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Phase difference between long-term magnetic feature activity and flare activity of solar-type stars

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Abstract. In the light curves of some solar-type stars, both rotational modulation (caused by corotating bright or dark magnetic features) and flare phenomena can be seen simultaneously. Based on these light curve observations, the relation between stellar magnetic feature activity (reflected by the rotational modulation component of the light curves) and flare activity can be investigated. Here, we analyze the light curve data of a flare-abundant solar-type star, KIC 6034120, observed with *Kepler* space telescope, and describe magnetic feature activity property by fluctuation range of light curves and flare activity property by time occupation ratio of flares. Distinct phase difference between long-term magnetic feature activity and flare activity is found for this star, which indicates that the source regions of stellar flares (e.g., starspots) on this star do not dominate the rotational modulation of light curves, yet they might be related to a same stellar dynamo process.

Keywords. stars: activity, stars: flare, stars: magnetic field, stars: solar-type, stars: spots

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1. Introduction

Kepler space telescope (Borucki *et al.* 2010; Koch *et al.* 2010) provides the light curves of a large sample of solar-type stars. For some solar-type stars, both rotational modulation (light-curve fluctuation caused by corotating bright or dark magnetic features on the stellar surface) and flare phenomena can be seen in their light curves (Debosscher *et al.* 2011; Maehara *et al.* 2012; Yun *et al.* 2016, 2017). It is commonly believed that the fluctuation range of rotational modulation reflects the spatial size or coverage of magnetic features on solar-type stars and hence can be used as an indicator of magnetic activity levels of stars (García *et al.* 2010; Basri *et al.* 2010). Statistical studies for the solar-type stars observed with *Kepler* have shown that flare stars tend to have larger amplitudes of light-curve fluctuation (Balona 2015; Karoff *et al.* 2016). According to the knowledge of the Sun, energetic flares usually originate from large sunspot groups (Shibata & Magara 2011; He *et al.* 2014; Benz 2017), and large sunspots in turn lead to large fluctuation range of rotational modulation (He *et al.* 2015). This relation for the Sun had been used to interpret the superflare activities of solar-type stars (Shibata *et al.* 2013; Notsu *et al.* 2013). Our previous works (He *et al.* 2015; Mehrabi *et al.* 2017; He *et al.* 2018a) based on the *Kepler* data showed that the rotational modulation behaviors of most solar-type stars are different from that of the Sun. Especially for the stars with larger amplitude

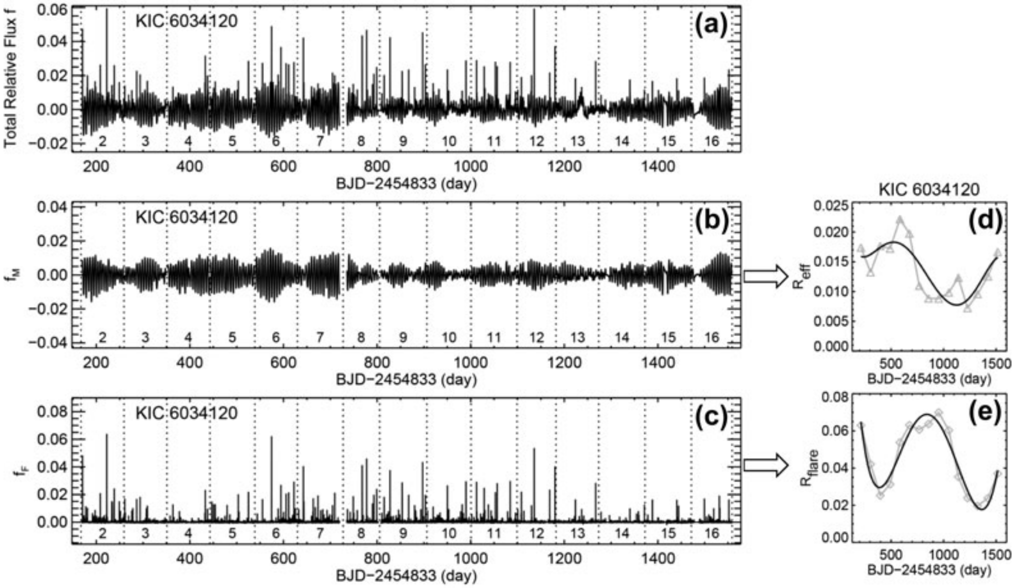

Figure 1. Data analysis process for the *Kepler* light curve of KIC 6034120. (a) Original light curve observed by *Kepler* (expressed in relative flux f). The light curve segments of different quarters are separated by vertical dotted lines. The corresponding quarter numbers (Q2–Q16) are given below the light curve. (b) Rotational modulation component f_{M} extracted from the original light curve. (c) Flare component f_{F} extracted from the original light curve. (d) Grey curve: Variation of R_{eff} vs. time derived based on the f_{M} flux data (see main text for details). Each triangular symbol corresponds to one quarter. Black curve: Long-term trend of the R_{eff} variation fitted by a 5th-degree polynomial. (e) Grey curve: Variation of R_{flare} vs. time derived based on the f_{F} flux data (see main text for details). Each diamond symbol corresponds to one quarter. Black curve: Long-term trend of the R_{flare} variation fitted by a 5th-degree polynomial.

of rotational modulation, the light curves of the stars have stronger periodicity than the light curve of the Sun, which means that the magnetic features that dominate the rotational modulation on these stars are more stable in contrast to the rapidly evolving sunspots on the Sun.

