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Statistical properties of starspots on solar-type stars and their correlation with flare activity

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Abstract. We analyzed the statistical properties of starspots on solar-type stars and the correlation between properties of starspots and flare activity using observations from the *Kepler* mission. We found the size distribution of starspots on solar-type stars shows the power-law distribution and both size distributions of starspots on slowly-rotating solar-type stars and of relatively large sunspots are roughly lie on the same power-law line. We also found that the frequency-energy distributions for superflares and solar flares from spots with different sizes are the same for solar-type stars and the Sun. These results suggest that the magnetic activity on solar-type stars and that on the Sun are caused by the same physical processes

Keywords. stars: flare, stars: spots

1. Introduction

Recent high-precision photometry by the Kepler mission found a large number of "superflares" on solar-type stars (e.g., Maehara *et al.* 2012). Most superflare stars show quasi-periodic brightness modulations caused by the rotation of the star with starspots (e.g., Notsu *et al.* 2013). According to Shibata *et al.* (2013), the energy of the largest flares on the solar-type stars increases as the area of starspots estimated from the amplitude of the rotational modulations increases. They also found that the energy of the largest flares is comparable to ~ 10 % of the magnetic energy which can be stored near the spots. These results suggest that the existence of large starspots is a key factor to produce superflares. We analyzed the statistical properties of starspots on solar-type stars and their correlation with the flare activity by using the data from the *Kepler* (rotational variations: McQuillan *et al.* 2014; flares: Shibayama *et al.* 2013) combined with the stellar parameters updated by *Gaia* DR2 (Berger *et al.* 2018).

2. Starspots on solar-type stars

Assuming the empirical relation between temperatures of spot and photosphere (Berdyugina 2005), we estimated the area of starspots on the stars from the amplitude of brightness variations caused by the rotation (McQuillan *et al.* 2014) and radius of the stars (Berger *et al.* 2018). Figure 1 (a) shows the scatter plot of the area of starspots on solar-type stars (main sequence stars with $5600 < T_{\rm eff} < 6000$K) in units of micro solar hemispheres (MSH; 1 MSH$= 3 \times 10^{16}$ cm^2) as a function of the rotation period. Small dots indicate solar-type stars in the Kepler field and open squares indicate solar-type stars showing superflares with the energy of 10^{33} erg. In the case of solar-type stars with $P_{\rm rot} > 13$ days, the area of the largest starspots rapidly decreases as the rotation period increases. On the other hand, the largest starspots area among the stars with $P_{\rm rot} < 13$

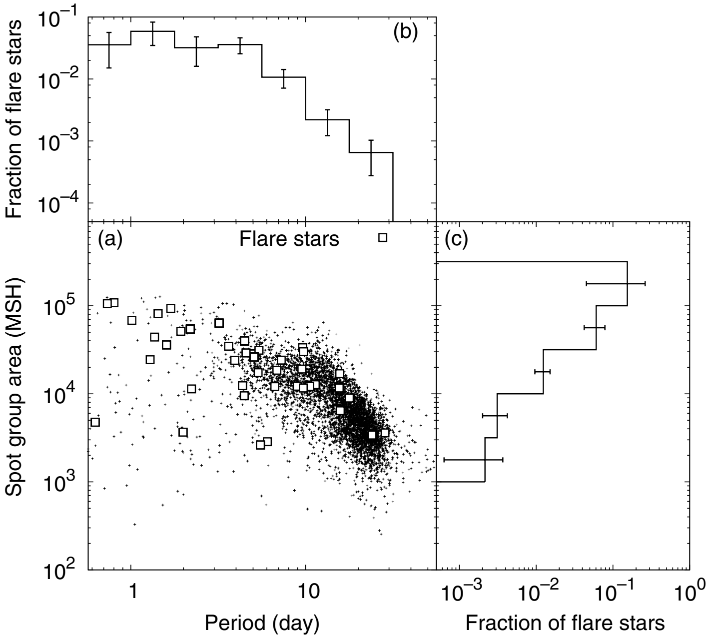

Figure 1. (a) Scatter plot of the area of starspots as a function of rotation period. (b) Fraction of flare stars as a function of rotation period. (c) Fraction of flare stars as a function of the area of starspots.

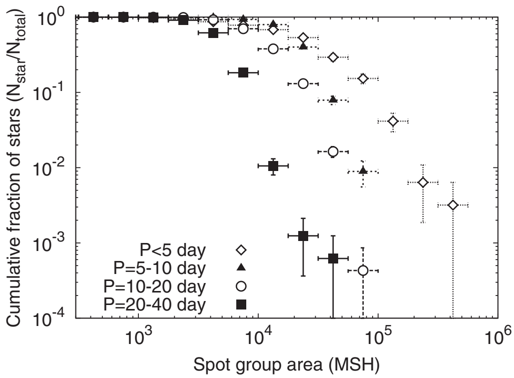

Figure 2. Cumulative fraction of stars as a function of the area of starspots.

