From Starspots to Stellar Coronal Mass Ejections - Revisiting Empirical Stellar Relations

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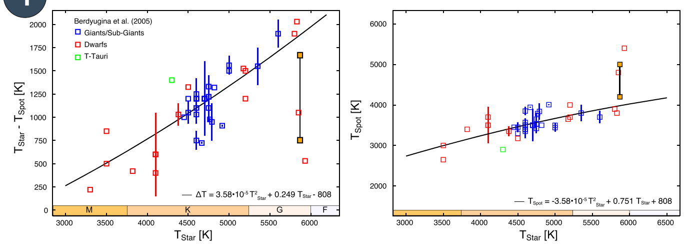
Upcoming missions, including the James Webb Space Telescope, will soon characterize the atmospheres of terrestrial- type exoplanets in habitable zones around cool K- and M-type stars by searching for atmospheric biosignatures. Recent observations suggest that the ionizing radiation and particle environment from active cool planet hosts may be detrimental to exoplanetary habitability. Since no direct information on the radiation field is available, empirical relations between signatures of stellar activity, including the sizes and magnetic fields of starspots, are often used. Here, we revisit the empirical relation between the starspot size and the effective stellar temperature and evaluate its impact on estimates of stellar flare energies, coronal mass ejections, and fluxes of the associated stellar energetic particle events.

Introduction

The increasing sensitivity of ground- and space-based instruments has led to an exponential growth in the detection and characterization of stellar flares. Space missions such as Kepler, Gaia, and TESS have contributed significantly to our understanding of the statistical properties of energies and frequencies of flares and the underlying mechanisms generating them. These new statistical studies of stellar flares complemented with multiwavelength observations of eruptive events opened a new window to search for signatures of flare associated coronal mass ejections (CMEs) and stellar energetic particle (SEP) events and their impact on exoplanetary environments (e.g., Airapetian et al. 2020; Atri 2019; Herbst et al. 2019; Scheucher et al. 2020). Thereby, the amplitude of the rotationally modulated brightness variation and the effective (photospheric) stellar temperature are directly derived from observations. In contrast, the evaluation of the starspot temperatures (e.g., Notsu et al. 2013; 2019) is based on an empirical scaling with the effective temperature of the star derived by Berdyugina (2005). Although this relation often is applied to derive the starspot areas cool stars (e.g., Yamashiki et al. 2019; Howard et al. 2020a), more accurate observations and stellar targets are required for the validation and revision of the current empirical equation. Here, we reanalyze the stellar sample by Berdyugina (2005) and obtain a revised empirical relation, quantifying for the first time an error band. Additionally, we expand the data set utilizing data from Biazzo et al. (2006) and Valio (2017) to derive an updated empirical relation and investigate its impact on empirical estimates of the fundamental properties of stellar flares and CMEs.

1 The Empirical Relation between Stellar and Starspot Temperatures



The empirical relation derived by Berdyugina (2005) is a second-order polynomial fit to the data representing the starspot temperature contrast with respect to the effective temperatures of cool dwarfs and giant stars, utilizing the Doppler Imaging method for 17 G to K (super)giants, eight main-sequence stars (two G-types and four K- and M-types each), and one pre-main-sequence star. As shown in the left panel of Fig. 1, Berdyugina (2005) found that the relation between the effective stellar temperature (T_{Star}) and the starspot temperature (T_{Spot}) for the cool star regime is best described as:

$$\Delta T(T_{Star}) = T_{Star} - T_{Spot} = 3.58\times10^{-5}\,T_{Star}^2 + 0.249\,T_{Star} - 808$$

and

$$T_{Spot} = -3.58\times10^{-5}\,T_{Star}^2 + 0.751\,T_{Star} + 808.$$

Reanalysis and Extension of the Stellar Sample

Assuming the nature of starspots to be the same in all active stars, a more reliable correlation that is able to describe the data of all three samples is needed. Therefore, in a second step, we:

1. extended the sample used by Berdyugina (2005) by including the data from Biazzo et al. (2006) and Valio (2017), and
2. used the scipy.optimize.leastsq fitting routine to derive more universal relations for both T_{Spot} and $\Delta T(T_{Star})$ and to introduce an error estimate.

