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Flare stars across the H-R diagram

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Abstract. Flare stars appear to be as common among the hottest stars as among the coolest. Starspots, which are closely associated with flares, are likewise common among stars of all spectral types. This finding contradicts the long-help belief that only stars with convective envelopes can sustain magnetic fields. It is found that rotation is a dominant factor in inducing flares: flare stars nearly always have shorter rotation periods than non-flare stars. These findings have important implications for the atmospheres of A and B stars as well as providing clues for the formation of the corona.

Keywords: Stars: flare, Stars: activity

1. Workshop on stars with superflares

I attended the Workshop on Superflares on Solar-type stars and Solar flares in which I was invited to give a talk. I am grateful to Professor Shibata for the opportunity to interact with the Superflare group of Kyoto University who originally discovered superflares in the data from the *Kepler* spacecraft and are recognized as leading researchers in this field. The meeting was also attended by internationally renowned researchers on flare stars who contributed excellent talks and stimulated lively discussions. I thank Professor Shibata and his group for organizing such a productive workshop.

2. Stellar activity across the H-R diagram

It is accepted that stellar magnetic fields are either of fossil origin (the star was born with the magnetic field already present) or are generated by convection in accordance with the dynamo theory. The only main sequence stars with fossil fields appear to be the Ap stars which have strong global fields in the range 1-30 kG. Most other stars, such as the Sun, generate their own magnetic fields provided they have convective envelopes. Stars with convective envelopes are those cooler than about 7500 K (stars later than spectral type F5). Flares and starspots, which are indicators of surface magnetic fields, should therefore only be present in such cool stars.

The advent of high-precision, low noise, photometric observations from space from the *Kepler* satellite not only provided the opportunity for the discovery of superflares on cool stars (Maehara *et al.*, 2012; Shibayama *et al.*, 2013), but also lead to the discovery of superflares on stars hotter than 7500 K (the A stars; Balona, 2012). Furthermore, it became evident from examination of the light curves of A stars, that most of these stars were variable in a way which strongly suggested that they have spots, just as the Sun has spots. A statistical analysis of the periods of the A stars, as determined from their light variations, showed that they have the distribution expected from rotation (Balona, 2013). Analysis of the light curves of the even hotter B stars from the *Kepler* and *K2* missions show that these stars, too, have starspots (Balona, 2016).

There have been previous reports of flares on A stars. Schaefer (1989) reported cases of several B and A stars where strong flares may have been observed. Wang (1993) detected a flare on the A5/8V star BD+47 819. Bhatt et al. (2014) found X-ray flares in two late-B stars belonging to the young open cluster NGC 869. Pye et al. (2015) found an X-ray flare in HD 31305 (A0). Miura et al. (2008) detected an intense X-ray flare on the A1 IV/V star HD 161084. Robrade & Schmitt (2011) detected a large X-ray flare in the A0p star IQ Aur.

The presence of flares and spots on A and B stars implies that our long-held belief in the necessity of a convective envelope to maintain a magnetic field needs to be revised. It seems that any star, whether it has surface convection or not, is capable of hosting a magnetic field. This has an immediate implication for the production of a corona, for example. It is supposed that the upper solar atmosphere is heated through the medium of a magnetic field, which essentially deposits the energy of surface convection, thus heating it to over a million degrees and producing the corona. The corona can be detected in stars because its high temperature results in the emission of X-rays. Observations indicate, as expected, that A and B stars do not emit X-rays (Schröder & Schmitt, 2007). What the new results from *Kepler* tell us is that while A and B stars may not have coronae, they still have a magnetic field. This suggests that the role of convection is an essential requirement for the formation of the corona. Without convection, the magnetic field cannot heat the upper stellar atmosphere to the required high temperatures.

Superflares discovered on A stars have typically the same amplitude as on the cooler stars, with maximum relative intensities of about 3 parts per thousand (Balona, 2012). However, the number of detected stars with superflares decreases from about 10 percent for the cool K and M dwarfs to about 2.5 percent for the hot A and F stars (Balona, 2015). This is not surprising because the hotter and more luminous the star, the larger the flare energy required for the flare to be detected. A flare on an A star, for example, needs to be about 100 times more energetic than a flare on an M star to have the same relative amplitude. Because of this effect, it is natural that the number of detectable flare stars should decrease with effective temperature. In other words, the fact that, in the past, only cool dwarfs were recognized as flare stars is purely a selection effect. In reality, the relative number of flare stars seems to be much the same right across the H-R diagram, no matter the spectral type.

