



Statistical Properties of Superflares on Solar-type Stars: Results Using All of the Kepler Primary Mission Data

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Solar flares are energetic explosions in the solar atmosphere, and superflares are the flares having the energy $10 - 10^6$ times larger than that of the largest solar flare. Recently, many superflares on solar-type (G-type main-sequence; effective temperature is 5100 – 6000 K) stars were found in the initial 500 days data obtained by the Kepler spacecraft (Maehara et al. 2012; Shibayama et al. 2013). Notsu et al. (2019) conducted precise measurements and binarity check on the basis of spectroscopic observations and the Gaia-DR2 data. As a result, the number of Sun-like (effective temperature is 5600 – 6000 K and rotation period is over 20 days) superflare stars significantly decreased.

We report the latest statistical analyses of superflares on solar-type stars using all of the Kepler primary mission data and Gaia-DR2 catalog. We updated the flare detection method by using highpass filter to remove rotational variations caused by starspots. We also examined the sample biases on the frequency of superflares, taking into account gyrochronology and flare detection completeness. The sample size of solar-type stars and Sun-like stars are ~4 and ~12 times, respectively, compared with Notsu et al. (2019). As a result, we found 2341 superflares on 265 solar-type stars, and 26 superflares on 15 Sun-like stars. This enabled us to have a more well-established view on the statistical properties of superflares. The observed upper limit of the flare energy decreases as the rotation period increases in solar-type stars. The frequency of superflares decreases as the stellar rotation period increases. The maximum energy we found on Sun-like stars is 4×10^{34} erg. Our analysis of Sun-like stars suggest that the Sun can cause superflares with energies of 7×10^{33} erg (~X700-class flares) and 1×10^{34} erg (~X1000-class flares) once every ~3,000 years and ~6,000 years, respectively (Okamoto et al. 2021).

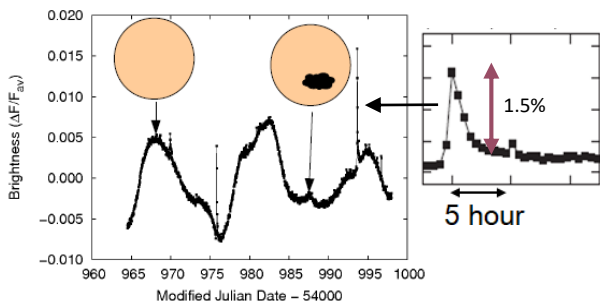
1. Can our Sun produce superflares?

Superflares are the flares having energy $10 - 10^6$ times larger than that of the largest solar flares ($\sim 10^{32}$ erg)

Large solar flares can have severe impacts on our Earth. We do not know the superflares occur on our Sun with only modern solar observations (since 1859).

→ Using the data of solar-type (G-main sequence) stars!

2. Discoveries of superflares with initial Kepler data



[Maehara+2012, Shibayama+2013]

We discovered more than 1,000 superflares on ~300 solar-type (G-type main sequence) stars from initial Kepler ~500 days data.

[Notsu+2019]

Removing contamination of subgiants, using stellar radius updates from Gaia-DR2

→ The number of superflares are much smaller than Shibayama+2013.

3. Superflare analysis using all of the Kepler data

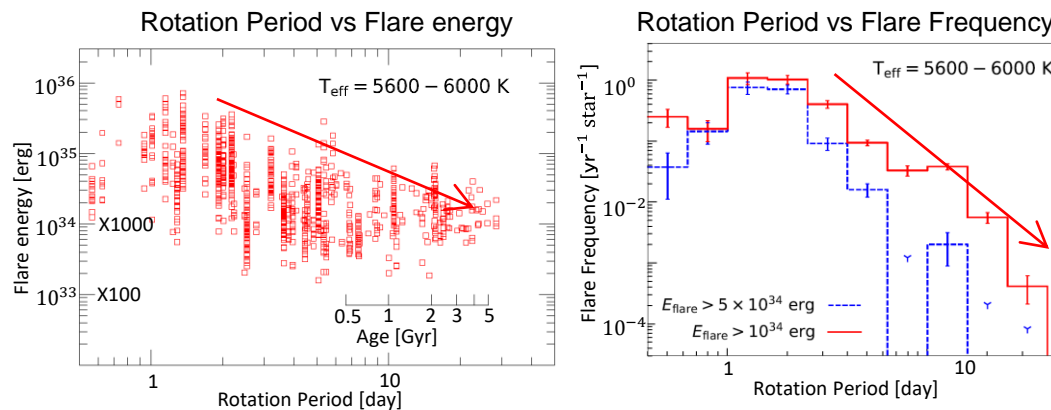
[Okamoto+2021]

- Including stars previously identified as subgiants but newly as main-sequence thanks to Gaia-DR2 data.
- Using all the Kepler data of 4-years and Gaia-DR2 data

→ The total size of analyzed data of Sun-like stars ($P_{rot} > 20$ day, 5600-6000K) is ~12 times compare to Notsu+2019.

