Active solar-type stars show large quasi-periodic brightness variations caused by stellar rotation with star spots, and the amplitude changes as the spots emerge and decay. The *Kepler* data are suitable for investigations of the emergence and decay processes of star spots, which are important to understand the underlying stellar dynamo and stellar flares. In this study, we measured the temporal evolution of the star-spot area with *Kepler* data by tracing the local minima of the light curves. In this analysis, we extracted the temporal evolution of star spots showing clear emergence and decay without being disturbed by stellar differential rotation. We applied this method to 5356 active solar-type stars observed by *Kepler* and obtained temporal evolution of 56 individual star spots. We calculated the lifetimes and emergence/decay rates of the star spots from the obtained temporal evolution of the spot area. As a result, we found that the lifetimes ($T$) of star spots range from 10 to 350 days when the spot areas ($A$) are $0.1\%-2.3\%$ of the solar hemisphere. We also compared them with sunspot lifetimes and found that the lifetimes of solar spots are much shorter than those extrapolated from an empirical relation of sunspots ($T \propto A$), while being consistent with other research on star-spot lifetimes. The emergence and decay rates of star spots are typically $5 \times 10^{20} \text{Mx hr}^{-1}$ (8 MSH hr$^{-1}$) with an area of $0.1\%-2.3\%$ of the solar hemisphere and mostly consistent with those expected from sunspots, which may indicate the same underlying processes.

**Key words:** stars: activity – starspots – stars: solar-type – sunspots

**Supporting material:** figure set, machine-readable table

1. Introduction

Recent studies have shown that flaring activity and spot generation are seen not only on the Sun but also on other solar-type stars (G-type main-sequence stars). These phenomena may share common underlying mechanisms that therefore bridge the solar and stellar physics communities. Interestingly, some of the solar-type stars show extremely high magnetic activity that is not expected from the 150 yr solar observations (Cliver & Dietrich 2013; Hathaway 2015). They possess gigantic spots with areas of 10,000–100,000 millions of a solar hemisphere (MSH, $10^6\text{ MSH} = 2\pi R_\odot^2 = 3.1 \times 10^{22}\text{ cm}^2$; Maehara et al. 2017), which is by far larger than the largest sunspot (6132 MSH; Aulanier et al. 2013; Hayakawa et al. 2017; Toriumi et al. 2017), and they sometimes show extraordinarily large flares called superflares ($10^{34-36}\text{ erg}$; Maehara et al. 2012; Shibayama et al. 2013). It is indicated that superflares occur by the same process as solar flares, i.e., through magnetic reconnection (Notsu et al. 2013; Maehara et al. 2015; Karoff et al. 2016; Namekata et al. 2017). However, little is known about the process to generate the magnetic fields of the spots. Since the spots are visible proxies of the magnetic field on the stellar surface (e.g., Brun & Browning 2017), observations of the spot properties may provide a clue to the universal understanding of the solar and stellar dynamo (e.g., Shibata et al. 2013).

In the case of sunspots, the magnetic fluxes are generally thought to emerge from the deep convection zone to the solar surface thanks to magnetic buoyancy and convection (e.g., Parker 1955; Cheung & Isobe 2014) and decay as soon as (even before) the sunspots are completely formed (McIntosh 1981). As for the decay process, granular motion can be a possible mechanism, though other processes, such as surface flows (moat/Evershed flows; e.g., Kubo et al. 2008) and subsurface convection and reconnection (Schrijver & Title 1999), can also contribute to spot decay. It typically takes hours to days for sunspot formation (<5 days; Harvey & Zwaan 1993), while spot decay takes longer, typically weeks to months (Hathaway & Choudhary 2008). Since the decay phase is longer than the emerging phase, sunspot lifetimes have been discussed with regard to the decay mechanism. Spot decay rates ($dA/dt$) as a function of spot area ($A$) have been best discussed so far. There are two models, a linear decay law ($dA/dt \propto A$; Bumba 1963) and a parabolic decay law ($dA/dt \propto A^{1/2}$; Martinez Pillet et al. 1993). In the former case, a relation between the lifetime ($T$) and spot area ($A$) can be formulated into $T \propto A$, which is called the “Gnevyshev–Waldemeier” (GW) law (Gnevyshev 1938; Waldmeier 1955). In the latter case, the lifetime–area relation can be expressed as $T \propto A^{1/2}$ (Martinez Pillet et al. 1993), while $T \propto A$ can also be derived by considering the maximum size dependency (Petrovay & van Driel-Gesztelyi 1997). Observationally, the lifetimes of sunspot groups are roughly consistent with the GW law, though a large scattering around the GW law can be seen (e.g., Henwood et al. 2010).
Star spots are also universally observed on various kinds of stars, including solar-type stars (see Berdyugina 2005 for review). Stars having large spots show large quasi-periodic brightness variations caused by stellar rotation (Notsu et al. 2015; Karoff et al. 2016), which helps us investigate the star-spot properties. Although the temporal evolution of star spots can be a clue to the understanding of the supply and dissipation of the magnetic field on the stellar surface, they have not been extensively investigated due to difficulty in observation. However, investigations of the temporal evolution of star spots may exert a huge impact on a variety of research fields for several reasons. (1) It can be a tool to understand how the superflares are triggered and enable us to estimate how long surrounding planets are exposed to the danger of flares and coronal mass ejections (e.g., Takahashi et al. 2016; Lingam & Loeb 2017). (2) Estimating the diffusion coefficient of the stellar surface would be helpful for numerical modeling of the stellar dynamo. (3) It can provide a constraint for the light-curve modeling calculations to reconstruct surface intensity distributions, which are helpful for detections of exoplanet transits (Giles et al. 2017).

In the 1990s, several researchers reported the lifetimes of star spots on active young stars, cool stars (mainly M- and K-type stars), and RS CVn-type stars (close binary stars) on the basis of ground-based observations (e.g., Hall & Henry 1994; Strassmeier et al. 1994; Henry et al. 1995). They indicated that the lifetimes of star spots linearly increase with the spot area in the domain of small spots, while they decrease in the domain of large spots, possibly because of differential rotation (Henry et al. 1995). For the huge spots, the estimated lifetimes are quite long and sometimes exceed 2 yr (Strassmeier et al. 1994). Furthermore, the development of Doppler imaging techniques surprisingly revealed that active young stars have large polar spots that have persisted for more than a decade (Strassmeier et al. 1999; Carroll et al. 2012). More recently, light-curve modeling has been carried out by many authors (see Strassmeier 2009 for review), and inversion modeling has been developed (Savanov & Strassmeier 2008), which may reveal the spot temporal evolution, although there may be more or less degeneracy in inversions.

