

## Comparative Statistics of Solar Flares and Flare Stars

Jonathan Katz<sup>1</sup>  · Mustafa Bharmal<sup>2</sup> ·  
Matthew Ju<sup>3</sup> · Nathan Whitsett<sup>1</sup>

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**Abstract** The distribution of interval times between recurrent discrete events, such as Solar and stellar flares, reflects their underlying dynamics. Log-normal functions provide good fits to the interval time distributions of many recurrent astronomical events. The width of the fit is a dimensionless parameter that characterizes its underlying dynamics, in analogy to the critical exponents of renormalization group theory. If the distribution of event strengths is a power law, as it often is over a wide range, then the width of the log-normal is independent of the detector sensitivity in that range, making it a robust metric. Analyzing two catalogues of Solar flares over periods ranging from 46 days to 37 years, we find that the widths of log-normal fits to the intervals between flares are wider than those of shot noise, indicating memory in the underlying dynamics even over a time much shorter than the Solar cycle. In contrast, the statistics of flare stars are consistent with shot noise (no memory). We suggest that this is a consequence of the production of Solar flares in localized transient active regions with varying mean flare rate, but that the very energetic flares of flare stars result from global magnetic rearrangement that reinitializes their magnetohydrodynamic turbulence.

**Keywords:** Flares, Dynamics; X-Ray Bursts, Association with Flares

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✉ J. I. Katz  
[katz@wuphys.wustl.edu](mailto:katz@wuphys.wustl.edu)  
M. Bharmal  
[mbharmalk@gmail.com](mailto:mbharmalk@gmail.com)  
M. Ju  
[matthew95129@gmail.com](mailto:matthew95129@gmail.com)  
N. Whitsett  
[whitsett.n@email.wustl.edu](mailto:whitsett.n@email.wustl.edu)

<sup>1</sup> Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Mo. 63130 USA

<sup>2</sup> St. Xavier's College, Ahmedabad, India

<sup>3</sup> Lynbrook High School, San José, CA 95129 USA

## 1. Introduction

It is sometimes possible to gain insight into physical phenomena without being able to calculate them in detail. The classic examples are the universality classes of critical points (Pelissetto and Vicari 2002), in which phenomena as diverse as liquid-gas and ferromagnetic critical points may be found to have fundamental similarities, despite their very different microscopic physics. In fact, these similarities may be found without quantitative theories of the phenomena.

Many astronomical phenomena consist of separated but repeating events. Examples include Solar flares, the flares of flare stars, Soft Gamma Repeaters, repeating fast radio bursts, neutron star X-ray bursts, recurrent novæ, dwarf novæ, pulsar glitches and pulsars themselves. The distribution of intervals between successive events contains information about their underlying dynamics. Extreme superflares on Sun-like stars (Vasilev et al. 2024) may have significant terrestrial effects if they occur on the Sun. This increases interest in the comparative statistics of the giant flares of flare stars (that may be considered superflares) and Solar flares. These authors found that the rate of superflares is consistent with extrapolation of observations of lesser Solar flares, suggesting a common mechanism, although it is not possible to compile interval statistics of such rare events.

Some recurrent events are very accurately periodic, with the intervals between successive events almost exactly the same, at least over feasible durations of observation. For example, pulsar pulses repeat with the very stable rotation period of the neutron star that emits them. Recurrent novæ and neutron star X-ray bursts are quasi-periodic, as accreted matter accumulates on (respectively) a white dwarf or neutron star until there is enough to trigger nuclear burning. Other phenomena are far from periodic, and the distribution of the intervals between the events is much broader. These include Solar flares, the flares of flare stars, Soft Gamma Repeaters and repeating fast radio bursts.

Many single-peaked distributions are well-fit by log-normal functions, Gaussian fits to the distribution of the logarithms of the variable, in this case the intervals (waiting times) between successive events. A log-normal distribution has only three parameters: its mean value (the peak of the distribution of the logarithms of the intervals), its width (the standard deviation of the Gaussian fit) and a normalizing factor. The ability of a log-normal to fit an empirical distribution does not, itself, give insight into the underlying physics because this functional form is very flexible. However, the width of the fitted log-normal is analogous to a critical point exponent of renormalization group theory:

- i) It is dimensionless
- ii) Disparate phenomena may be united by similar log-normal widths (in analogy to the universality classes of renormalization group theory)
- iii) If the distribution of event strengths is a power-law, as is often the case, the width is independent of the sensitivity of the observing system.