	Number of all stars	Number of superflare stars	Number of superflares
Solar-type stars (5100-6000K)	11601	265(113)	2341(527)
Solar-type stars with 5600-6000K	5074	117(45)	929(154)
Sun-like stars (20 day < P_{rot} , 5600-6000K)	1641	15(3)	26(3)

4. Dependence on rotational period of solar-type stars



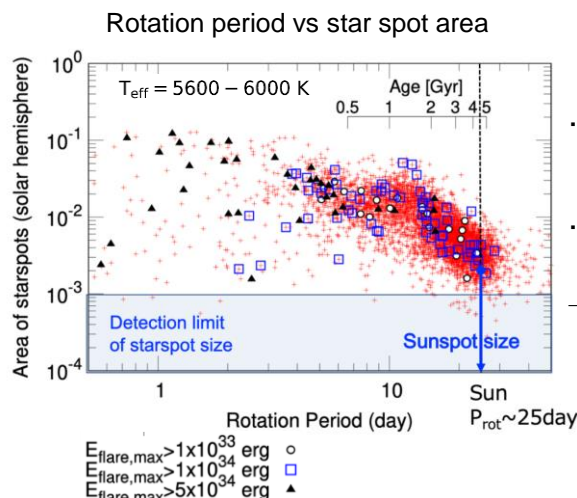
Upper limit of flare energy slightly depends on the rotation period.

Flare frequency also decreases as rotation period increases ($P_{rot} > 2-3$ days).

Superflare analysis solar-type stars (G-type main sequence, 5100-6000K)

- Even Sun-like stars (5600-6000K, $P_{rot} > 20$ days, Age~4.6Gyr) can have superflares up to 5×10^{34} erg.
- Young rapidly-rotating stars ($P_{rot} \sim 2-3$ days, Age~a few hundreds Myr) can have superflares up to 10^{36} erg and flare frequency is ~100 times larger than slowly-rotating Sun-like stars.

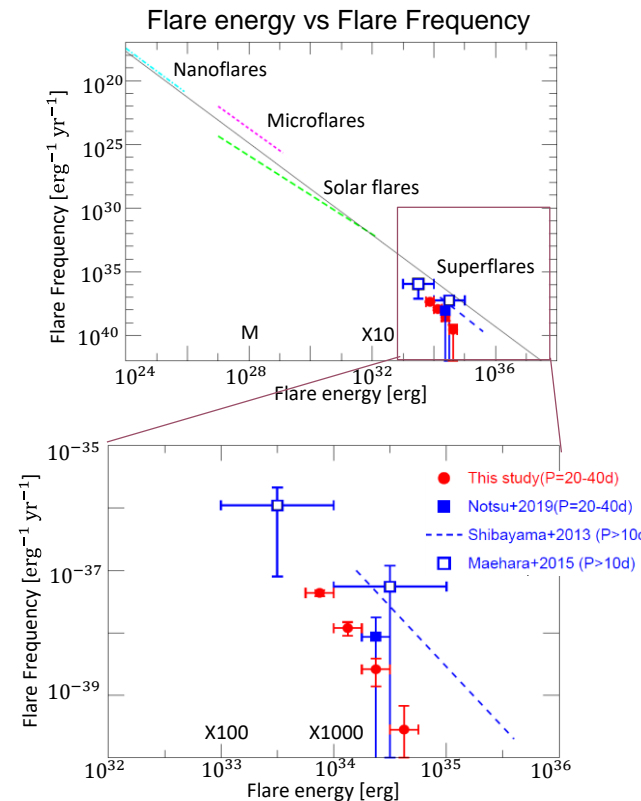
5. The large starspots are needed to occur superflares



- Large starspots (~1% of solar hemisphere) still can exist on slowly-rotating Sun-like stars (5600-6000K, $P_{rot} > 20$ days, Age~4.6 Gyr).
- Superflares are occur on the stars with large starspots.

→ Magnetic energy is necessary for superflares.

6. Frequency distribution of superflares on Sun-like stars and solar flares



From Sun-like stars (5600-6000K, $P_{rot} > 20$ days), the Sun can produce superflares:

- ~ 7×10^{33} erg, X700 class : once in 3000 years
- ~ 1×10^{34} erg, X1000 class : once in 6000 years

• Many superflares (>2000) on many solar-type (G-type main sequence) stars (>265) were discovered from all the Kepler 4-year data and Gaia-DR2 data.

- Flare activities depends on stellar age (rotation period). Young rapidly-rotating stars have more frequent and energetic flares than Sun-like stars ($P_{rot} > 20$ days).
- From Sun-like stars analysis, (5600-6000K, $P_{rot} > 20$ days) our Sun can occur superflares
 - ~ 7×10^{33} erg X700 class : once in 3000 years
 - ~ 1×10^{34} erg, X1000 class : once in 6000 years

*Sun: $T \sim 5780$, $P_{rot} \sim 25$ days **Number in “()” are those in Notsu+2019