In 2009, the Kepler satellite was launched to observe a huge number of long-term stellar light curves (∼4 yr), and the high-sensitivity observations have enabled us to research the temporal evolution of star spots on solar-type stars using several methods. Fröhlich et al. (2012) performed light-curve modeling to reconstruct the spot evolution of two solar-type stars, though their applications have been limited to short observational periods (∼130 days), which does not clearly cover the whole spot lifetimes. Bradshaw & Hartigan (2014) and Davenport (2015) estimated the lifetimes and areas of star spots on solar-type stars on the basis of the surface distributions reconstructed by the stellar brightness variation during exoplanet transits. They showed that star spots with areas of 10,000–100,000 MSH have much shorter lifetimes (∼10–200 days) than those expected from the solar GW relation (1000–10,000 days). More recently, Giles et al. (2017) developed a method to derive an indicator to characterize the star-spot lifetime on solar-type stars by applying the autocorrelation function to the Kepler light curves. Although this is only a proxy of the typical spot decay time of the star, it enables a statistical study of large samples and, interestingly, shows a trend similar to that in Davenport (2015). What we still need to do for revealing the universal star-spot physics are (1) more statistical analyses of the detailed temporal evolution of individual star spots and (2) comparison with sunspots whose properties are well known.

In this study, we develop a method to measure the temporal evolution of star spots on solar-type stars by tracing the local minima of the Kepler light curves. This enables us to estimate not only the lifetime–area relation but also the emergence and decay rates of star spots. In Section 2, we introduce our sample selection, method, and detection criteria. We also describe how to calculate lifetimes, areas, and emergence and decay rates. In Section 3, we show several results of our analysis and comparisons with the solar data. Finally, we discuss the results in Section 4.

2. Data and Analysis Method

2.1. Sample Selection

It is expected that the spot emergence, decay, and dynamo mechanism are all closely related to the stellar surface temperature and gravity (e.g., Kippenhahn & Weigert 1990). In order to assess the diversity and similarity of the star spots by comparing them with the sunspots, we here selected solar-type stars (G-type main-sequence stars) as target stars from the Kepler data set on the basis of the stellar effective temperature ($T_{\text{eff}}$) and surface gravity (log g) listed in the Kepler Input Catalog (Kepler Data Release 25 Notes; Thompson et al. 2016). In this study, we defined solar-type stars with a criterion of $5000 \text{ K} < T_{\text{eff}} < 6000 \text{ K}$ and log $g > 4.0$. For each star, we used all of the available Kepler pre-search data conditioning long-cadence (30 minutes) data (Kepler Data Release 25; Thompson et al. 2016) in which instrumental effects are removed.

The active stars show quasi-periodic variations due to stellar rotation with large, dark star spots, which form local minima in the light curves corresponding to times when the star spots are on the visible side of the stars. The brightness variation amplitude corresponds to the spot area compared to the stellar disk (e.g., Notsu et al. 2013, 2015). The idea of this study is that the temporal evolution of the star spots is measurable if we can trace the local minima in a time series, as introduced in the following section. In inactive stars, it is difficult to detect and trace the local minima because of the low signal-to-noise ratio. We therefore only selected stars showing high magnetic activity with an additional criterion: the amplitude of periodic variability taken from McQuillan et al. (2014) is above 1%. The 5356 active solar-type stars are finally selected as our target stars.

2.2. Detection and Tracing of Local Minima

We used a simple method similar to that of Hall & Henry (1994) to measure the temporal evolution of the star spots. In this method, each star spot can be identified by the repetition of the local minima over the rotational phases (see below Figure 1). The light curve of a rotating star with star spots shows several local minima when the spots are on the visible side (Figure 1(a)). The time separation of each local minimum corresponds to the rotational period. For example, if a star has two large star spots at separated longitudes, the light curve exhibits two local minima during one rotational period, and the separation of the two local minima gives the difference of the longitudes. This difference makes it possible to identify longitudinally separated star spots. In the time-phase diagram
of local minima (Figure 1(c)), an individual star spot is distinguishable as a common straight line (e.g., the gray line in Figure 1(c)). This is how the individual star spots are identified, and their temporal evolution is measured from the light curves (Figure 1(d)). This method is our basic idea to discuss the temporal evolution of star spots and has been applied to the ground-based observation of young stars, cool stars, and RS CVn stars (e.g., Henry et al. 1995).

However, this method contains a problem caused by the stellar differential rotation. If two spots are located at different latitudes, the time separation of two local minima changes in time because of the differential rotation (see, e.g., Strassmeier & Bopp 1992). The differential rotation finally combines the two local minima into one. This difficulty prevents us from tracing the whole time evolution of the identical star spots from appearance to disappearance. Therefore, this method cannot distinguish whether the spot disappears or combines with other spots at the same longitude. Moreover, changes in the relative longitudes of the spots lead to changes in the depths of local minima, which makes it difficult to estimate the variation rates of the spot area (see Notsu et al. 2013).

To overcome these difficulties, we introduce the following conditions: we focus on light curves that have a pair of spots (1) rotating with a common period and (2) located on the reverse rotational phase (i.e., a longitude separation of the two spots of approximately 180°). As for the pair of spots satisfying condition (1), the absolute values of the spot latitudes are considered the same. When a light curve satisfies conditions (1) and (2), the local minima can be traced without being disturbed by the differential rotation, as well as brightness variation, of the other spots. Although this method can contain some selection biases, the simplicity enables an application to a huge amount of the Kepler data set.

Based on the above idea, we developed an algorithm to automatically detect such star spots as follows. First, we derived rotational periods by the discrete Fourier transform of the whole light curves. We selected stars with rotational periods of more than 1 day and less than 30 days because too rapid or slow rotation complicates tracing the local minima for a long time. Investigating a dependence of rotational periods on lifetimes is not our main purpose in this paper, though it should be investigated in our future works. Next, we obtained the smoothed light curve by using locally weighted polynomial regression fitting (LOWESSFIT; Cleveland 1979) to remove the flare signature and noise. In the LOWESSFIT algorithm, a low-degree polynomial is fitted to the data subset by using weighted least-squares, where more weight is given to the nearby points. We used the lowess function incorporated to the

Figure 1. An example of the temporal evolution of one star spot successfully measured in this study. (a) The background black line is the observed Kepler light curve, and the red line is the fitted one. Vertical gray lines correspond to the observational gaps longer than 5 hr. Filled circles are the local minima of a detected spot candidate, and open circles are the local minima of another spot. (b) Residual errors between the original Kepler light curve and the fitted one. (c) Phase-time diagram, where the vertical axis corresponds to phases of the local minima detected in the upper panels compared to the rotational period (see Carrington longitude). Symbols are the same as above. Open circles correspond to other spot candidates, but they are not included in our catalog because their temporal evolution is not well measurable. (d) Temporal evolution of the depth of the local minima from the nearby local maxima of the spot candidates that we focus on. The filled triangle is the local minima near the observational gaps. The open triangles indicate the upper limit of the brightness variation before the spot emerges and after the spot disappears. The black solid lines are the fitted lines of the emergence and decay phase (for data unaffected by data gaps), and the dashed lines are the same as the solid ones but fitted only for the black circles. Figures for the other 55 spot candidates are available in the online version of the Journal.