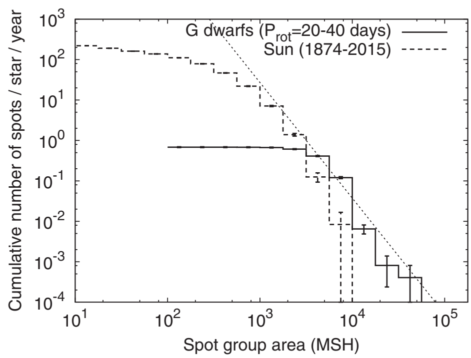

Figure 3. Size distributions of starspots and sunspots.

days is roughly constant ($\sim 5 \times 10^4$-1×10^5 MSH)). Figure 1 (b) and (c) show the fraction of flare stars as a function of rotation period and starspot area respectively. The fraction of flare stars decreases as the rotation period increases ($P_{\rm rot} > 3$ days) and as the area of starspots decreases.

Figure 2 shows the cumulative fraction of stars as a function of the starspot area for the stars with different rotation periods. The fraction of the stars with a given starspot area increases as the rotation period decreases. This suggests that rapidly-rotating stars can produce large starspots more frequently than slowly-rotating stars like our Sun.

We compared the size distribution of large starspot groups on slowly-rotating ($P_{\rm rot} > 20$ days) solar-type stars with that of sunspot groups observed during recent 140 years. The size distribution of starspots shows the power-law distribution and the size distribution

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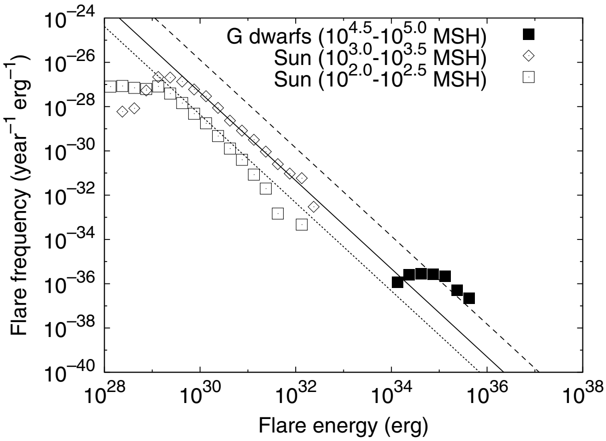

Figure 4. Comparison between occurrence frequency distribution of superflares from the solar-type stars with the starspot area of $10^{4.5}$-$10^{5.5}$ MSH and those of solar flares from the sunspot with the area of $10^{2.0}$-$10^{2.5}$ and $10^{3.0}$-$10^{3.5}$ MSH, respectively.

of relatively large sunspots lies on this power-law line (Figure 3). This result implies that the large starspots with the area of $\sim 1 \times 10^4$ MSH could appear once in a few hundred years on the slowly-rotating solar-type stars like our Sun.

3. Correlation between the area of spots and flare activity

Figure 4 shows the comparison between the occurrence frequency distribution of superflares and solar flares originating from the different spot sizes. The solid line is the power-law fit to the occurrence frequency distribution of solar flares from the sunspots with the area of $10^{3.0}$-$10^{3.5}$ MSH (power-law index: -1.99 ± 0.05). Dashed and dotted lines indicate power-law distribution with the same power-law index but 30 times and 1/10 of the occurrence frequency of the solid line. The frequency distributions of superflares from the stars with the spot area of $10^{4.5}$-$10^{5.5}$ MSH and solar flares from the sunspot with the area of $10^{2.0}$-$10^{2.5}$ MSH are roughly on the dotted and dashed lines respectively. This suggests that the frequency of flare with a given energy is roughly proportional to the spot area.

4. Summary

We analyzed the statistical properties of starspots and their correlation with the activity level of flares. Our analysis suggest that the area of the largest starspots on solar-type stars rapidly decreases as the rotation period increases for slowly-rotating solar-type stars ($P_{\rm rot} > 13$ days). We found the size distribution of starspots on solar-type stars with $P_{\rm rot} = 20$-40 days and that of relatively large sunspots lie on the same power-law line. We also found that the occurrence frequency distributions for flares originating from spots with different sizes are roughly the same for solar-type stars and the Sun. These results suggest that the magnetic activity on solar-type stars with superflares and that on the Sun are caused by the same physical processes (for more details, refer to Maehara *et al.* 2017).

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