Space Weather of the Heliosphere: Processes and Forecasts
Proceedings IAU Symposium No. 335, 2017
C. Foullon & O.E. Malandraki, eds.

doi:10.1017/S1743921317007670

Magnetic Activity Discrepancies of Solar-Type Stars Revealed by *Kepler* Light Curves

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Abstract. Magnetic activity information is concealed in the shape of stellar light curves owing to the process of rotational modulation. We developed approaches to extract magnetic activity characteristics from stellar light curves, and applied the method to a solar-type star observed with *Kepler* space telescope and also to the Sun for comparison. The result reveals distinct magnetic activity discrepancies between the solar-type star and the Sun. (1) The light-curve periodicity of the solar-type star is generally stronger than that of the Sun. (2) For the solar-type star, when the range of light-curve fluctuation is larger, the periodicity is also higher; while for the Sun, only during the solar minima with minimal range of fluctuation, the light curves show some periodicity. We propose that on the solar-type star, it is the large-scale magnetic field that leads to the light curves with both high periodicity and large range of fluctuation.

Keywords. stars: activity, stars: magnetic field, stars: rotation, stars: solar-type, Sun: activity

1. Motivation

Magnetic activity properties of solar-type stars can be revealed by the shape of stellar light curves as demonstrated by the light curve of the Sun (Shapiro *et al.* 2016). The dark or bright magnetic features (such as spots and faculae) on the surface of a star cross the stellar disk along with the stellar rotation and cause regular or irregular fluctuation of light curves. This process is known as rotational modulation (Debosscher *et al.* 2011). By careful investigation on the light curves of the Sun, it can be found that the fluctuation range of the solar light curves is larger during solar maxima and smaller during solar minima, and such fluctuation range is in phase with the variation of the sunspot number. This property indicates that the rotational modulation of the Sun is dominated by sunspots. In addition, a wavelet or Fourier analysis of the solar light curves shows that the fluctuation of the light curves is more regular (periodic) during solar minima and irregular during solar maxima (Lanza *et al.* 2003). The irregular light curves during solar maxima can be understood by the rapid evolution of sunspots; while the possible magnetic features that cause the more regular light-curve modulation during solar minima need further investigation since sunspots are rarely seen during solar minima. He *et al.* (2015) compared the light curve of the Sun with the simultaneously observed photospheric magnetograms and found that it is the bright faculae associated with the enhanced network magnetic field that lead to the regular modulation. The spatial size of facula regions on the surface of the Sun is much larger than sunspots, and they are more stable and have a longer lifetime than sunspots. Thus the light curves modulated by the facula regions during solar minima is more regular and periodic than the light curves dominated by the sunspots during solar maxima.

From the analysis carried out on the light curves of the Sun, it can be seen that the shapes of the solar light curves show two kinds of cyclic variation: the cyclic variation of the range of fluctuation and the cyclic variation of the degree of periodicity. Both the two kinds of variations reflect the magnetic activity characteristics of the Sun. We want to know if these activity properties also exist on the solar-type stars other than the Sun. The *Kepler* space telescope (Borucki *et al.* 2010; Koch *et al.* 2010) observed a large number of solar-type stars in its field and provided continuous light curves of these solar-type stars for about four years. We developed a method to infer the general properties of the magnetic field of a star through the study of its light curve, and we applied our method to both a solar-type star observed with *Kepler* space telescope and the Sun for comparison. The result of our analysis reveals distinct magnetic activity discrepancies between the solar-type star and the Sun. In Section 2, we briefly explain the analytical method for the light curves. In Section 3, we present the result of our analysis.

2. Method

We aim to employ two mathematical measures to quantitatively evaluate the time variation of the fluctuation range and the degree of periodicity of a light curve. The original light-curve data are normalized by the median value to yield the relative flux expression. The definitions of the two measures are based on the relative flux data.