We find T_{Spot} and $\Delta T(T_{Star})$ to be best repre-sented by:

$$T_{Spot} = -3.58\times10^{-5}\,T_{Star}^2 + 1.0188(\pm0.068)\,T_{Star} + 239.3(\pm317.8).$$

and

$$\Delta T(T_{Star}) = 3.58\times10^{-5}\,T_{Star}^2 - 0.0188(\pm0.068)\,T_{Star} - 239.3(\pm317.8).$$

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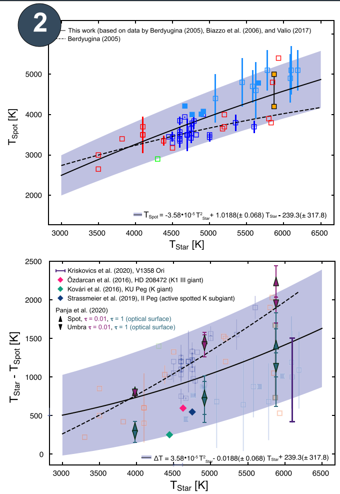

As can be seen from Fig.2, the newly-derived relations are able to represent the entire cool star sample including, for the first time, the well-known solar sunspot temperature variations (orange squares). To test the validity of the latter equation, a comparison with most recent measurements and simulations is performed (lower panel). Shown are the results of the Doppler Imaging of V1358 Ori, a young G9- type star (purple line; Kriskovics et al. 2019), the K-giants HD208472 (magenta diamond; Özdarcan et al. 2016), and KU Peg (green diamond; Kővári et al. 2016), the active K subgiant II Peg (blue diamond; Strassmeier et al. 2019), and the new 3D MHD model results by Panja et al. (2020; colored triangles).

However, $\Delta T(T_{Star})$ is often used as a semi- empirical quantity to derive other stellar relations like, for example, to estimate starspot areas (e.g., Shibata et al. 2013), stellar flare energies (e.g., Howard et al. 2020a), and/or the properties of stellar CMEs (e.g., Takahashi et al. 2016).

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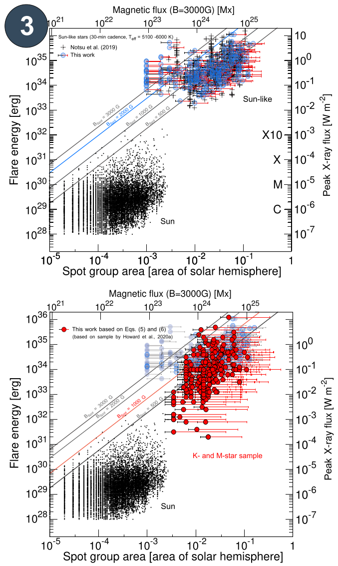

From Starspot Temperatures to the Estimation of the Starspot Size

Assuming the existence of a few large starspot groups on the stellar surface and starspot lifetimes exceeding the rotational period of the star the area of the starspots normalized to the area of the solar hemisphere ($A_\odot$) further can be expressed as:

$$A_{Spot} = \left(\frac{R_{Star}}{R_\odot}\right)^2 \frac{T_{Star}^4}{T_{Star}^4 - [T_{Star} - \Delta T(T_{Star})]^4}\,\frac{\Delta F}{F_{Star}}$$

The upper panel of Fig. 3 shows a comparison of the solar spot group areas (black dots), the 30 minute cadence sample of Sun-like stars (T_{Star}= 5100–6000 K) by Notsu et al. (2019; black crosses), and the the observed values based on the newly derived relations (blue dots). Although the derived stellar spot group areas are in fairly good agreement, the newly derived $A_{Spot}/A_\odot$ values based on the sample by Notsu et al. (2019) indicate a previous underestimation of the starspot sizes of Sun-like stars.

For the K- and M- star regime, however, a more substantial impact can be seen (lower panel), where the *Evryscope* light-curves of 113 cool stars with intense stellar flares (Howard et al. 2019, 2020a) have been reanalyzed.