Hence the fitted log-normal width is a robust single-parameter description of the distribution of some quantity. That quantity may be the strength of discrete events, or the waiting times between them.

Katz (2024) reviewed the use of log-normal fits to the intervals between events in several types of repeating episodic, but aperiodic, astronomical phenomena. That paper’s emphasis was on repeating Fast Radio Bursts, but it also presented results for Soft Gamma Repeaters (powered by the magnetostatic energy of “magnetars”, hypermagnetized neutron stars), the magnitudes of and waiting times between microglitches (small sudden increases of rotation rate) of the Vela pulsar (believed to result from sudden increases in coupling between the rotation of solid and superfluid components of the neutron star, but not understood in detail) and flares of flare stars.

The widths of the log-normal fits to the distribution of intervals may be compared to the calculated standard deviation 0.723 of the log-normal fit to a “shot noise” process, a process (like radioactive decay) in which individual events do not influence each other (Katz 2024). A larger width indicates memory: the object’s activity varies, with active periods in which events are frequent and intervals are short and inactive periods in which events are infrequent and intervals are long, spreading their distribution. A smaller log-normal width indicates a different kind of memory, like that of a relaxation oscillator, in which events are less likely to occur shortly after a previous event. The limiting case of this is a periodic phenomenon like pulsar pulses, in which the distribution of intervals is narrowly peaked, approaching a Dirac  $\delta$ -function.

The distributions of variables other than intervals may also be fit by log-normal functions. For example, the strength of an event may be fit; then zero width would indicate that all events have the same strength (“standard candles”), while a broad width would indicate a broad distribution of strengths. The magnitudes of microglitches of the Vela pulsar are an example; their strengths vary, but less than the intervals between shot noise events, while the microglitch intervals are described by shot noise statistics (Katz 2024). More prosaic examples include relaxation oscillators. However, distributions of strength are often power laws, which are not well-fit by log-normal functions.

The statistics of waiting times between Solar flares have long been studied, and there is an extensive literature. Recent studies include Snelling et al. (2020); Aschwanden and Johnson (2021); Aschwanden, Johnson, and Nurhan (2021), who have found and quantified evidence of memory from their waiting time distributions. Our log-normal fits quantify this information in a different manner than used in the earlier work. Kychenthal and Morales (2023) have calculated the Lu and Hamilton (1991) model (but not the data used here) and fitted the distribution of waiting times between extreme events in that model with log-normals.

The novelty of this paper is the application of log-normal fits to distributions of intervals between Solar flares and their comparison to log-normal fits of the distributions of intervals between outbursts of flare stars. We consider two Solar flare databases, the recently published (Valluvan et al. 2024) Chandrayaan-2 XSM Catalogue and the long-established and very large GOES database (Plutino et al. 2023). These two databases classify flares differently, Chandrayaan-2 XSM into types on the basis of their temporal structure and GOES into classes on the basis of strength. Comparison of the log-normal widths of waiting times between flare types or classes in the same catalogue and between catalogues may show

which have fundamentally similar or different physics. In fact, we find that all the varieties of Solar flares have similar statistics, but that these differ from the statistics of flares on flare stars.

In contrast to the other astronomical events whose distributions of waiting times were studied by Katz (2024), Solar flares are much better understood, both phenomenologically (in association with the Solar cycle) and theoretically. The purpose of the log-normal method is to find (or exclude) commonalities between superficially different phenomena by comparing their distributions of intervals.

## 2. Solar Flares: The Chandrayaan-2 XSM Catalogue

The X-Ray Solar Monitor aboard the Chandrayaan-2 satellite in a low (about 120 km above the surface) Lunar orbit (Mithun et al. 2020, 2021) observed 6266 Solar flares over a three-year period from 2019 to 2022 (Valluvan et al. 2024). This observing period began in the Solar activity minimum between sunspot cycles 24 and 25 and continued roughly half-way to the maximum of cycle 25 anticipated for 2025. The data may be found in Chandrayaan-2 XSM Catalogue (2024)<sup>1</sup>.