(The complete figure set (56 images) is available.)
R package. The fitting passbands were selected to be $4 \times P_{\text{rot}}$ to avoid over- and undersmoothing. We detected the local minima as downward convex points of the smoothed light curve; i.e., the smoothed stellar fluxes $F(t)$ satisfy $F(t_{(n-m)}) < F(t_{(n-m-1)})$ and $F(t_{(n+m)}) < F(t_{(n+m+1)})$. Here $m$ takes a value of $\{0, 1, 2\}$, $t$ is time, and $n$ is time step. [A] We start to trace them from an arbitrary local minimum ($T_0$), and at first, we search another local minimum whose time is between $T_0 + 0.8 \times P_{\text{rot}}$ and $T_0 + 1.2 \times P_{\text{rot}}$ (see Figure 2 for visual explanations of the procedure ([A]–[E])). This range was determined to be able to cover the range of the solar-like differential rotation ($\Delta P/P_{\text{rot}} \sim 0.2$). In case we find the next local minimum, we identify it as a next one ($T_1$). If we successfully trace more than three local minima in the same manner, we identify them as a single spot candidate and continue the tracking. [B] After $T_2$, we decide to search the next local minimum as time in between $T_2 + 0.9 \times P_{\text{spot}}$ and $T_2 + 1.1 \times P_{\text{spot}}$, where $P_{\text{spot}}$ is the rotational period of the spot candidate that is obtained in step [A]. [C] In case there are some observational data gaps, our algorithm is designed to be able to search a next local minimum until three rotational periods ahead. The algorithm also searches the local minima before the start point ($T_0$) in the same manner. If there is no local minimum in the next rotational phase, the algorithm stops the trace and switches to the next starting point ($T_0$).

After searching the spot candidates in a given star, the dubious candidates are automatically removed in the following procedure. [D] First, for a given spot candidate, if there are other local minima within $\pm 0.35 \times P_{\text{rot}}$ of each $T_n$ ($n = 0 \sim N$, where $N + 1$ is the total number of local minima of the spot candidate), we remove the candidate because the spot area can be largely affected by the other spots. [E] Second, we extrapolate the “virtual” local minima for three periods ahead and behind ($T_{-3,-2,-1} = T_0 - m \times P_{\text{rot}}$, $T_{N+1,N+2,N+3} = T_N + m \times P_{\text{rot}}$, where $m$ is 1, 2, 3). If there are other local minima within $\pm 0.3 \times P_{\text{rot}}$ of each “virtual” local minimum, we also remove the candidate because the spot can still survive and combine with the other spot in longitude which is originally located at the different longitude. The values of 0.35 and 0.3 are the longitude separation over which we regard a pair of spots located on the reverse phase (i.e., longitude separation $>126^\circ$, $108^\circ$) and were determined based on the number of missed detections. If the values become smaller, the contamination and merging of other spots would not be negligible. Lastly, we measure the local depth of the local minima from the near local maxima as an indicator of spot area. To investigate the nature of a single star spot, as well as to remove the beating spot candidate, we also remove the spot candidates whose local depth variations do not show clear emergence and decay phases. Here we simply use the $\chi^2$ test to judge whether or not it shows an emergence or decay phase.

We applied the above automatic detection method to the 5356 solar-like target stars observed by Kepler and obtained 147 spot candidates. Visually checking all of the light curves, phase-time diagrams of local minima, and temporal variations of local depth, we selected spot candidates that satisfy the following conditions. (1) The temporal variations show clear emergence and decay phases. We use a threshold that the first spot area $A(T_0)$ and final one $A(T_N)$ should be smaller than 70% of the maximum size ($A_{\text{max}}$), i.e., $A(T_0) < 0.7 \times A_{\text{max}}$ and $A(T_N) < 0.7 \times A_{\text{max}}$. See Section 2.3 for detailed definitions of the spot area $A(t)$. This threshold was determined to exclude the
Table 1
Physical Parameters of Star Spots and Host Stars

| No. | Kepler ID    | $T_{\text{eff}}$ (K) | log $g$ | $R_{\text{spot}}$ (R$_{\odot}$) | $P_{\text{rot}}$ (days) | $T$ (days) | $A_{\max}$ (10$^3$ MSH) | $\Phi_{\text{spot}}$ (10$^{20}$ Mx) | $d\theta_{\text{spot}}/dt$ (10$^{20}$ Mx hr$^{-1}$) |
|-----|-------------|----------------------|--------|-------------------------------|-------------------------|------------|-------------------------|-----------------------------------|----------------------------------|
| 1   | 10186360    | 5994                 | 4.48   | 0.92                          | 7.3                     | 73.7 ± 8.3 | 2.7$^{+0.9}_{-0.6}$     | 1.4$^{+0.8}_{-0.4}$               | 1.0$^{+1.0}_{-0.6}$               |
| 2   | 1032873S    | 5631                 | 4.48   | 2.07                          | 5.1                     | 63.9 ± 1.7 | 27.7$^{+1.2}_{-1.0}$    | 72.1$^{+2.1}_{-1.1}$              | 86.6$^{+7.4}_{-8.9}$              |
| 3   | 1073686S    | 5505                 | 4.44   | 1.16                          | 6.3                     | 57.2 ± 20.1| 9.1$^{+1.7}_{-1.5}$    | 7.5$^{+1.2}_{-1.1}$               | 9.1$^{+1.9}_{-2.8}$               |
| 4   | 10802309B   | 5403                 | 4.61   | 1.43                          | 2.0                     | 65.0 ± 21.7| 17.5$^{+4.1}_{-3.3}$   | 21.9$^{+9.4}_{-6.9}$              | 26.8$^{+14.4}_{-9.9}$             |
| 5   | 10818810    | 5869                 | 4.38   | 0.96                          | 6.0                     | 17.0 ± 5.1 | 3.6$^{+0.9}_{-0.6}$    | 2.0$^{+0.5}_{-0.4}$               | ...                              |
| 6   | 10936008    | 5271                 | 4.58   | 0.75                          | 9.3                     | 37.2 ± 18.5| 2.2$^{+0.7}_{-0.6}$    | 0.7$^{+0.3}_{-0.2}$               | ...                              |
| 7   | 10969615    | 5380                 | 4.50   | 0.95                          | 5.5                     | 58.6 ± 10.5| 4.9$^{+1.2}_{-0.9}$    | 2.7$^{+0.8}_{-0.6}$               | 5.5$^{+4.1}_{-2.5}$               |
| 8   | 11033729    | 5399                 | 4.59   | 0.74                          | 10.2                    | 244.4 ± 19.3| 4.8$^{+0.9}_{-0.7}$   | 1.6$^{+0.5}_{-0.4}$               | 0.3$^{+0.1}_{-0.0}$               |
| 9   | 11046341    | 5597                 | 4.39   | 0.84                          | 16.3                    | 111.1 ± 29.9| 6.3$^{+1.1}_{-1.0}$   | 2.7$^{+0.8}_{-0.7}$               | 1.6$^{+1.1}_{-1.0}$               |
| 10  | 11080702    | 5307                 | 4.58   | 0.88                          | 9.2                     | 86.7 ± 3.7 | 4.2$^{+0.5}_{-0.4}$    | 2.0$^{+0.4}_{-0.3}$               | 2.3$^{+1.0}_{-0.7}$               |
| 11  | 11137355    | 5397                 | 4.54   | 0.77                          | 15.1                    | 109.8 ± 19.4| 4.5$^{+1.1}_{-0.9}$   | 1.6$^{+0.5}_{-0.4}$               | 1.6$^{+1.3}_{-1.0}$               |
| 12  | 11200185    | 5272                 | 4.57   | 0.96                          | 4.4                     | 13.8 ± 0.6 | 2.2$^{+0.4}_{-0.3}$    | 1.2$^{+0.3}_{-0.2}$               | ...                              |
| 13  | 11244615    | 5199                 | 4.62   | 0.84                          | 1.6                     | 46.6 ± 1.9 | 3.2$^{+1.0}_{-0.8}$    | 1.4$^{+0.7}_{-0.5}$               | 1.6$^{+0.9}_{-1.0}$               |
| 14  | 11444615    | 5199                 | 4.62   | 0.84                          | 1.6                     | 26.5 ± 6.4 | 9.2$^{+3.2}_{-2.8}$    | 4.0$^{+1.7}_{-1.0}$               | 9.0$^{+5.2}_{-3.0}$               |
| 15  | 11520290    | 5406                 | 4.50   | 0.86                          | 1.3                     | 37.9 ± 10.5| 11.2$^{+3.6}_{-3.2}$  | 5.0$^{+1.7}_{-1.1}$               | 7.3$^{+6.2}_{-3.2}$               |
| 16  | 11520290    | 5406                 | 4.50   | 0.86                          | 1.3                     | 23.1 ± 2.2 | 4.8$^{+1.6}_{-1.2}$    | 2.2$^{+1.3}_{-1.0}$               | 5.3$^{+4.3}_{-2.3}$               |
| 17  | 11571518    | 5040                 | 4.69   | 0.93                          | 6.5                     | 48.9 ± 3.9 | 4.1$^{+1.6}_{-1.4}$    | 2.2$^{+1.3}_{-1.0}$               | 5.3$^{+4.3}_{-2.3}$               |
| 18  | 1166525     | 5440                 | 4.62   | 1.23                          | 5.2                     | 46.5 ± 1.6 | 7.9$^{+3.3}_{-2.9}$    | 7.3$^{+3.7}_{-2.9}$               | 9.8$^{+8.2}_{-5.0}$               |
| 19  |             |                      |        |                               |                         |            |                        |                                   |                                  |
| 20  | 9408373     | 5782                 | 4.49   | 0.91                          | 5.1                     | 31.7 ± 1.6 | 2.8$^{+0.7}_{-0.6}$    | 1.4$^{+0.7}_{-0.6}$               | 2.9$^{+2.4}_{-1.4}$               |
| 21  | 9579266     | 5164                 | 4.60   | 0.83                          | 10.6                    | 63.2 ± 10.0| 2.6$^{+0.7}_{-0.6}$    | 1.1$^{+0.7}_{-0.6}$               | ...                              |

