

Superflares on Giant Stars

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Abstract

The Kepler mission identified huge flares on various stars including some of solar type. These events are substantially more energetic than solar flares, and so they are referred to as superflares. Even a small probability of such a superflare on the Sun would be a menace to modern society. A flare comparable in energy with that of superflares was observed on 24th and 25th September on the binary HK Lac. Unlike the Kepler stars, there are observations of differential rotation for HK Lac. This differential rotation appears to be anti-solar. For anti-solar differential rotation, dynamo models can give magnetic activity waves of dipole symmetry as well as quasi-stationary magnetic configurations with quadrupole symmetry. The magnetic energy of such stationary configurations is usually about two orders of magnitude higher than that associated with activity waves. We believe that this mechanism could provide sufficient energy to produce superflares on late type stars, and present some simple models in support of this idea.

Keywords

stars: giants, stars: late-type, stars: flares, stars: individual: HK Lac, stars: dynamo

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Introduction

Data from the *Kepler* mission [1] has revealed the existence of stellar "superflares" [2, 3]. Some of the superflaring stars are G dwarfs with long rotation periods $P_{\text{rot}} > 10$ days [3], and some seem to be very similar to the Sun in their surface temperature and rotation rate, [4]. The energies of stellar flares observed belong to in the wide range from 10^{33} to 10^{37} erg [3] while the highest energy of any observed solar flares is approximately $(2 - 3) \times 10^{32}$ erg.

Observations of superflares on Sun-like stars are challenging for solar and stellar physics in general and for the stellar dynamo in particular. A dynamo scenario to explain the accumulation of magnetic energy sufficient to support superflares has been recently suggested by [5] and is further developed by [6]. The idea of this scenario is that dynamo action on superflaring stars, instead of producing stellar cycles similar to the solar Schwabe 11-year cycle, excites a quasi-stationary magnetic configuration with a much higher magnetic energy, simply because the dynamo drivers only have to build and maintain a steady field, whereas the solar dynamo has also to drive magnetic field reversals during the course of the cycle. The scenario proposed by [5] suggests that a quasi-stationary behaviour appears for a limited time as a result of fluctuations in the dynamo governing parameters while [6] considers that quasi-stationary behaviour is a normal magnetic field config-

uration in superflaring stars. Observations of the *Kepler* superflaring stars are consistent with these interpretations. Certainly they do not provide sufficient information for its verification, nor do they allow choice between these scenarios.

Remarkably, there is a giant, HK Lac, for which a very strong optical event is known from ground-based optical observations, and observational information required for understanding of the origin of the strong magnetic field origin.

Observing superflares for magnetoactive evolved giant stars is challenging as well. From the very high precision *Kepler* data [7] found 653 flaring giant stars from the Kepler sample of 22837 giants, which means 2.86% flare incidence. Comparing to the flare incidence of 2.90% and 5.28% for the G and K–M dwarfs respectively, there is little difference. For giants generally, the flare energies are somewhat higher and the durations are longer than those observed on dwarfs [7].

From the ground however, the observational scatter is much larger than that of the *Kepler* observations, and so the flares are usually outshone by the brightness of the giant stars, i.e. the low amplitude events simply disappear in the observational scatter, so only the rare, most energetic ones, can be obtained. Moreover, the ground based observations do not provide continuous monitoring, rather one or a few data-points per night are observed. Summing up, the probability of observing a superflare on a giant star from the ground is very low, but fortunately there are nevertheless a (very) few

examples.

The aim of our paper is to attract attention in this context to the strong H_α flare that occurred on HK Lac on the 24th and 25th September, 1989 [8]. In our opinion, the observational data concerning this flare support the *Kepler* results for some giant superflaring stars [9, 7], as well as the corresponding dynamo interpretation suggested by [6].