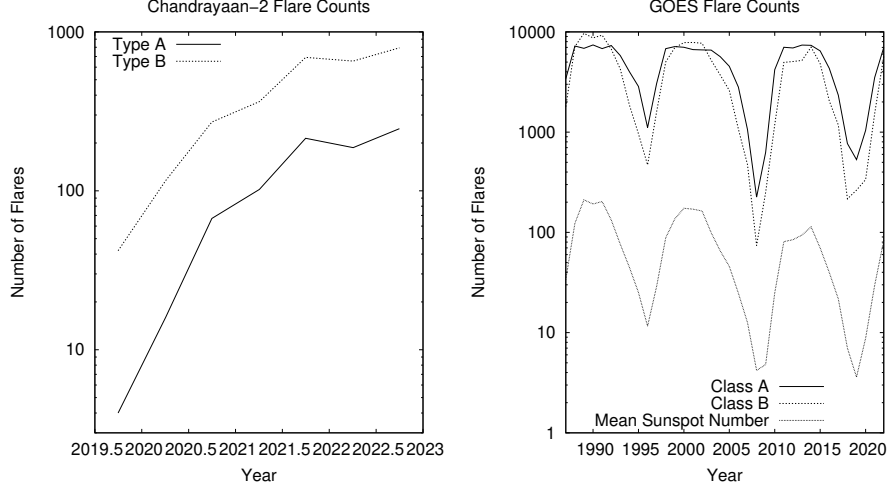
The Lunar orbit of Chandrayaan-2 is perpendicular to the ecliptic, as shown in Fig. 3 of Mithun et al. (2021). At some times (referred to as “dawn-dusk”) its orbital axis points to the Sun and it views the Sun continuously. At other times (“noon-midnight”) its orbital axis is normal to the direction to the Sun and it is in the Moon’s shadow for nearly half its orbit (Table 2 of Mithun et al. (2020)). At these latter times, and during much of the intermediate periods, Lunar shadowing implies that some flares are missed (Fig. 1 of Valluvan et al. (2024) illustrates the effect on the rate of flare detections) and it is not possible to measure flare intervals. As a result, we limit our analysis to the periods, 46 days long and occurring every six months, during which the Sun is continuously observed by the satellite. These give the flat-topped portions of the detection rates shown in Fig. 1 of Valluvan et al. (2024). Fig. 1 (left panel) shows the counts of flares of Types A and B in the Chandrayaan-2 XSM catalogue.

We fit log-normals to the distributions of intervals for flares of types A and B (as designated in Chandrayaan-2 XSM Catalogue (2024) on the basis of their temporal structure). Because variations in the mean flare rate broaden the distribution of intervals, we fit log-normals to intervals in all the six 46 day “dawn-dusk” periods over three years taken together, during which the mean flare rate changed by a large factor, and separately to the final 46 day “dawn-dusk” period of unobscured observation, during which the mean flare rate appears to have been roughly constant (Fig. 1).

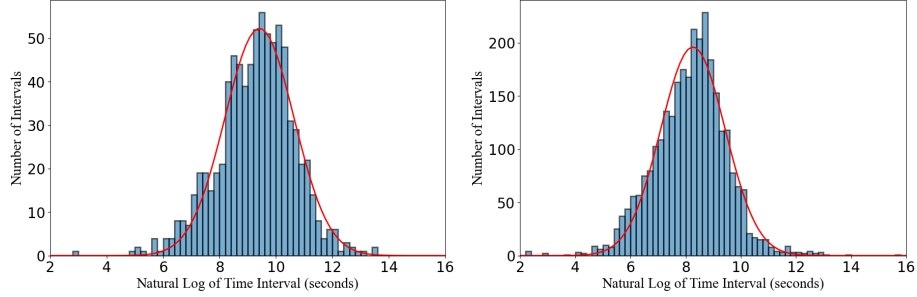
Fig. 2 shows the distributions of intervals and log-normal fits using flares from all the 46 day periods in the Chandrayaan-2 database during which the Sun is never obscured by the Moon, taken together (the spurious very long intervals between the last flare in one 46 day period and the first flare in the next are

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<sup>1</sup>The data file contains seven type B and six type A flares at h:m:s=00:00:00 that appear to be spurious and are ignored.