Notes.

* Stellar effective temperature taken from the Kepler Input Catalog (Kepler Data Release 25 Notes; Thompson et al. 2016).
* Stellar surface gravity taken from the Kepler Input Catalog.
* Corrected stellar radii by Berger et al. (2018).
* Stellar rotational periods.
* Lifetimes of star spots.
* Maximum star-spot area and magnetic flux in units of MSH and Mx, respectively.
* Emergence and decay rates of star spots in units of Mx hr$^{-1}$.
* Subgiant or main-sequence binary candidates (Berger et al. 2018). The detailed classification can be seen in the online tables.

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

Maehara et al. (2012) and removed them with spline interpolation. After this process, we fit the long-period spot modulations by LOWESSFIT, where the fitting parameters are manually adjusted for each light curve. Then we redetected the local minima and traced them in the same manner. These redetected values are listed in Table 1.

2.3. Area Estimation

We estimated the area of the star spots based on the brightness depth of each local minimum ($\Delta F$) from the nearby local maximum. Deriving the spot area from the $\Delta F$ requires measurements of the spot temperature (e.g., Poe & Eaton 1985). However, since Kepler conducted single-bandpass observations, we cannot distinguish a decrease of the spot temperature from an increase of the spot area and vice versa. Here we used the following empirical relation of spot temperature as a function of stellar effective temperature. According to Maehara et al. (2017), the area ($A_{\text{spot}}$) can be derived as a function of the normalized amplitude ($\Delta F/F_{\text{star}}$), stellar effective temperature ($T_{\text{star}}$), and stellar radius ($R_{\text{star}}$):

$$A_{\text{spot}} = \left( \frac{R_{\text{star}}}{R_{\odot}} \right)^2 \frac{T_{\text{star}}^4}{4} \frac{\Delta F}{F_{\text{star}}}$$

---

5
\[
\Delta T(T_{\text{star}}) = T_{\text{star}} - T_{\text{spot}} = 3.58 \times 10^{-3}T_{\text{star}}^2 + 0.2497T_{\text{star}} - 808, \tag{2}
\]

where \( \Delta T \) is the temperature difference between the photosphere and spot derived based on Berdyugina (2005). The spot temperature is basically estimated by the Doppler imaging technique of several main-sequence stars. Since this relation is just an empirical one, the spot area can change if the actual spot temperature varies. However, the variation of the temperature by 500 K (1000 K) could vary the spot area by only 11% (23%). Therefore, our results would not be significantly affected by the assumption of temperature. Here the stellar effective temperature \( T \) is based on the Kepler Input Catalog (Kepler Data Release 25; Thompson et al. 2016). As for the stellar radius, we use the radius values updated by using the recent Gaia Data Release 2 (Berger et al. 2018; Lindegren et al. 2018).

Note that the estimated area can be somewhat underestimated due to inclination of the stellar rotational axes and contamination of brightness from other spots. The latter may be corrected by modeling the light curves, but we simply use the local depth of the light curves as an indicator of spot area. Moreover, the faculae on the stellar surface can also contribute to the over- and underestimation of the star-spot area. In Section 4.5, the uncertainties of those effects are clarified, while they are not incorporated into the estimations in this paper. In the Appendix, we simply evaluate the accuracy of the area estimation on the basis of the Sun-as-a-star analysis.

2.4. Lifetime Estimation

We measured the lifetimes \( (T_1) \) of the 56 star spots based on how long the local minima are detectable (i.e., \( T_1 - t \)). The lifetimes \( (T_1) \) can, however, be underestimated because the detectable limits of the amplitude can largely suffer from the noise and contamination of other spots. Therefore, we fitted the emergence and decay phases with linear relations (solid lines in Figure 1(d)) and estimated the lifetimes \( (T_2) \) from spot emergence to disappearance. In the following section, we define the lifetime \( (T) \) as \( (T_1 + T_2)/2 \), the lower limit as \( T_1 \), and the upper limit as \( T_2 \). Note that \( T_2 \) is not exactly the upper limit value but an extrapolated one by assuming the linear emergence and decay. As mentioned in the following, it may be better to fit by assuming parabolic decay. However, the decay phases do not necessarily show the clear parabolic decay curves, so we use this assumption.