From Starspot Sizes to Stellar Flare Energies

Stellar flares are sudden releases of magnetic energy that is stored in magnetic active regions. According to Sturrock et al. (1984), Shibata et al. (2013), and Notsu et al. (2019), the upper limit of the total released flare energy Eflare can be described as constant fraction of the total non-potential (stressed) magnetic field energy of the active region (see Emslie et al. 2012), and thus as a rather simple scaling law in the form of

$$E_{flare} \approx a\left(\frac{f}{0.1}\right)\left(\frac{B}{10^3\,G}\right)^2\left(\frac{A_{Spot}/(2\pi R_\odot^2)}{0.001}\right)^{3/2},$$

where $a = 7\times10^{32}$ erg, f gives the fraction of magnetic energy released as flare energy (usually assumed to be in the order of 10%), and B represents the magnetic field strength of the solar/stellar active region (AR). It becomes apparent that the derived spot temperature is a critical parameter for determining the flare energy plotted in the panels of Figure 3.

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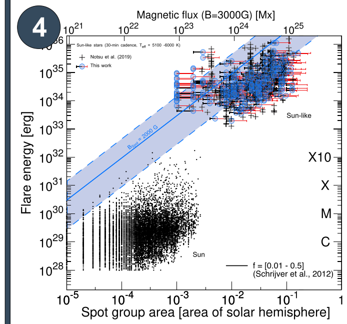

Keeping in mind that the contours reflect the maximum energy release limit, Equation (10) can be used to study the influence of the magnetic field strength of starspots on the energy released in a flare. Therefore, the panels of Fig. 3 show the corresponding contours for B-values of 3000 G, 2000 G, 1000 G, and 500 G. Contrary to the previous findings by Notsu et al. (2019) and Howard et al.(2020a) we can show that stellar Sun-like and K-/M-star magnetic fields of at least 2000 G and 1000 G,respectively are most consistent with the measurements. However, note that upper f-limits of 50% (see Schrijver et al., 2012) or even higher (see Aschwanden et al. 2014) have been reported. The resulting enclosing envelop around the B = 1000G level is shown in Fig. 4

From Stellar Flares to Coronal Mass Ejections

The total flare energy can further be scaled with the energy released in an associated CME. It is known that fast and energetic CMEs induce shocks in the corona that serve as sites of gradual SEP events with the flux of accelerated protons to energies of a few GeV (e.g., Fu et al. 2019). According to Takahashi et al. (2016) the CME mass (M_{CME}), the CME speed (v_{CME}), and the corresponding released energetic peak proton flux (F_P) are related to E_{flare} based on simple power-law relations:

$$E_{CME} = \frac{1}{2}M_{CME}V_{CME}^2 \propto E_{flare} = f\frac{B^2}{8\pi}A_{spot}^{3/2}$$

and

$$F_p \propto \left(4.427\times10^{34}\cdot f\cdot B\cdot\left(\frac{A_{Spot}}{2\pi R_\odot^2}\right)^{3/2}\right)^{5/6}.$$

Consequently, based on the latter, the proton flux of particularly M-stars utilizing the previously reported upper magnetic field strength values would be underestimated by about 40%.

Summary and Conclusions

- $\Delta T(T_{Star})$-values vary between 500 K (M4-type) up to about 1500 K (G0-type); consequently, the higher-contrast of spots with respect to the photosphere of hotter stars is not necessarily as pronounced as previously thought
- the average difference of the derived A_{Spot}/A_{Star}-values based on the former relations by Berdyugina (2005) and the newly derived relation discussed in this study is in the order of 20% in the case of G-type stars while being up to 40% in the case of M-type stars, which implies that previous studies most likely underestimated the starspot sizes of cool stars
- for G-type (K-/M-type) stars, we found that the stellar magnetic fields of at least 2000 (1000) G are most consistent with the measurements, reducing previously published upper limits by about 1000 G (enhancing the previous published upper limit by about 500 G)

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published as
Herbst et al. (2021), *ApJ*, 907, 89.

https://iopscience.iop.org/article/10.3847/1538-4357/abcc04
https://arxiv.org/abs/2011.03761

Acknowledgements:
KH acknowledges the support of the DFG priority program SPP 1992 "Exploring the Diversity of Extrasolar Planets (HE 8392/1-1)". The authors acklowledge the International Space Science Institute (ISSI) and the supported Team 464 „*The Role Of Solar And Stellar Energetic Particles On (Exo)Planetary Habitability (ETERNAL)*". VSA would like to acknowledge the TESS Cycle 1 support. DA acknowledges support by the New York University Abu Dhabi (NYUAD) Institute research grant G1502.