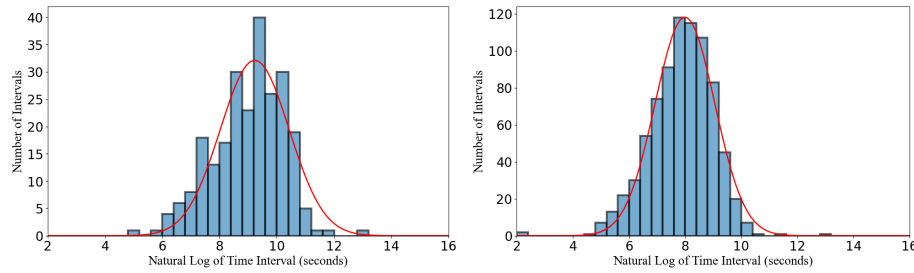


**Figure 1.** Left panel: Chandrayaan-2 types A and B flare counts in each of the 46 day “dawn-dusk” periods of continuous Solar visibility of the Chandrayaan-2 XSM catalogue (Chandrayaan-2 XSM Catalogue 2024). Observations began during the sunspot minimum between Solar cycles 24 and 25 (the first five days of the September 7–October 23, 2019 “dawn-dusk” period were not included), and continued roughly half-way to the maximum of cycle 25 predicted for 2025. Right panel: Classes A and B GOES flare counts and annual mean sunspot numbers 1987–2022 (Plutino et al. 2024; SILSO World Data Center 1986–2022); flare activity follows the Solar cycle (Chandrayaan-2 flare types are unrelated to GOES flare classes).



**Figure 2.** Distributions of natural logs of intervals (in s) between Chandrayaan-2 type A flares (left panel) and between type B flares (right panel) and log normal fits to these distributions for all Chandrayaan-2 data during 46 day periods when the Sun was never obscured by the Moon. Solar activity, as measured by sunspot numbers and by flare detections, was rapidly increasing during this approximately 2 1/2 year period at the beginning of Solar cycle 25, as shown in Fig. 1.

ignored). Because the mean rate of flares varied rapidly during that time the log-normal width and kurtosis are expected to be greater than their “instantaneous” values. However, these differences are small because the statistics are dominated by the much larger number of intervals observed when the flare rate is higher and likely to be roughly steady (Fig. 1 left panel).



**Figure 3.** Distributions of natural logs of intervals (in s) between Chandrayaan-2 type A flares (left panel) and between type B flares (right panel) and log normal fits to these distributions during the period September 7–October 23, 2022 when the satellite observed the Sun continuously (without obscuration by the Moon). Solar activity, as measured by sunspot numbers, was roughly half-way to the maximum of Solar cycle 25 and the mean rate of flares was not rapidly varying.

Fig. 3 shows the distribution of intervals and log-normal fits for the final 46 day period, when sufficient flares were observed to obtain meaningful statistics, but the mean flare rate is expected to have been approximately steady. Fig. 1 shows that the mean rate of flares was not rapidly changing around that time, so that these results approximate their “instantaneous” values.

The statistics are summarized in Table 1. The widths of the log-normals fitted to all the (“dawn-dusk”) periods when there was no Lunar obscuration, during which the mean flare rate changed by a large factor (Fig. 1), are slightly, but only slightly, greater than those fitted to a subset when the mean flare rate was not rapidly changing. All datasets have moderate negative skewness, indicating an excess of short intervals and a memory effect, as expected from the variation of Solar activity as active regions form and dissipate. The expected excess of long intervals from periods of low Solar activity, that would produce positive skewness, is almost unobservable, perhaps because few flares occur during periods of low activity.

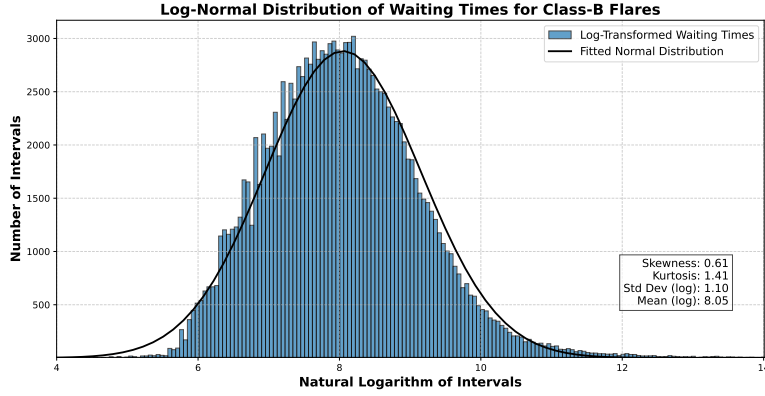
The fact that the widths are greater than that (0.723) of shot noise, even when the mean flare rate is not rapidly changing, implies that there are periods of activity greater than the mean, and necessarily also periods of lesser activity. This is consistent with the well-known fact that the Sun has active regions with correlated sunspot and flare activity; as these regions grow and decay the mean flare rate, as well as the sunspot number, increase and decrease. This is also quantified by the excess (over 3, its value for Gaussian statistics) kurtosis in three of the datasets, particularly for Type B flares.