2.5. Calculation of Emergence and Decay Rates of Star Spots

We estimated the emergence \( (d\Phi_{\text{e}}/dt) \) and decay \( (d\Phi_{\text{d}}/dt) \) rates of the star spots based on the variation rates of the star-spot area. The variation rates are considered to be better indices when comparing with sunspot properties because they are unaffected by the detectable limits of local minima, unlike the lifetimes. We derived the variation rates of the star-spot area (emerging rate \( d\Phi_{\text{e}}/dt \) and decay rate \( d\Phi_{\text{d}}/dt \)) by applying the linear-regression fitting method to spot area variations. Many papers have reported the variation rates of sunspots in units of \( \text{Mx} = \text{G cm}^2 \) (e.g., Norton et al. 2017). Taking this fact into account, we calculated the emergence and decay rates by assuming that the mean magnetic field of the star spots is 2000 G, considering the typical magnetic field strength of sunspots (Solanki 2003):

\[
\frac{d\Phi_{\text{e,d}}}{dt} = 2000 \times \frac{dA_{\text{e,d}}}{dt}. \tag{3}
\]

The error values are mainly estimated based on the errors of the fitted slopes, stellar effective temperature, and stellar radius.

3. Result

3.1. Temporal Evolution of Star Spots

Figure 1 shows an example of the temporal evolution of star spots in our catalog. Figure 1(a) shows a light curve, and the circles are the detected local minima. Figure 1(c) shows a phase-time diagram, where the vertical axis is the rotational phase of the detected local minima. The gray solid line is an individual spot component that we detected. Figure 1(d) shows the temporal evolution of the local depth of each local minima that corresponds to the star-spot area. As described in Section 2, we selected star spots showing clear emergence and decay, and such features can also be seen in Figure 1.

As a result of these analyses, the area of the detected star spots is 1500–23,000 MSH at the maximum, and the lifetime is 10–350 days (see Table 1). A lifetime of 1 yr is the longest ever observed for the solar-type stars (\( \lesssim 200 \) days in the previous studies; Bradshaw & Hartigan 2014; Davenport 2015; Giles et al. 2017). In the case of the sunspots, there is a notable asymmetry in the emergence and decay phases, as mentioned in Section 1. However, in the case of star spots, the averaged emergence rates, \( 6.6 \times 10^{20} \text{Mx hr}^{-1} \) (11 MSH hr\(^{-1}\)), are not so different from the averaged decay rates, \( 5.2 \times 10^{20} \text{Mx hr}^{-1} \) (8.5 MSH hr\(^{-1}\)). Interestingly, in several spots, the emergence phase is longer than the decay phase (see the figures in the online version of the Journal for details). There is a possibility that not only the area but also the lifetime can have some uncertainties caused by the data sensitivity and analytical method. The uncertainties are discussed in Section 4.5.

3.2. Star-spot Properties versus Stellar Properties

Figure 3 shows the stellar radius as a function of the effective temperature (i.e., the H-R diagram). Background black shading indicates the distributions of the Kepler stars, and colored symbols indicate our catalog. The vertical axis values are plotted with revised radii based on quite recent Gaia DR2 parallaxes provided by Berger et al. (2018). According to Berger et al. (2018), four of our “solar-type” stars are classified as subgiant stars or main-sequence binary stars (green triangles), and two are classified as main-sequence binary star candidates (blue diamonds), although they are solar-type stars according to the Kepler Input Catalog. In the following figures and discussions, we only focus on the temporal evolution of star spots on main-sequence stars.

Figure 4 shows a comparison between stellar effective temperature and lifetimes of star spots. There seems to be no clear temperature dependence even for a given spot size, although Giles et al. (2017) reported that cooler stars have spots that last much longer. This might be due to our small number of samples and range of temperature. We focus only on G stars, while they analyzed F, G, K, and M stars. In this paper, we do not discuss the relation between stellar effective temperature and star-spot properties because of a shortage of samples and range of stellar properties. Nevertheless, the dependence of temperature on lifetime is quite interesting to investigate the
role of differential rotation and convection in spot fragmentation. This dependence is subject to consideration in a future study.

Figure 5 shows a comparison between the rotational periods and lifetimes of star spots, and there looks to be a positive correlation. Please note that there is an undetectable region because our algorithm can detect spots whose lifetimes are longer than a couple of rotational periods.

3.3. Comparison with Sunspot I: Lifetime versus Maximum Area

Figure 6 shows a comparison between the maximum area and lifetime of the detected star spots on solar-type stars. The area is plotted in units of MSH (1 MSH = 10^6 \times 2\pi R_e^2). The size of each circle represents the stellar rotational period. Blue and red colors correspond to the spots with \( P_{\text{rot}} < 7 \text{ days} \) and \( P_{\text{rot}} > 7 \text{ days} \), respectively.

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Figure 7 shows a comparison between the maximum area and lifetime of sunspots and star spots on solar-type stars. Black and gray points are sunspot data taken from Petrovay & van Driel-Gesztelyi (1997) and Henwood et al. (2010), respectively. These sunspot data are basically measured by using the Debrecen Photoheliographic Results and Greenwich Photoheliographic Results, respectively. They are available in the databases recording day-to-day individual sunspot areas. Note that, since the identification of recurrent sunspots is based only on their longitude and latitude, the succeeding spot emergence in the decaying active regions can be identified as a single spot. For example, Kopecky (1984) reported long-lived sunspot groups surviving during eight solar rotations through use of the Greenwich Photoheliographic Results. The temporal development of the spot area, however, shows several peaks, which indicates successive episodes of spot emergence in the same region. Our main purpose is to reveal a star-spot physics from the basic sunspot physics, and the comparison with such sunspots with several emergences would lead to more complex discussions. Therefore, as for the data of Henwood et al. (2010), we have excluded the sunspots whose temporal...
evolution shows multiple growths for matching our star spots that have only simple emergence-decay patterns. The resulting lifetimes of sunspots are up to six solar rotational periods (~200 days), and the area is up to ~6000 MSH. The dashed line indicates the GW relation mentioned in Section 1 \( A = DT, \ D \sim 10 \ MSH \ day^{-1} \). In Figure 7, we also plot star spots on solar-type stars with red and blue filled circles for slowly \( (P_{\text{rot}} > 7 \) days) and rapidly \( (P_{\text{rot}} < 7 \) days) rotating stars, respectively. We found that the lifetimes of large star spots (10–350 days) are shorter than those expected from the GW relation (300–1000 days). This trend is similar to the results reported in the previous research. We plotted the star spots that were reported in Bradshaw & Hartigan (2014), Davenport (2015), and Giles et al. (2017). Note that the data of Giles et al. (2017) are given in units of brightness variation amplitude in their paper, so we plotted their G-type star data by assuming that all of the effective temperatures and radii are the same as the solar values. As a result, we found that our results are consistent with those of Giles et al. (2017) and partly similar to those of Bradshaw & Hartigan (2014). The spot areas of Davenport (2015) are much larger than our data, while the lifetimes are similar to our results.