Superflares occur on close binaries like HK Lac. A higher flaring frequency at epochs of periastron passage in this type of star [10] implies their binary nature to be somehow related to superflares. Recent analysis by [11] however shows that binarity can provoke superflares if sufficiently high magnetic energy is available but it is not the reason for high magnetic energy. This is why we seek dynamo mechanisms producing the abnormally high magnetic energy.

In order to facilitate this comparison we present the data concerning HK Lac as a superflaring star following the logic of the *Kepler* mission, i.e. from the data relating a particular superflare to the data concerning physical parameters of the star and then to the dynamo model.

On one hand, the origin of superflares on giant stars is interesting in itself. On the other hand however, the data concerning superflaring giant stars can help us to a better understanding of the origin of superflares on solar-like stars. The point is that we can here use observational data concerning the differential rotation of HK Lac. In this respect, the case of HK Lac plays an exceptional role in the following.

1. Basic parameters and differential rotation of HK Lac

HK Lac is the K0 III primary star ($T_{\text{eff}} \approx 4700$ K) of an RS CVn-type binary system with an unknown secondary star. The early history of the binary since its discovery until the observed H_α flares is summarized by [12] and references therein. The mass of HK Lac is not known; for more information on the problem of deriving masses of highly active giants – see e.g. [13].

Briefly, HK Lac is the primary star of a close binary system with an orbital period of 24.4284 days and mass function of 0.105 [14]. The orbital eccentricity is close to zero so the system is tidally locked, therefore the observed rotational period is close to the orbital. The rotational period is changing slightly because of the differential rotation. Using Doppler imaging techniques the differential rotation of HK Lac is found to be of anti-solar type with $\alpha = -0.05 \pm 0.05$ [15] and [16], see their Fig. 2, though the value is uncertain. The very low *absolute* value of the differential rotation of HK Lac is probably due to its binary nature similar to that of others on giant RS CVn binaries in close, tidally locked systems [15].

Strong chromospheric activity was observed on HK Lac by the IUE satellite between about 1300–3000 Å, including the MgII h&k lines. Strong turbulent motions in the chromosphere were indicated by the widths of these lines above the

rotational broadening [17]. HK Lac has multiple and changing spot cycles between 5.4 and 5.9 years and 10 to 13.3 years [18]. We believe that these cycles could be similar to the (also changing) solar cycles but however do not require oscillating eigensolutions of dynamo equations responsible for the 11-year cycle. This is a challenge for dynamo theory and also perhaps for observations and their interpretation.

Single giants of the same spectral type rotate much more slowly than the close binary primary of HK Lac [19]; nevertheless they can have large spots and show magnetic activity. This probably implies that in HK Lac the dynamo is highly supercritical.

2. The superflare of 24th and 25th September 1989 on HK Lac

According to [8], the total energy released in the H_α line during the event is estimated as 1.3×10^{37} erg, see also [20], and the estimated total released energy is in the order of 10^{39} erg. This conclusion is based on the analysis of Fig. 2 from [21]. The superflare was localized at about the same longitude as the newly emerged large spotted area found by [21]. Similar coincidences of H_α flares and newly emerged spots were found in 1977 by [8] – Fig. 5 of that paper. The H_α observations by [22] reported extreme emission variations in the H_α profile on Sept. 5, 1976, which were still present on the following day with lower flux. The remainder of their H_α data observed between 1976 and 1978 did not show such any strong emission.

Apart from the 6 day long H_α flare in 1989, two other smaller flare-like events in H_α were observed on HK Lac in 1993 and 1994, the latter lasting for 2 or 3 days, Fig. 2 in [23].

Sudden changes in surface activity suggest that giant long-lasting flares may have appeared during such abrupt changes.

3. The dynamo modelling

We believe that superflares as well as usual stellar and solar flares are associated with strong magnetic fields. Stellar magnetic fields are believed to be created by a dynamo. We have to show how this mechanism can create the huge magnetic energy supply required to produce such strong nonstationary processes and why this mechanism does not produce it on other stars, and on the Sun in particular.