It is natural to suppose that a flare observed on an A star does not originate on the A star itself, but on a supposed cool K or M dwarf companion. This idea can be rejected by the fact that a flare on a cool companion would be completely obliterated by the high luminosity of the primary A star, reducing the relative flare amplitude by a factor of 50-100 and rendering it undetectable in the *Kepler* data.

In my talk I also discussed the connection between starspots and flares. In the Sun, flares are typically associated with active spot regions, and one would expect the same in stars (Notsu *et al.*, 2013). However, the correlation between spot size, as estimated from the rotational light amplitude, and flare energy is weak. On the other hand, there is a strong correlation between the flare energy and the stellar radius (Balona, 2015). This is not surprising because the light amplitude is not only a measure of the spot size, but is determined by the distribution and number of spots and their brightness relative to the surrounding photosphere. The energy stored in the magnetic field is proportional to the volume of an active region (the product of the area of the active region and the scale height). The larger the star, the greater this volume and therefore the larger the flare energy. Stellar radius is therefore a better measure of the possible size of the active region than the light amplitude. One can estimate the approximate magnetic field strength on this basis and it turns out to be of the order of 1 kG, allowing for a 10 percent conversion of magnetic energy during the reconnection process. This is similar to the typical field strengths in active solar regions. However, it is not really possible to compare sunspots with spots on superflare stars because typical sunspots are at least an order of magnitude smaller than detectable starspots. The Sun would not be detected as a flare star (and quite possibly not a spotted star either) with the *Kepler* satellite. This is why the relationship between spot size and flare energy is different between the Sun and stars (Notsu *et al.*, 2013).

One of the most important findings is that there is a correlation between flare energy and rotation rate (Notsu *et al*., 2013). A large number of *Kepler* stars have well-determined rotation periods because they are spotted. Many of these stars with known rotation periods also have superflares. Stars with superflares have considerably shorter rotation periods than those without superflares (Balona, 2015). This shows that rotation plays a dominating role in the generation of superflares. This may imply that differential rotation is the key factor. Differential rotation has, in fact, been supposed to be an effective mechanism in generating magnetic fields in much the same way as the dynamo action in convective envelopes (Spruit, 2002; Maeder & Meynet, 2004). This could explain why A and B stars have spots and flares. It would be very interesting to compare differential rotation on stars with superflares and without flares by monitoring the spot periods.

3. Discussion

The discussion around my talk produced many interesting comments. One important comment that was brought up has to do with flares in A stars being attributed to a cooler companion. The idea is that perhaps the companion need not be a faint K or M dwarf, but a more luminous F dwarf, for example. In such a case, the dilution in amplitude would be much smaller because the difference in luminosity between the A and F stars is smaller. The problem then is that the A star would be greatly affected by its rather luminous companion and would therefore be classified as a somewhat cooler star on the basis of its modified colour. Also, there are superflares in stars as early as B9 and quite a few stars have well-determined spectral types, showing no hint of an F star companion.

Another discussion concerns the role of magnetic field strength in producing superflares. An important result from the *Kepler* study of A stars is that although there about ten well-observed Ap stars in the field, not a single Ap stars was observed to flare. It seems that these stars, which have by far the strongest global magnetic fields on the main sequence, do not generate superflares. One possibility is that the large magnetic field prevents differential rotation, which means that the field lines cannot become entangled and cannot store the magnetic energy required for reconnection.

4. Impressions of the Workshop

There is no doubt that this Workshop stimulated much discussion, providing many ideas for the future study of superflares. Can the Sun generate a superflare? This question was frequently asked and the answer seems to be that it can, because there is sufficient energy in the solar magnetic field (Shibata *et. al*., 2013). However, rotation is a very important factor in determining the occurrence of superflares. The *Kepler* data shows that of the 296 G stars brighter than 12-th magnitude with rotation periods in the range 20-40 d, only 5 stars have detectable superflares. This means that there is less than a 1.7 percent chance that a G star with a rotation period similar to that of the Sun will show a superflare. On the other hand, the fraction of superflare stars among G stars rotating with periods shorter than 10 d is 16 percent. While it is still possible that a superflare might occur on the Sun, we need to understand the role of rotation before this question can be answered.

