e_{1–3}) versus effective temperature, surface gravity, and luminosity. The T_{eff} and $\log g$ values from the revised catalogue of *Kepler* targets for the Q_{1–17} (DR25) (Mathur et al. 2017) were adopted. The red dots represent Am/Fm stars and blue triangles are normal A stars. The black dashed lines indicate the fits between the respective parameters and the value of the correlation coefficient (r) is given in the top right corner.

Am/Fm and normal A stars, respectively. These results indicate that spots in normal A and Am/Fm stars are significantly smaller compared to the previously estimated sizes, 541 ± 86 ppm for normal A and 93 ± 25 ppm for Am/Fm stars by Balona (2013) and Balona et al. (2015), respectively. However, based on the limitations discussed in Section 3.3, our analysis gives the lower limit of the spot sizes.

By fitting the ACFs of the light curves with appropriate models, no peaks were observed in the ACFs of some stars, a phenomenon that suggests the absence of repeated patterns in their light curves, and hence of corotating structures (star-spots). Since such stars have ‘hump and spike’ features in the periodograms, star-spots may not

be a major requirement to produce spikes in frequency spectra. Based on our R_{spot} values and absence of peaks in the 40 per cent of the ACFs, spots in most normal A and Am/Fm stars could be very weak or actually absent.

The lifetime of the star-spots was found to be in the order of a few days. The sizes of the spots in normal A and Am/Fm stars are in general very similar. In comparison with G, K, and M stars, the spots in normal A and Am/Fm stars are short lived. This is attributed to the much thinner outer convective zone in normal A and Am/Fm than in G, K, and M stars.

In the next paper of the series, we shall present the high-resolution spectroscopic analysis of a number of ‘hump and spike’ stars

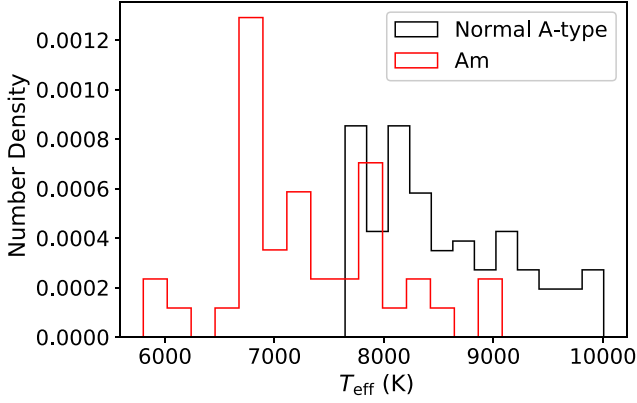


Figure 14. The distribution of the effective temperature for normal A and Am/Fm stars in our study.

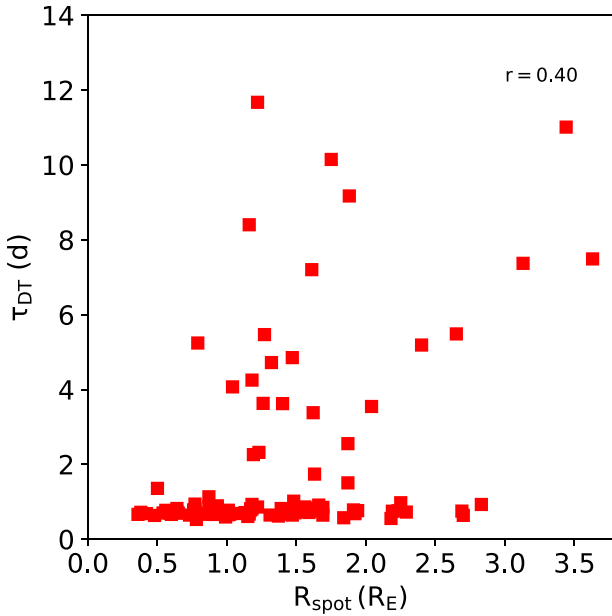


Figure 15. The correlation between the spot radius (R_{spot}) and the decay time-scale (τ_{DT}) for normal A and Am/Fm stars. The black dashed line shows the fit. The correlation coefficient (r -value) is given at the top right corner.

observed from La Palma using High-Efficiency and high-Resolution Mercator Echelle Spectrograph (HERMES). In the near future, we also intend to make follow-up studies for K2 and *TESS* targets showing ‘hump and spike’ features in their frequency spectra.