Consider a dynamo driven in a spherical shell by differential rotation and mirror-asymmetric convection. The problem is that we cannot expect to know the internal hydrodynamics of this particular star with an accuracy comparable with that known for the Sun, especially since our available knowledge of internal solar hydrodynamics is still insufficient to reconstruct all the details of the solar dynamo. This is why we consider two possible examples of the rotation curve (Fig. 1), which are extrapolations of synthetic solar rotation laws to a deep convective shell of 60% of the stellar radius.

Red giants are known to possess extended convective envelopes. Asteroseismology detects strong radial differential rotation with rotation rate increasing with depth in RGB stars [25, 26]. The subrotation can be related to predominantly downward convective transport of angular momentum in slowly rotating single giants, cf. Fig.3. in [27]. Latitudinal transport can be more efficient in faster rotating (large Coriols/small Rossby numbers) binaries thus producing latitudinal rotational inhomogeneities.

Dynamos driven by joint action of differential rotation and mirror-asymmetric convection are described by the following mean-field equations

$$\frac{\partial \mathbf{B}}{\partial t} = \text{rot}(\alpha \mathbf{B} + \mathbf{V} \times \mathbf{B}) - \beta \text{rot rot } \mathbf{B}, \quad (1)$$

where \mathbf{B} is large-scale magnetic field, α is a measure for the mirror asymmetry of convection (the α -effect), β is convective diffusivity and \mathbf{V} is large-scale velocity, here just differential rotation. Nonlinear dynamo saturation is described in the framework of the simplest model by algebraic α -quenching.

The intensity of dynamo action in the model is controlled by a single parameter, known as the dynamo number D , which can be positive or negative. This sign distinguishes between solar and anti-solar types of differential rotation. The sign of D depends on its definition and we use a definition which gives solar type differential rotation when $D < 0$, and anti-solar when $D > 0$. In the course of the modelling we just change the sign of D to move from solar to anti-solar differential rotation and keep the shape of the rotation law unchanged.

According to [28], magnetic activity occurs in typical giant stars which rotate much more slowly than HK Lac. If in the former stars D is sufficiently supercritical to support dynamo action, it is natural to expect that the dynamo number for HK Lac is highly supercritical, possibly 10 times larger than the critical value. [29] explain how a highly supercritical value of D might be compatible with smaller fractional differential stellar rotation (in fact the ratio of toroidal field winding time to diffusion time is more important here; our simple models do not take account of this). E.g., red dwarf stars smaller than the Sun also have smaller differential rotation but are also more dynamo-efficient [29].

We made several experiments in the spirit of [6], to test the applicability of these ideas to giant stars with deep sub-surface convection zones, such as HK Lac. We began with a modification of the synthetic solar rotation law used by [24], now extended throughout the deeper convection zone with base at fractional radius 0.6 and nominal overshoot layer thickness 0.05, see Fig. 1a. If we take the absolute values of the dynamo number used in the solar case by [6], then both negative and positive values of D give oscillatory solutions. If we take the hint that the dynamo number of HK Lac may be much more supercritical, and so double the absolute value of the dynamo number, then with $D > 0$ the dynamo is steady, and with $D < 0$ it is oscillatory (see Fig. 3). If we

now take the rotation law of Fig. 1b, we find a very similar result – see Fig. 2. From these experiments we can deduce that, as in the solar case examined by [6], we can find dynamo models in which anti-solar differential rotation gives steady solutions of significantly higher magnetic energy than found in the standard oscillatory solutions. Results are sensitive to some details of the rotation law, and to the value of the dynamo number.

4. Large flares on some other late-type stars

As far as we know, the large H_α flare on HK Lac is the only example of a possible superflare (estimated total released energy of approximately 10^{39} erg) reported on a giant star with well-known rotational parameters and decades-long photometric record of its magnetic activity.