The fluctuation range of a light curve is evaluated by using the rms algorithm (e.g, García *et al.* 2010; Chaplin *et al.* 2011). After calculating the rms of the light curve using the relative flux data, we multiply the rms value by a factor of $2\sqrt{2}$ to reflect the intuitive range between crest and trough of the light curve. For example, given a sine curve $A\sin(\omega t)$, the rms is $\frac{A}{\sqrt{2}}$, while $2\sqrt{2}\cdot\mathrm{rms} = 2\mathrm{A}$, which is just the true range between crest and trough. Since the fluctuation of a real light curve is generally not uniform, we call this quantity the effective range (R_{eff}) of the light curve.

The degree of periodicity of a light curve is evaluated by using the autocorrelation algorithm (e.g., Chatfield 2003). Firstly, the autocorrelation function $\rho(h)$ is derived for the whole light curve with the time lag h from 0 to $N-1$, where N is the total number of the data points in the light curve. Then the average value of $|\rho(h)|$ for the first half of the autocorrelation function ($h \leqslant \frac{N}{2}$) is calculated. We call this quantity the autocorrelation index (i_{AC}) of the light curve. Larger i_{AC} value means higher (i.e., stronger) periodicity. We do not use the second half of the autocorrelation function to evaluate i_{AC} because if $h > \frac{N}{2}$, not all data points in the light curve are utilized to calculate $\rho(h)$, thus the second half of the autocorrelation function cannot reflect the global property of the light curve.

Here, we only give a brief description of the two measures. The detailed definitions and formulas can be found in He *et al.* (2015).

3. Result

We applied the two measures of light curve, R_{eff} and i_{AC}, to a solar-type star observed with *Kepler* (*Kepler* object ID: KIC 10864581). This star was selected from a superflare star catalog compiled by Shibayama *et al.* (2013) using the *Kepler* observations. The light-curve data of *Kepler* is arranged by quarters, in which quarters 2 to 16 (Q2–Q16) are full-length quarters (1 quarter $\sim$ 3 months). We evaluated the two measures for the light curves of the solar-type star quarter by quarter from Q2 to Q16, and obtained the time variation information of the two measures with the quarters. Before deriving the two measures, the noises and outliers in the original light curve data had been filtered