### 3. GOES Data

The GOES satellite constellation has been collecting X-ray solar flare data since 1986 (Plutino et al. 2023). These satellites are in geosynchronous orbits and are continuously illuminated by the Sun. We analyze data (Plutino et al. 2024) from June 1, 1986–April 30, 2023 for Class B flares. Because GOES flares are classed on the basis of their strength, with Class B the second weakest, the sampling of

**Table 1.** Summary of Solar flare data. Chandrayaan-2 XSM indicated by SD-CH2. Note that Chandrayaan-2 flare types are not the same as GOES classes, even when denoted by the same letter. Uncertainties are purely statistical and do not include the effects of non-stationary Solar behavior. Variations in Solar activity increase  $\sigma$  and kurtosis and may affect skewness in either direction; the separate computations for the entire Chandrayaan-2 dataset and its last 46 day period show this effect (except for kurtosis). The flare stars are TESS TOI 176.01, 218.01, 1224.01 and 1450.01. The uncertainty of  $\sigma$  for the flare stars is the standard deviation of the values computed for each of the stars; the  $N$  are too small to justify computation of skewness or kurtosis.

Flare Type and Period	$N$	$\sigma$	Skewness	Kurtosis
SD-CH2 Type A, Last	246	$1.22 \pm 0.11$	$-0.40 \pm 0.16$	$3.09 \pm 0.31$
SD-CH2 Type B, Last	794	$1.12 \pm 0.06$	$-0.42 \pm 0.09$	$4.52 \pm 0.17$
SD-CH2 Type A, All	1463	$1.34 \pm 0.05$	$-0.32 \pm 0.06$	$3.79 \pm 0.13$
SD-CH2 Type B, All	4790	$1.29 \pm 0.02$	$-0.07 \pm 0.04$	$4.38 \pm 0.07$
GOES 1986–2023 B-class	144086	$1.10 \pm 0.004$	$0.61 \pm 0.006$	$4.41 \pm 0.013$
TESS four flare stars	104–324	$0.683 \pm 0.016$		



**Figure 4.** Distributions of natural logs of intervals (in s) between class B flares and log-normal fit to this distribution for 1986–2023 GOES data. These data span more than three Solar cycles. The positive skewnesses shown in Table 1 are evident, and result from long intervals occurring around Solar minima.

Class B flares is likely nearly complete, in contrast to the weaker Class A flares that we ignore. This period includes more than three entire solar cycles, during which the rate of Solar activity varied greatly. A total of 144,086 Class B flares were recorded during this period; this number is larger than cited by Plutino et al. (2023) because we use about three more years of data. The distribution of intervals and its fitted Gaussian is shown in Fig. 4.

The statistical parameters that fit the GOES data are shown in Table 1. The large size of the database means that formal statistical uncertainties of the fitted parameters (width, skewness and kurtosis) are negligible,  $\lesssim 0.01$ . Systematic

uncertainties resulting from longer-term variations of the Sun dominate, but cannot be estimated from shorter datasets.

Despite the variation of the rate of Solar flare activity through the Solar cycle, the widths of the distributions are somewhat less than those of the Chandrayaan-2 distributions over the rising portion of one Solar cycle and even slightly less than the Chandrayaan-2 distribution over a single period during which the mean flare rate may be nearly constant. Fig. 4 more clearly shows tails of the distributions at long intervals, produced in periods of low flare activity, that contribute to the positive skewnesses of the GOES data. The absence of these tails in the Chandrayaan-2 data may possibly be attributed to its smaller dataset, so that rare long intervals are not found at all, but may more likely be the result of greater Solar variability in the more extended GOES dataset. A period of 37 years (GOES) may include a broader range of Solar states than the six 46 day periods, distributed over about three years, of the Chandrayaan-2 data.