Similar large flares were observed by the *Kepler* satellite on KIC 2852961 [9], consisting of 4 or 5 events with total energies between $10^{37} - 10^{38}$ ergs each, in the short-cadence mode, during 29 days, see Table 1. Several other flares were observed in the long-cadence mode as well, lasting from several hours to about a day. This star was also observed by the ASAS survey [30] and those data revealed an average rotational period of 35.58 days. Not much is known about this star, but because of its rotational period (35.58 days, ASAS), but its $T_{\text{eff}} = 4722$ K, $\log g = 2.919$ (KIC input catalog), and V-I color index 1.15 (ASAS), it is very probably a giant.

A long-duration (9 days) optical flare with $E \approx 1.8 \times 10^{39}$ erg is reported on the fast rotating ($P_{\text{rot}} = 9.55$ days) FK Com type star YY Men = HD 32918 (K1 III) by [31].

For the primary of the close binary II Peg = HD 224085 (K2 IV, $P_{\text{orb}} = 6.7$ days) a hard X-ray flare with $E \approx 10^{38}$ erg (Swift/BAT data) is reported [32]; in the cited paper superflares in radio wavelengths on two other subgiant stars (HR 1099, UX Ari) are also mentioned. All three systems belong to the RS CVn type.

For CF Tuc = HR 5303 (G0 IV+K4 IV), the longest (lasting 9 days, also with an exceptional rise time of 1.5 days) coherent stellar X-ray flare ever observed by ROSAT has $E \approx 1.4 \times 10^{37}$ erg [33]. This is also a RS CVn-type partially eclipsing binary system [33].

For the active eclipsing binary system SZ Psc (F8 V+K1 IV) of RS CVn type [34] a flare with $E \approx 4.5 \times 10^{36}$ erg is observed by IUE in ultraviolet [35]. For this system, there are observations of strong flares in optical and X-ray ranges as well.

In contrast to the HK Lac case, we have no observational evidence to support either solar or anti-solar rotation laws for these stars. The general impression is that large flares on giants and subgiants are not frequent events. However the flare observed on HK Lac is not an isolated example. This seems consistent with a dynamo explanation of the phenomenon as presented in this paper.