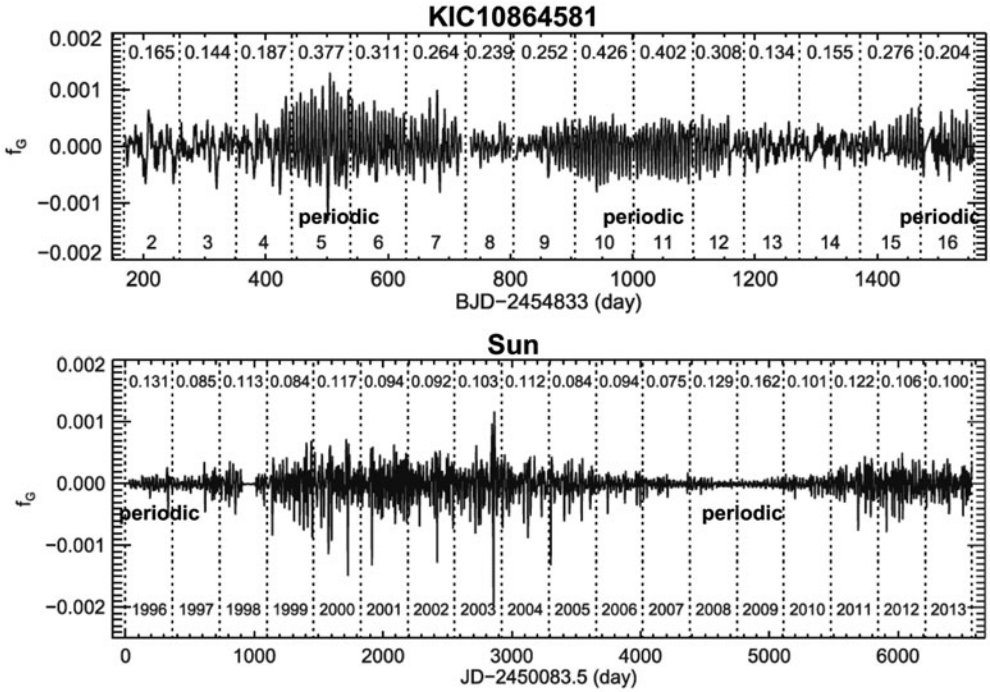

Figure 1. Top panel: Processed light curves (Q2–Q16) of the solar-type star (KIC 10864581) observed with *Kepler*. The quarter numbers are given below the light curves. The decimal numbers above the light curves are $i_{\rm AC}$ values of each quarter. Bottom panel: Processed light curves of the Sun (1996–2013) observed with *SOHO*. The year numbers are given below the light curves. The decimal numbers above the light curves are $i_{\rm AC}$ values of each year.

out. The processed light curves of the solar-type star (in relative flux expression) are shown in the top panel of Figure 1.

For comparison, we also applied the two measures to the light curves of the Sun. The solar light curves employed in this paper are from the total solar irradiance (TSI) data during 1996–2013, which were observed by the VIRGO instrument (Fröhlich *et al.* 1997) aboard the *SOHO* spacecraft (Domingo *et al.* 1995). The long-term trend in the TSI data was filtered out before calculating the two measures since it is irrelevant with the rotational modulation (Fröhlich & Lean 2004). The noises in the light curves were also filtered out. The two measures were evaluated year by year based on the processed light curves which are shown in the bottom panel of Figure 1.

Figure 1 demonstrates that the light curves of the solar-type star do have cyclic variation of fluctuation range and of periodicity, and the dynamic range (upper limit value of $R_{\rm eff}$) of the light curves has the same order of magnitude as the Sun (about 10^{-3}).

However, the result of the analyses also reveals distinct magnetic activity discrepancies between the solar-type star and the Sun. (1) The light-curve periodicity of the solar-type star is generally stronger than the one of the Sun, which is indicated by the relatively higher $i_{\rm AC}$ values of the solar-type star than the $i_{\rm AC}$ values of the Sun (see Figure 1). (2) For the solar-type star, when the range of light-curve fluctuation is larger, the periodicity is also higher; while for the Sun, only during the solar minima with minimal range of fluctuation, the light curves show some periodicity (see 'periodic' labels in Figure 1).

Based on the above result, we propose that on the solar-type star, it is the large-scale magnetic field (e.g., Vidotto *et al.* 2014) that dominates the rotational modulation and

https://doi.org/10.1017/S1743921317007670 Published online by Cambridge University Press

leads to the light curves with both high periodicity and large range of fluctuation, which is different from the dominant role of sunspots (associated with relatively small-scale magnetic field) on the Sun.

The statistic analysis of thousands of G-type main sequence stars by Mehrabi *et al.* (2017) based on the *Kepler* data shows that most of the G-type stars in their sample have the similar activity properties as the star discussed in this paper. The comparative analysis between the rotational modulation component and the flare component in the *Kepler* light curves of the superflare stars by He *et al.* (2018) also suggests the dominant role of large-scale magnetic field in the rotational modulation process. In a future work, we will investigate the magnetic activity discrepancies between solar-type stars and the Sun, through the study of the chromospheric activity.

Acknowledgements

This paper includes data collected by the *Kepler* mission. Funding for the *Kepler* mission is provided by the NASA Science Mission directorate. The *Kepler* data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). We acknowledge receipt of the updated data set (Version: 6_004_1411) of the VIRGO Experiment on *SOHO* from the VIRGO Team through PMOD/WRC. *SOHO* is a project of international cooperation between ESA and NASA. This work is jointly supported by National Natural Science Foundation of China (NSFC) through grants 11403044, 11603040, 11473040, 40890160, 40890161, 10803011, National Science and Technology Basic Work Program of China (grant 2014FY120300), and Strategic Priority Research Program on Space Science, Chinese Academy of Sciences (grant XDA04060801).

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