#### 4. Flare Stars

Flare stars, dim low-mass M-dwarfs with flares that may multiply their luminosities by large factors, are believed to resemble scaled-up versions of Solar flares (Benz and Gudel 2010). The TESS satellite (Ricker et al. 2015) observed a sufficient numbers of flares from a few flare stars to permit fitting log-normals to their distributions of interval times.

This study used observations (Whitsett and Daylan 2025) of four flare stars, each with the most (between 104 and 324) TESS-detected flares, sufficient to calculate log-normal widths with about 10% accuracy. Their distributions of intervals include outlying tails of extremely short (minutes to an hour) and extremely long (up to a year) intervals, in contrast to the peaks of the distributions at intervals at  $\sim 1$ –10 days. We attribute these short intervals to substructure within flares rather than to intervals between distinct flares (a similar excess of short intervals between Fast Radio Bursts has long been known (Katz 2018, 2019)). The extremely long intervals are attributed to gaps in observational coverage. We therefore exclude all intervals whose logarithms are more than five standard deviations (of the distribution of logarithms for that particular flare star) from the mean, iterated to self-consistency.

The mean fitted log-normal width was  $\sigma = 0.683 \pm 0.016$  (the uncertainty is computed from the scatter of the four values of  $\sigma$ ). This is slightly less than the  $\sigma = 0.723$  of shot noise. The difference has a nominal significance of 2.5 standard deviations. If real, it would hint at quasi-periodicity. It is very significantly less than the  $\sigma = 1.1$ –1.3 fitted in Table 1 to the widths of the interval distributions of Solar flares. The comparatively small flare star datasets mean that the skewnesses and excess kurtoses, more sensitive to outliers than the widths of their interval distributions may not be useful for comparison to these parameters for Solar flares.

However, the difference in widths between the fits to the interval distributions of Solar flares and that of the (much more energetic) flare stars is sufficient to establish that these phenomena differ in more than scale. A possible explanation

may be that flares on flare stars involve a global rearrangement of their magnetic fields (perhaps analogous to the giant outbursts of Soft Gamma Repeaters), in contrast to the localized nature of Solar flares.

## 5. Discussion

The flares of flare stars have the statistics of shot noise, while Solar flares show memory. The latter conclusion is expected, because the Sun's activity varies greatly with the Solar cycle (Fig. 1), broadening the distribution of interval times. But even in a shorter period of Chandrayaan-2 observations during which the mean level of Solar activity is expected to be roughly constant (Fig. 3), Solar flares show memory, as indicated by  $\sigma = 1.22 \pm 0.11$  (Chandrayaan-2 type A flares) and  $\sigma = 1.12 \pm 0.06$  (Chandrayaan-2 type B flares), differing from the shot noise value by 4.5 and 6.7 standard deviations, respectively. Integrating over the Solar cycle, the  $\sigma$  fitted to the GOES data differs from the shot noise value by a nominal  $\sim 100$  standard deviations. This may be regarded only as consistency with the Solar cycle, but comparison to the flare star data emphasizes that flare stars do not appear to have comparable cycles, at least on the time scales of the TESS data.

A plausible explanation is that this reflects the existence of comparatively persistent, but not permanent, active regions on the Sun, often only one at a time. When such a region is present and facing the Earth the mean rate of observed flares is higher, while when there is no such region, or any such region is on the far side of the Sun, the mean rate of observed flares is less. This broadens the distribution of intervals. In contrast, flares on flare stars are believed (on the basis of their energy) to result from global reorganization of the stars' magnetic fields. Once such a reorganization occurs, the star returns, statistically, to a pre-flare state. If the magnetohydrodynamic turbulence that builds up magnetic energy is stochastic, it makes the distribution of intervals to the next flare resemble that of shot noise. This hypothesis might be explored by numerical simulation of the turbulence, as well as by collection of additional flare star data.

The fact that the statistics of flare stars and Solar flares differ, implying fundamentally different mechanisms, implies that global reorderings of the magnetic field may not occur on the Sun. This does not, however, mitigate the concern (Vasilev et al. 2024) that a superflare like those observed on other Solar-type stars might occur on the Sun.

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