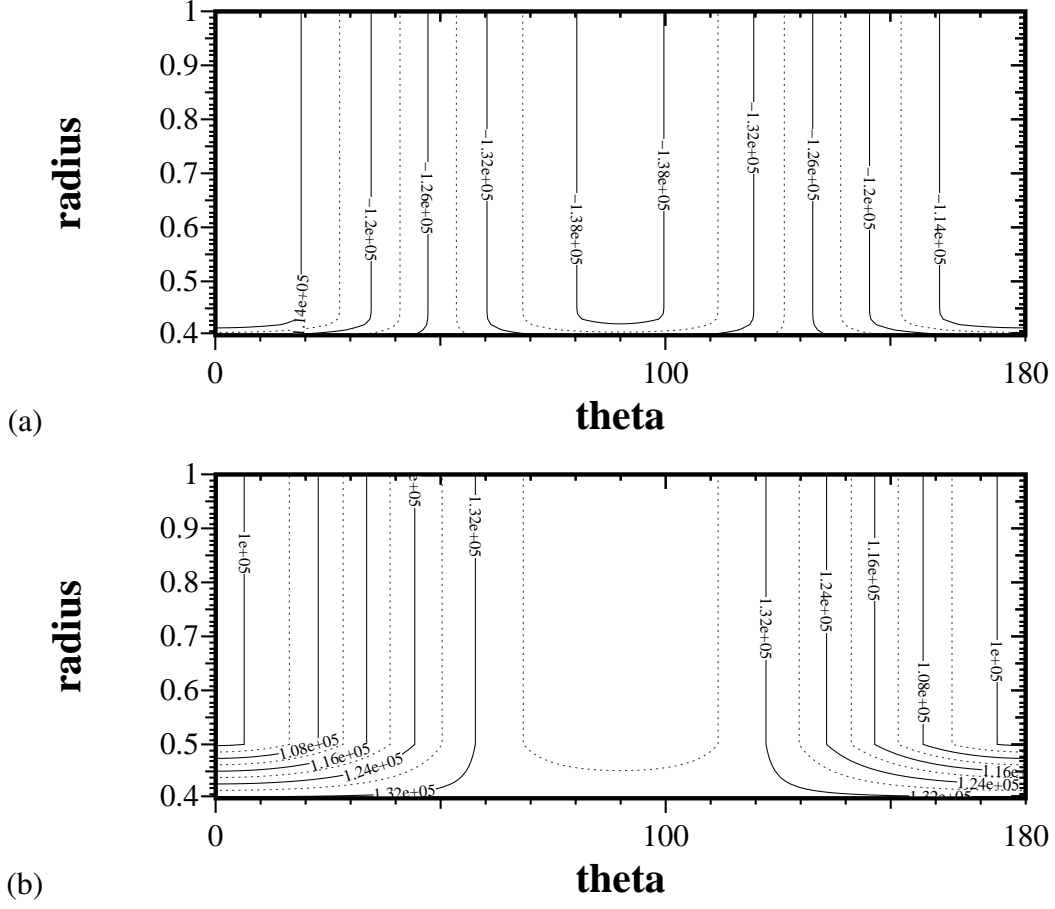


Figure 1. Rotation laws used in the dynamo modelling. a) modified [24] rotation curve with the nominal width of the convective shell 0.60 stellar radius; b) modification of an alternative synthetic solar rotation law.

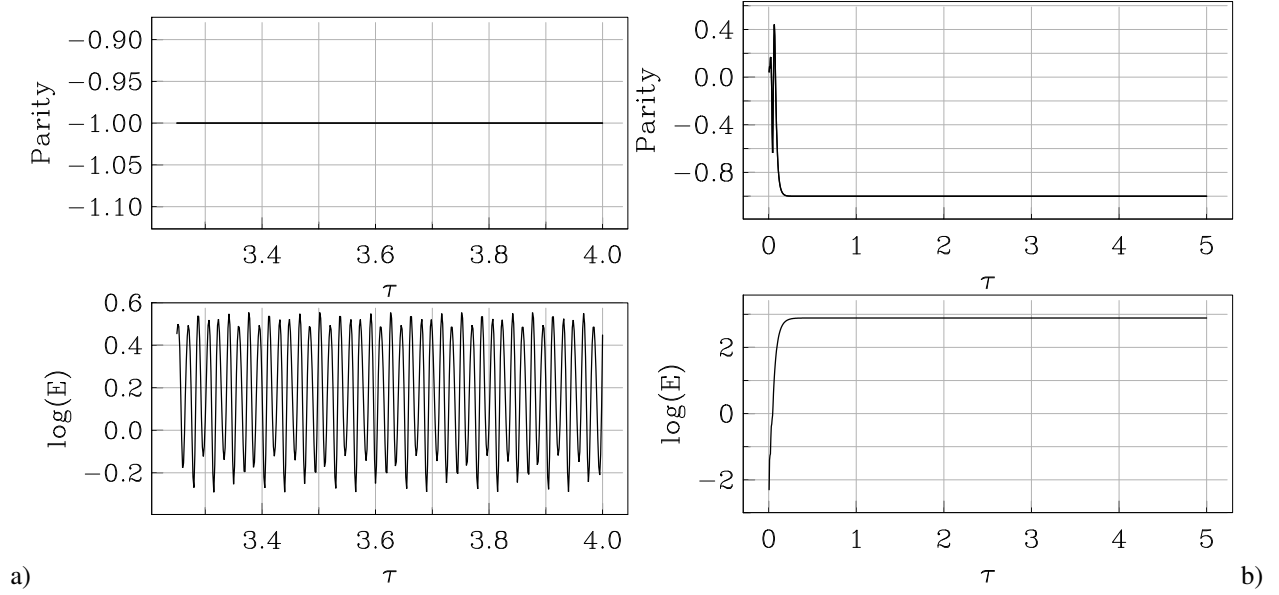


Figure 2. Results of dynamo modelling with the rotation law of Fig. 1a. a) with solar-like differential rotation, $D < 0$, b) with anti-solar type differential rotation, $D > 0$. A parity of +1 corresponds to a quadrupole-like magnetic geometry, -1 to dipole-like. E is a measure of the global magnetic energy and τ is dimensionless time.