The role of exoplanet habitability was also discussed. It is true that most stars can probably host planets in the habitable zone, but the role of stellar activity needs to be taken into account. About 40 percent of all *Kepler* stars, irrespective of spectral type, have detectable starspots. These spots must be much larger than on the Sun, which means that there are probably few stars with activity as low as the Sun. The Sun is one of the least active stars. Therefore, even if an Earth-like planet is found in the habitable zone of a star, only a fraction of such planets are likely to have an inactive star as host, thus reducing the chances of habitability quite considerably.

The Workshop was a great success and should be repeated on a regular basis. I would, however, recommend that a larger amount of time be set aside for discussion on well-defined topics, independently of the talks. I also feel that it is time to persuade solar astronomers of the great opportunities that await observations of the Sun as a star. We will never understand solar flares without understanding stellar flares and to do this we need to observe the Sun as a star.

5. References

Balona, L. A., Kepler observations of flaring in A-F type stars. *Monthly Notices of the Royal Astronomical Society*, **423**, 3420, 2012

Balona, L. A., Activity in A-type stars. *Monthly Notices of the Royal Astronomical Society*, **431**, 2240, 2013

Balona, L. A., Flare stars across the H-R diagram, *Monthly Notices of the Royal Astronomical Society*. **447**, 2714, 2015

Balona, L. A., Rotational modulation in B stars observed by the Kepler K2 mission. *Monthly Notices of the Royal Astronomical Society*, **457**, 3724, 2016

Bhatt, H., Pandey, J. C., Singh, K. P., Sagar, Ram and Kumar, B., X-ray Flares Observed from Six Young Stars Located in the Region of Star Clusters NGC 869 and IC 2602. *Journal of Astronomy and Astrophysics*, **35**, 39, 2014

Maeder, A. and Meynet, G., Stellar evolution with rotation and magnetic fields. II. General equations for the transport by Tayler-Spruit dynamo. *Astronomy and Astrophysics*, **422**, 225, 2004

Miura, J., Tsujimoto, M., Tsuboi, Y., Maeda, Y., Sugawara, Y., Koyama, K. and Yamauchi, S., Suzaku Detection of an Intense X-Ray Flare from an A-Type Star, HD161084. *Publications of the Astronomical Society of Japan*, **60**, 49, 2008

Maehara, H., Shibayama, T., Notsu, S., Notsu, Y., Nagao, T., Kusaba, S., Honda, S., Nogami, D. and Shibata, K., Superflares on solar-type stars. *Nature*, **485**, 478, 2012

Notsu, Y., Shibayama, T., Maehara, H., Notsu, S., Nagao, T., Honda, S., Ishii, T. T., Nogami, D. and Shibata, K., Superflares on Solar-type Stars Observed with Kepler II. Photometric Variability of Superflare-generating Stars: A Signature of Stellar Rotation and Starspots. *Astrophysical Journal*, **771**, 127, 2013

Pye, J. P., Rosen, S., Fyfe, D. and Schröder, A. C., A survey of stellar X-ray flares from the XMM-Newton serendipitous source catalogue: HIPPARCOS-Tycho cool stars. *Astronomy and Astrophysics*, **581**, A28, 2015

Robrade, J. and Schmitt, J. H. M. M., New X-ray observations of IQ Aurigae and α^2 Canum Venaticorum. Probing the magnetically channeled wind shock model in A0p stars. *Astronomy and Astrophysics*, **531**, A58, 2011

Schaefer, B. E., Flashes from normal stars. *Astrophysical Journal*, **337**, 927, 1989

Schröder, C. and Schmitt, J. H. M. M., X-ray emission from A-type stars. *Astronomy and Astrophysics*, **475**, 677, 2007

Shibata, K., Isobe, H., Hillier, A., Choudhuri, A. R., Maehara, H., Ishii, T. T., Shibayama, T., Notsu, S., Notsu, Y., Nagao, T., Honda, S. and Nogami, D., Can Superflares Occur on Our Sun? *Publications of the Astronomical Society of Japan*, **65**, 49, 2013

Shibayama, T., Maehara, H., Notsu, S., Notsu, Y., Nagao, T., Honda, S., Ishii, T. T., Nogami, D., Shibata, K., Superflares on Solar-type Stars Observed with Kepler. I. Statistical Properties of Superflares. *Astrophysical Journal Supplement Series*, **209**, 5, 2013

Spruit, H. C., Dynamo action by differential rotation in a stably stratified stellar interior. *Astronomy and Astrophysics,* **381**, 923, 2002

Wang, J. –J., A Flare Event on the A-Type Star BD +47 819. *Information Bulletin on Variable Stars*, 3836, 1, 1993