3.4. Comparison with Sunspot II: Emergence Rate versus Maximum Flux

Figure 8 shows a comparison between the emergence rates and maximum fluxes of sunspots and star spots on solar-type stars. The solar values are based on the magnetogram observation carried out by Otsuji et al. (2011), Toriumi et al. (2014), and Norton et al. (2017). The gray dotted lines are the 95% confidence intervals of the sunspot observational data. As a result of comparison, 76% of the star spots are consistently included inside the extrapolated 95% confidence intervals of sunspots. Particularly, the emergence rates of star spots are consistent with an empirical line \( (d\Phi_e/dt \propto \Phi^{0.5}) \) derived by Norton et al. (2017). The standard deviations of the differences between the star-spot observations and the empirical line are \( 7.1 \times 10^{20} \text{ Mx hr}^{-1} \). On the other hand, they are mostly smaller than those expected from a simple theoretical line \( (d\Phi_e/dt \propto \Phi^{1.5}) \) derived by Otsuji et al. (2011). The standard deviations of the differences between the star-spot observations and the theoretical line are \( 9.5 \times 10^{20} \text{ Mx hr}^{-1} \). Moreover, the emergence rate of the star spots looks to be dependent on the stellar rotational period dependence. The star spots on slowly rotating stars show relatively small values, which is similar to the case of the lifetimes of star spots.

3.5. Comparison with Sunspot III: Decay Rate versus Maximum Flux

Figure 9 shows a comparison between the decay rates and maximum fluxes of sunspots and star spots on solar-type stars. The black points are based on the visible sunspot observations (Petrovay & van Driel-Gesztelyi 1997; Hathaway & Choudhary 2008), while the green points are based on the magnetogram observations (Kubo et al. 2008; Norton et al. 2017). The gray dotted lines are the 95% confidence intervals of the sunspot observational data of Hathaway & Choudhary (2008). The order of the confidence intervals is about one order of magnitude, which is roughly the same as those of the emergence rates. As a result, the decay rates of star spots are also consistent with those of sunspots, while some parts are smaller than those expected from the sunspot distributions. Included inside the extrapolated 95% confidence intervals of the sunspot data of Hathaway & Choudhary (2008) are 89% of the star spots. The decay rates, including simulations, are roughly on the same lines (solid line in Figure 9; \( d\Phi_d/dt \propto \Phi^{0.5} \)) over a wide range of magnetic flux.
(10^{21}-10^{24} \text{ Mx}, 20-20,000 \text{ MSH}). A rotational period dependence can also be seen in the case of decay rates.

4. Discussion

4.1. Emergence of Star Spots

We showed that the emergence and decay rates of star spots as a function of maximum fluxes are mostly consistent with those extrapolated from the sunspot observations. This may suggest that the temporal evolution of sunspots and star spots can be universally explained by the same underlying physical processes. As for the emergence, we found that the emergence rates of star spots favor the empirical relation \(d\Phi_e/dt \propto \Phi^{0.3}\) (Norton et al. 2017) but are smaller than those expected from the theoretical scaling relation \(d\Phi_e/dt \propto \Phi^{0.5}\) (Otsuji et al. 2011).

Otsuji et al. (2011) derived the simple theoretical scaling law \(d\Phi_e/dt \propto \Phi^{0.5}\) by assuming that (1) the emerging flux is self-similar in its size \((\Phi_e \propto w h \propto w^2, \text{where } w \text{ is horizontal and } h \text{ is the vertical length of its cross section})\) and (2) the rise velocity \(\dot{v}\) is independent of its size \((d\Phi_e/dt \propto \dot{v} w \propto w)\). In spite of these rough assumptions, the scaling law agrees with their own observational data.

If we discuss the results on the basis of the theoretical scaling law \((d\Phi_e/dt \propto \Phi^{0.5})\), there is a possibility that the emergence rates of star spots are suppressed to lower values for some reason. One explanation for the lower values is that the observed large star spots \((\sim 3 \times 10^{23} \text{ Mx}, \sim 5000 \text{ MSH})\) can be conglomerates of relatively smaller sunspot-scale spots (e.g., \(\sim 10^{-22} \text{ Mx}, \sim 160 \text{ MSH}\)). If the large star spots are conglomerates of smaller spots, and the smaller spots emerge successively, the smaller emergence rates can be understood by extrapolating the emergence rates of sunspots.

On the other hand, from the standpoint of the solar empirical relation \((d\Phi_e/dt \propto \Phi^{0.3})\), Norton et al. (2017), some corrections of Otsuji’s scaling law are necessary to theoretically understand the small-power-law index. For example, if the emerging velocity has a negative dependence on the total flux (i.e., \(\dot{v} \propto \Phi^a, a < 0\)), the empirical relation could be theoretically explained. One explanation for the negative dependence is that the flux emergence could be suppressed to some extent if the surfaces are already filled with relatively strong magnetic fields. As another hypothesis, since the emergence of a weak flux tube can be affected by convective motions (Weber et al. 2011), the emergence velocity of the small weak flux becomes faster if the field strengths have a positive relation to the total fluxes.

As discussed above, the flux emergence process can be universally explained over a wide range of spot sizes, including sunspots and star spots \((10^{18-24} \text{ Mx}, 0.02-20,000 \text{ MSH})\), although the detailed understanding is not enough. It should be noted that our results may contain some uncertainties, and they can be updated by further studies. The emergence process of sunspots inside the convection zone is not well understood observationally even by local helioseismology. Although a comparison with numerical simulations can help us interpret the observations (e.g., Rempel & Cheung 2014), realistic ones with deep convection zones have not been done. More research on spot emergence by sunspot observations and simulations is necessary.

4.2. Decay of Star Spots

Our results show that the decay rates of star spots are consistent with those of sunspots, and the sunspot distributions \((d\Phi_d/dt \propto \Phi^{-0.19})\) almost correspond to the parabolic decay law \((d\Phi_d/dt \propto \Phi^{-0.5}; \text{Martinez Pillet et al.} 1993)\). This may suggest that sunspots and star spots are universally explained by the parabolic decay model, where spots decay by the erosion of the spot boundaries.

It should be noted here that Petrovay & van Driel-Gesztelyi (1997) suggested a corrected parabolic decay law in the form of \(dA/dt \propto (A/A_{\text{max}})^{0.5}\). This may not match our data because the theory predicts that \(dA/dt|_{A=A_{\text{max}}} = \text{a constant value independent of the spot size}\).

On the other hand, if we want to justify the linear decay theory \((dA/dt \propto \text{constant})\), some excuses may be necessary. In this case, decay rates should be, possibly apparently, enhanced only for large spots to explain the observations. Possible interpretations can be explained as follows. (1) The decay rates of large spots are apparently enhanced because large sunspots can consist of many small sunspots (e.g., Hathaway & Choudhary 2008) or different active regions on opposite latitudes. In addition, many large sunspots are classified into complex shapes, which can enhance flux cancellations (Martinez Pillet et al. 1993), although surface flux transport simulations are unsupportive of this (Ishik et al. 2007). (2) Stellar differential rotation can also contribute to the high decay rate of large spots (Hall & Henry 1994). Ishik et al. (2007) also showed that differential rotation can accelerate flux cancellations depending on the tilt angle of the dipole. (3) Bradshaw & Hartigan (2014)
tried to explain the high magnetic diffusivity on the stellar surface by assuming that supergranular scales determine the decay timescales, though the roles of supergranules are not well understood.