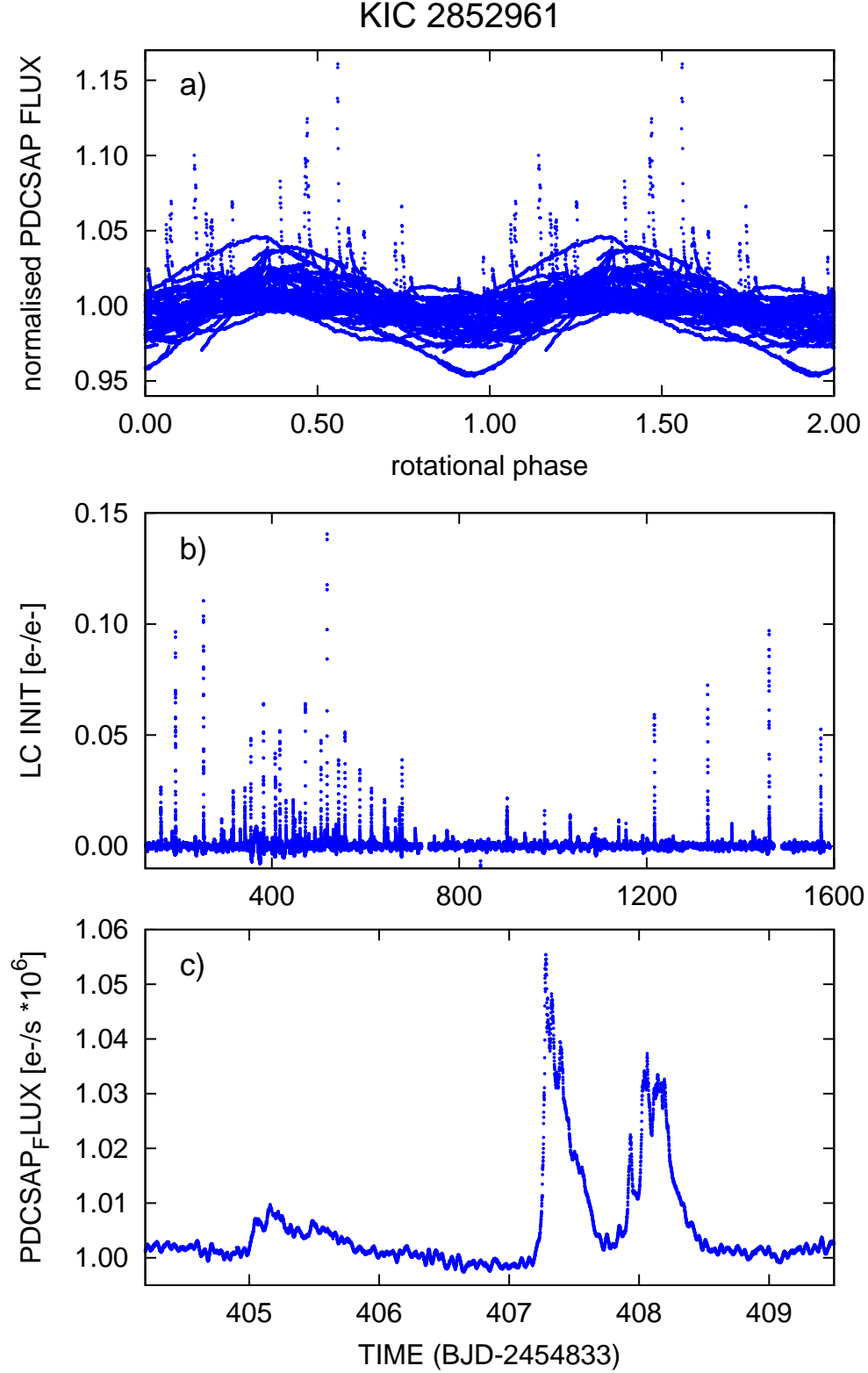


Figure 3. Superflares on KIC 2852961:

- a) Normalized Kepler data of KIC 2852961 phased with a rotational period of 35.58 days given by ASAS,
- b) Detrended, validated Kepler data (DR 25 DV, Q1-17) of KIC 2852961. Note, that the 36 days rotational modulation is also subtracted from the dataset, therefore the flare activity is well seen,
- c) The last three flares from Table 1 [9], from the Kepler short-cadence data of KIC 2852961. These flares erupted close to each other in time, probably the last two make up just one, complex flare event.

KIC	BJD	log(EW)	log(DF)	Dt	log(E)
2852961	5222.707	-1.308	-2.301	14.892	37.207
2852961	5234.205	-1.584	-2.253	6.980	36.930
2852961	5238.159	-0.750	-2.105	25.109	37.765
2852961	5240.281	-0.336	-1.265	14.058	38.179
2852961	5241.062	-0.276	-1.414	19.371	38.239

Table 1. Superflares on KIC 2852961 [9]: KIC – Kepler Input Catalog identifier, BJD – Julian date of peak of flare, log(EW) – the total integrated flux of the flare (ergs), log(DF) – the relative flare intensity, Dt – the total flare duration (hrs), log(E) – the total flare energy (ergs)

5. Discussion and conclusions

Our dynamo model demonstrates that a conventional dynamo based on differential rotation and mirror asymmetry of stellar convection can produce sufficient magnetic energy to support such superflares, provided that the differential rotation is anti-solar. Because the differential rotation of HK Lac seems to be anti-solar, dynamo modelling opens the possibility of producing sufficient magnetic energy on HK Lac (and similar active giants in close binaries) to get such superflares. Our models are deficient in that they do not produce unsteady behaviour – however we note that observational data for HK Lac is rather uncertain.