In this work, we investigate the relationship between magnetic feature activity and flare activity of solar-type stars from another point of view: the temporal relation between the long-term magnetic feature activity and flare activity of individual stars. Many solar-type stars were continuously observed by *Kepler* for about four years. Some stars also have relatively higher flare occurrence rate. Here, we employ a flare-abundant solar-type star observed with *Kepler*, KIC 6034120, as the representative star for our study. This star is included in the superflare star catalog compiled by Shibayama *et al.* (2013) and was also referred by Maehara *et al.* (2012) for illustrating stellar superflares. In Section 2, we describe the analysis process for the *Kepler* light curve data of the star. In Section 3, we give conclusion and discussion based on the analysis results.

2. Data analysis

We use the *Kepler* light curve data in full-length quarters (i.e., Q2–Q16, about 1388 days in total; 1 full-length quarter being about 3 months) for our analysis. Figure 1a shows the original *Kepler* light curve of the star KIC 6034120 (expressed in relative flux f). It can be seen from Fig. 1a that the light curve of KIC 6034120 presents prominent rotational modulation as well as intense flare activity. We extracted the rotational modulation component f_{M} and the flare component f_{F} from the original light curve f (see He *et al.* 2018b for details of the extraction process). The derived flux curves of f_{M} and f_{F} are shown in Figs. 1b and 1c, respectively.

The rotational modulation component f_{M} reflects the magnetic feature activity of KIC 6034120. We use the fluctuation range of f_{M} to quantitatively describe the magnetic feature activity property of the star for it is a proxy of the spatial size or coverage of magnetic features on stellar surface and its time variation indicates the change of magnetic activity level of stars (García *et al.* 2010; Basri *et al.* 2010). Since the amplitude of fluctuation is generally not uniform, we introduce the quantity R_{eff} to describe the effective fluctuation range of a light curve, which is defined using the rms algorithm (for details of R_{eff} definition and calculation, please refer to He *et al.* 2015, 2018b). We calculated the values of R_{eff} quarter by quarter based on the f_{M} flux data. The results are illustrated in Fig. 1d (grey curve, each triangular symbol corresponding to one quarter) which exhibits the long-term variation of the magnetic feature activity of the star KIC 6034120.

The flare component f_{F} reflects the pure flare activity of KIC 6034120. We use the time occupation ratio of flares, R_{flare}, to quantitatively describe the flare activity property of the star. R_{flare} is defined as the ratio of the total time occupied by the flares (T_{flare}) to the total valid observing time of the light curve (T_{obs}), that is, $R_{\mathrm{flare}} = T_{\mathrm{flare}}/T_{\mathrm{obs}}$. To determine the total time occupied by the flares, T_{flare}, we first picked out all the prominent flare spikes from the f_{F} flux curve using the threshold $f_{\mathrm{F}} \geqslant 0.001$, and then summed all the tiny time segments of the identified flares. (The threshold value 0.001 for identifying the flare spikes is just above the noise level of the f_{F} flux data; for more details about the threshold determination and the definition and calculation of R_{flare}, please refer to He *et al.* 2018b.) We calculated the values of R_{flare} quarter by quarter based on the f_{F} flux data. The results are illustrated in Fig. 1e (grey curve, each diamond symbol corresponding to one quarter) which exhibits the long-term variation of the flare activity of the star KIC 6034120.

Both the R_{eff} and R_{flare} curves in Figs. 1d and 1e reveal the long-term cyclic variations of magnetic feature activity and flare activity of KIC 6034120. To depict these long-term trends more clearly, we fitted the R_{eff} and R_{flare} curves with 5th-degree polynomials. The resultant curves of the polynomial fitting are displayed in Figs. 1d and 1e in black overlying the original curves.

3. Conclusion and discussion

By comparing the R_{eff} and R_{flare} polynomial fitting curves in Figs. 1d and 1e, it can be found that there is a distinct phase difference between the long-term cyclic variations of magnetic feature activity and flare activity of KIC 6034120. This result indicates that for this star, the source regions of the stellar flares (e.g., starspots) do not dominate the rotational modulation of the light curves, which is different from the behavior of the Sun. For the Sun, both the long-term variations of the fluctuation range of light curve and the flare occurrence rate (analogous to the measure R_{flare} employed in this work) are in phase with the solar cycle.

The curves of R_{eff} and R_{flare} in Figs. 1d and 1e also hint that the cycle lengths of their long-term variations are similar (see He *et al.* 2018b for detailed quantitative analysis). This suggests that the source regions of the flares and the source regions that dominate the rotational modulation might be related to a same stellar dynamo process.

Besides KIC 6034120, phase differences between long-term magnetic feature activity and flare activity were also found for the solar-type stars KIC 3118883 and KIC 10528093 (see He *et al.* 2018b). In future study, we plan to conduct a statistical study on this kind of stellar activity property for a large sample of solar-type stars observed with *Kepler*.

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