Recent MHD numerical simulations can give us more insight into star-spot decay. Rempel & Cheung (2014) performed three-dimensional numerical simulations of spot emergence and decay. The decay rate obtained by their simulations is plotted in Figure 9. In the first decay phase in their simulations, the dispersal of flux is mainly due to downward vertical convection motion. In the late phase, intrusions of plasma play a significant role in spot decay. However, the numerical box is limited only for the surface of the convection zone, and the subsurface morphology is little known observationally (Rempel & Schlichenmaier 2011). Further development of numerical simulations, including a deep convection zone, may reveal the spot decay mechanism.

Use of the Doppler imaging technique can let us measure the temporal evolution of star spots as well. The decay rate of the red giant star XX Triangulum was estimated to be $-5.6 \times 10^{-2} \text{Mx hr}^{-1}$ ($-920 \text{MSH} \text{hr}^{-1}$) with an area of $1.2-6.2 \times 10^{26} \text{Mx} (2-10 \times 10^8 \text{MSH})$, according to the Doppler imaging method (Künster et al. 2015). The decay rate is surprisingly consistent with the parabolic decay relation in our paper (Figure 9), although its surface effective temperature (4620 K) and gravity ($\log g = 2.82$) are quite different from those of solar-type stars. Red giant stars or cooler stars will be subjected to consideration in our next paper, as these stars are currently beyond the scope of this paper.

This is incipient research on the temporal evolution of unresolved star spots. Further development in sunspot and star-spot observations, as well as numerical simulations, is required for an understanding of the decay process of star spots.

4.3. Lifetime of Star Spots

Historically, spot evolution has been discussed in terms of lifetimes, and the simple GW law ($T \propto A$) has been used in the solar community (see Section 1). In contrast, the lifetimes (10–350 days) of star spots on solar-type stars are much shorter than those extrapolated from the GW relation (300–1000 days).

If we assume that the emergence and decay rates are independent of the (total) spot fluxes ($d\Phi_{e,d}/dt = \text{constant}$), spot lifetimes naturally follow the GW law (Meyer et al. 1974), which is inconsistent with star-spot data. However, as discussed in Sections 4.1 and 4.2, the emergence and decay rates clearly depend on the spot area across wide ranges of total fluxes ($d\Phi_{e,d}/dt \propto A^{0.3-0.5}$). This dependence of variation rates on maximum sizes would be one reason why the lifetimes of star spots are much less than those expected from the GW law. In this case, the relation between lifetimes and area can be expressed as $T \propto A^{0.5-0.7}$. We discuss detection limits and method dependence on star-spot lifetimes in Section 4.5.

Interestingly, ground-based observations have revealed that HR 7275, an RS CVn-type K1 III–IV star, has spots with much longer lifetimes (\sim 2.2 yr, on average; Strassmeier et al. 1994), although the spot areas are also huge. Moreover, cooler stars are reported to have longer lifetimes (Giles et al. 2017). The differences in lifetimes can reveal the role of surface convection in spot decay. Moreover, in the rapidly rotating young star V410 Tau, a large spot near the pole has persisted for at least 20 yr (Carroll et al. 2012), and the FK Comae giant HD 199178 has a polard spot whose lifetime is more than 12 yr (Strassmeier et al. 1999). These properties of polar spots can be different from the solar-like spots at lower latitude. The comparison between different types of stars is beyond the scope of this paper but will be addressed in future.

4.4. Rotational Period Dependence

Since the rotational period is a good indicator of stellar ages, the dependence on temporal evolution can be a hint about the understanding of the evolution of the stellar dynamo. As in Section 3, the star spots on rapidly rotating stars tend to show more rapid emergence and decay compared to the spots on slowly rotating ones. The rapid decay can be explained by the stellar differential rotation because rapidly rotating stars are thought to have a strong differential rotation (e.g., Hotta & Yokoyama 2011; Balona & Abedigamba 2016). Here we only selected star-spot pairs whose relative longitudes are considered to be unaffected by the stellar differential rotation. Since the rotational periods of the pairs are not completely the same, there is a possibility that the strong surface differential rotation on rapidly rotating stars makes it difficult to trace the local minima for a long time, which can result in short lifetimes in rapidly rotating stars. On the other hand, according to Giles et al. (2017), there is no clear dependence on rotational period on the decay timescale of star spots. However, they analyzed only the relatively slowly rotating stars (10 and 20 days), and the application to the more rapidly rotating stars has not yet been done. The detailed dependence of rotational periods should be researched in future.

4.5. Uncertainties on the Measurements of Lifetime and Area

Let us summarize here the uncertainties and biases of the results that can be caused by our method. First, we do not correct the star-spot area for the stellar inclination angles. The star-spot area, as well as the variation rates, can be somewhat underestimated if the stellar inclination angles ($\sin i$) are small (Notsu et al. 2015) or the spots are located on the high latitude. Under the assumption of the random orientation of rotational axes, the average inclination angle ($i$) can be derived as 1 rad. If we assume this typical inclination angle, the stellar inclination reduces the statistical value of the star-spot area by \sim 30% for the Sun-like star-spot distribution (latitude \sim 10\degree–30\degree; Solanki 2003).

Second, the determination of the unspotted brightness levels of the stars is subject to difficulty, affected by the existence of faculae and large polar spots and the inevitable Kepler’s long-term observational trend. However, we calculate the spot area from the brightness differences from the local maxima and minima. These are the relative values and less affected by the zero levels. Even if the stellar unspotted level becomes brighter by 1\% (e.g., solar faculae; Solanki et al. 2013), the spot size can decrease by only a few percent. Likewise, we ignore the contributions of stellar faculae to the stellar brightness variations because the distributions and filling factors are not well known. If the faculae are localized in a single hemisphere, and the brightness contributions of the faculae are comparable to those of spots, the spot area can be both over- and underestimated to some extent.
Third, since we used the local depth as the spot area, contamination of other spots is not corrected in this analysis. This also contributes the uncertainties of the estimation of spot area. To avoid this effect, light-curve modeling with several star spots would be necessary for more detailed analyses.

Moreover, it should be noted here that lifetimes can have some uncertainties due to observational and analytical problems. The star spots become difficult to detect as the spot area decreases, depending on the photometric errors and analysis methods, which leads to underestimation of the spot lifetimes. Although we extrapolated the lifetimes by assuming linear emergence and decay, it is just an assumption. In addition, there can be a selection bias that long-lived spots with lifetimes of \( \geq 1000 \) days can be missed because the \textit{Kepler} observational period is limited to only \( \sim 4 \) yr. In this case, the emergence and decay rates can be smaller than our results.