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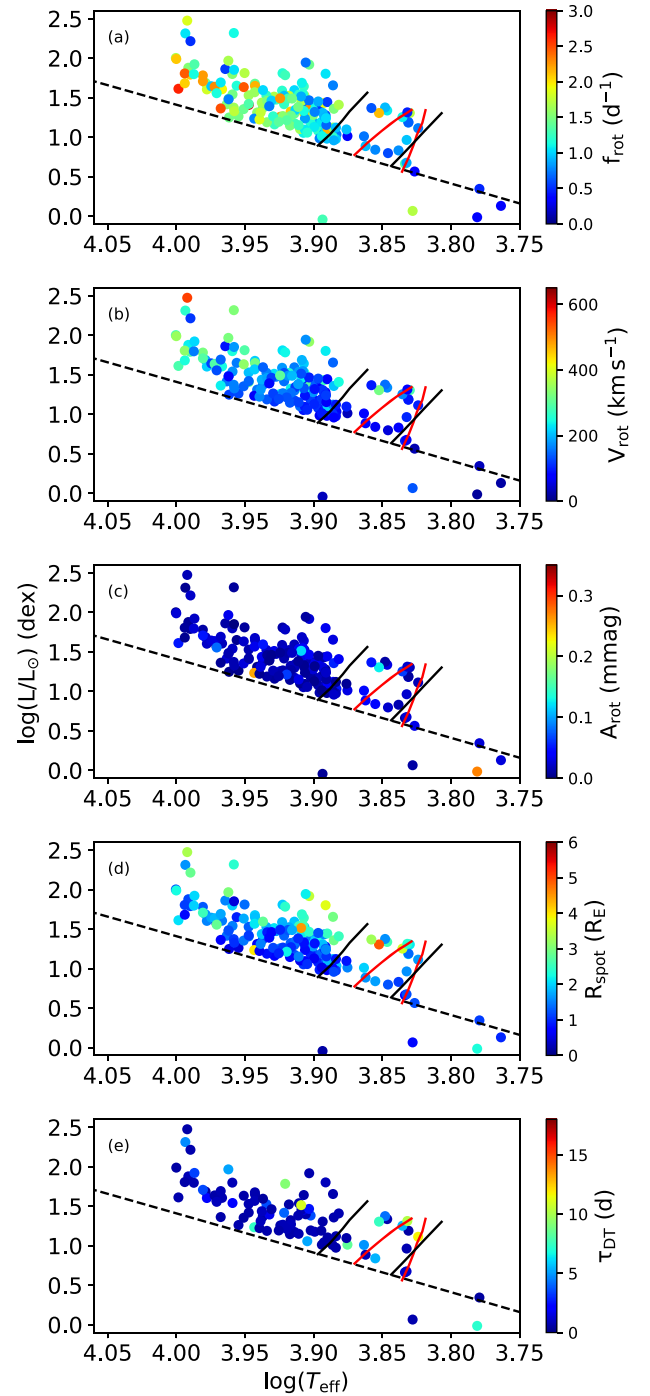


Figure 16. The distribution of the rotation and spot properties in the Hertzsprung–Russell diagram. The black dashed line represents the zero-age main sequence. The black and red solid lines indicate the theoretical δ Scuti and γ Doradus instability strips, respectively, as calculated by Dupret et al. (2004).

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SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

Table A1. List of normal A stars with ‘hump and spike’ features in their frequency spectra.

Table A2. List of Am/Fm stars with ‘hump and spike’ features in the frequency spectra.

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