Of course, we cannot *rigorously* claim that the actual interior rotation law of HK Lac is such as to support the dynamo state discussed above, simply because there are no detailed observational data concerning the differential rotation of HK Lac, and the theory of differential rotation of binaries and giants is not sufficiently developed. [36] discuss numerical modelling of the convection zone hydrodynamics that can produce anti-solar surface differential rotation, but inclusion of their results in our modelling does not seem feasible. However the results of dynamo modelling suggest this possibility, at least in principle.

We note that we need some (arguably plausible) tuning of parameters to obtain the desired configuration for the dynamo modelling. Our interpretation is that this means that superflaring star such as HK Lac will be rather rare in binaries containing giants. This looks consistent with the fact that such superflares are indeed quite rare events in previous searches for superflares in binary systems with giant primaries. On the other hand, this may be just a selection of brightness observational effect since giant stars are not monitored continuously because of their long rotational periods – tens of days – so observing a flare is not very probable. Of course, monitoring would be very helpful here as well as in many other aspects of stellar magnetic activity studies.

Any progress in the theory of differential rotation of binaries as well as in theory of stellar flares clearly would also be very helpful in understanding superflaring giants in binary systems. However development of such a theory is obviously far beyond the scope of this paper. We stress again that we have only attempted to demonstrate the possibility certain

anti-solar rotation laws are consistent with the production of high energy dynamo regimes, and suggest that this is a possible explanation of the superflaring phenomenon. It is beyond the scope or ambition of this paper to investigate a suite of rotation laws, and even less so to produce self-consistent models.

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