Bradshaw & Hartigan (2014) and Davenport (2015) reported the lifetime of star spots by using exoplanet transits, and their results are somewhat different from our results. Their methods have the advantage that they can spatially resolve the stellar surface, and their lifetime and star-spot area may more clearly represent the single star-spot properties. Note that the estimated area is different by a factor of \( 3 \) between the results of Bradshaw & Hartigan (2014) and Davenport (2015), though they analyze the same star (Kepler-17).

5. Summary and Conclusion

Many solar-type stars show extraordinarily high magnetic activity, which cannot be expected from the solar observations, such as spot activity and superflares. The large star spots are considered to be a key to understanding the superflare events, as well as the underlying stellar dynamo. The subject of this study is to investigate the emergence and decay processes of large star spots on solar-type stars by comparing them with well-known sunspot properties. We have developed a method to measure the temporal evolution of single star spots by tracing the local minima of visible continuum brightness variations. By applying this method to a huge amount of \textit{Kepler} data, we have successfully detected the temporal evolution of star spots showing clear emergence and decay phases.

We mainly obtained the following three results: (i) the emergence rates of star spots are consistent with those extrapolated from sunspots \((d\Phi_e/\text{d}t \propto \Phi^{0.3-0.5})\) under the assumption of spot magnetic field strengths of 2000 G; (ii) the decay rates of star spots are consistent with those extrapolated from sunspots \((d\Phi_d/\text{d}t \propto \Phi^{-0.5})\), which might be understood as erosion from the edge; and (iii) the lifetimes of star spots are much shorter than those extrapolated from the empirical GW relation of sunspots \((T \propto A)\), though the lifetimes are up to 1 yr. Results (i) and (ii) indicate that the emergence and decay of sunspots \((10^{18-22}\text{ Mx}, 0.02-2000\text{ MSH})\) and large star spots on solar-type stars \((10^{23-24}\text{ Mx}, 2000-20,000\text{ MSH})\) can be universally explained by the same underlying process, i.e., flux emergence from the stellar interior and a following flux diffusion in the stellar surface. Lifetimes have been used as an indicator of spot temporal evolution, but comparisons with sunspot lifetimes should be carefully made because the lifetimes of star spots can be underestimated due to data sensitivity. Nevertheless, the large star spots (\(\sim 10,000\text{ MSH}\)) with the potential to produce superflares (\(\sim 10^{34}\text{ erg}\); Shibata et al. 2013) are found to survive for up to \(\sim 1\) yr. This implies that the surrounding exoplanets can be exposed to the danger of superflares for such a long time. Moreover, according to the frequency distributions of the superflares, superflares of \(10^{32}\text{ erg}\) can occur about once a year on star spots with an area of \(\sim 10,000\text{ MSH}\) (Maehara et al. 2017). This may indicate that superflares can occur with high probability once such large spots emerge on the stellar surfaces.

In the light curves among our spot candidates, there are some transient brightness enhancements that are probably superflares (see online figures). In the case of the solar flares, it is known that many of the strong flares are caused by newly emerging flux adjacent to the preexisting sunspots (Zirin & Liggett 1987; Toriumi et al. 2017). In future work, the timing of the superflares in the spot temporal evolution should be investigated to understand how the superflares are triggered. Moreover, in the solar case, complex sunspots are considered to have high magnetic free energy (Toriumi & Takasao 2017) showing high flare occurrence rates (Sammis et al. 2000; Maehara et al. 2017) and short lifetimes (Martínez Pillet et al. 1993). This implies that flare occurrence rates and lifetimes can become an indicator of spot configurations (e.g., Maehara et al. 2017).

Finally, we also found that star spots on rapidly rotating stars show more rapid temporal evolution than those on slowly rotating stars. These dependence on rotational period as well as stellar effective temperature should be addressed in future work. Also, we have not examined some uncertainties described in Section 4.5. It is necessary to perform spot modeling (e.g., Fröhlich et al. 2012), inversion modeling (e.g., Savanov & Strassmeier 2008), and follow-up spectroscopic observations for further evaluation.

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Appendix

\textbf{Validation of Method: The Sun-as-a-star Analysis}

To evaluate the sensitivity of the estimation of the spot area, we simply tested our method using the solar data, since we can spatially resolve the sunspot distributions. We used the total solar irradiance (TSI) observed by the Total Irradiance Monitor on board the \textit{SORCE} satellite (Rottman 2005) as a proxy of the \textit{Kepler} light curve. The TSI is the spatially and spectrally integrated absolute intensity of solar radiation at the top of the Earth’s atmosphere. We use the 6 hr averaged time series from 2014 March 5 to 2015 March 5. After removing the high-frequency component of the light curve, we detected the local minima, measured the local depth of the local minima, and
estimated the spot area in the same manner as our star-spot analysis. Figure 10 shows the comparison between the Sun-as-a-star analysis (estimation from TSI) and the analysis based on spatially resolved sunspot data (answer from sunspot observations). The sunspot data are based on observations by the Royal Greenwich Observatory sunspot data (https://solarscience.msfc.nasa.gov/greenwch.shtml). The TSI well matches the light curve reconstructed from the daily sunspot area. The red solid line is the light curve of the TSI observed by the SORCE satellite. The data are plotted with a 6 hr time cadence, and the values are normalized by the median values of the TSI in the observational period. The black dashed line is the light curve reconstructed from the daily sunspot area. (b) Phase-time diagram. Red points correspond to the local minima detected in panel (a) compared to the rotational period (see Carrington longitude). Green and pink circles are the spatially resolved sunspot locations in the northern and southern solar hemisphere, respectively. In this panel, sunspot data are plotted only for sunspots with an area $>100$ MSH. Symbol sizes correspond to the spot area, but the scales of the red and others are different for visibility. (c) Temporal evolution of sunspot area. Red circles correspond to the area estimated from the depth of the local minima of the TSI. The dashed black line represents the daily total sunspot area, and the blue solid line is the area of the largest sunspot for each date.

**Figure 10.** Example of the Sun-as-a-star analysis from 2014 March 5 to 2015 March 5. (a) The red solid line is the light curve of the TSI observed by the SORCE satellite. The data are plotted with a 6 hr time cadence, and the values are normalized by the median values of the TSI in the observational period. The black dashed line is the light curve reconstructed from the daily sunspot area. (b) Phase-time diagram. Red points correspond to the local minima detected in panel (a) compared to the rotational period (see Carrington longitude). Green and pink circles are the spatially resolved sunspot locations in the northern and southern solar hemisphere, respectively. In this panel, sunspot data are plotted only for sunspots with an area $>100$ MSH. Symbol sizes correspond to the spot area, but the scales of the red and others are different for visibility. (c) Temporal evolution of sunspot area. Red circles correspond to the area estimated from the depth of the local minima of the TSI. The dashed black line represents the daily total sunspot area, and the blue solid line is the area of the largest sunspot for each date.

**Figure 11.** Comparison between the estimated spot area from the TSI and the real values in Figure 10(c). The data are plotted from MJD 2,456,722 to MJD 2,457,072.

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