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 spotfields, 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 characterisation of stellar flares. Space missions such as Kepler, Gaia, and TESS have contributed significantly to our understanding of the statistical properties of energies of flares and the underlying mechanisms generating them. Theoretical studies of stellar flares complemented with multiwavelength observations of eruptive events opened a new window to 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; Scheuch et al. 2020). Thereby, the amplitude of the rotationally modulated brightness variation and the effective (photospheric) stellar temperature are directly observed from determinations. In contrast, the evaluation of the starspot temperature (e.g., Notsu et al. 2019, 2015) is based on an empirical scaling with the effective temperature of the star derived by Berdyugina (2005). Although this relation is often applied to derive the starspot area cool stars (e.g., Yamashita et al. 2016; Howard et al. 2020a), more accurate observations and stellar targets are required in order to extend and revise this empirical equation. Here, we re-analyse 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 using data from Bizzaro 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.

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)giant, 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 (Teff) and the starspot temperature (Tspot) for the cool star regime is best described as:

\[ \Delta T_{\text{spot}} = T_{\text{spot}} - T_{\text{eff}} = 3.58 \times 10^{-3} \times T_{\text{eff}}^2 + 0.249 \times T_{\text{eff}} + 0.816 \]

and

\[ T_{\text{spot}} = 3.58 \times 10^{-3} \times T_{\text{eff}}^2 + 0.754 \times T_{\text{eff}} + 0.816. \]

Reanalysis and Extension of the Stellar Sample

Assuming the nature of starspots to be the same in all active stars, a more reliable correlation is 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 Bizzaro et al. (2006) and Valio (2017), and

2. used the scipy.optimize.leastsq fitting routine to derive more universal relations for both Tspot and \( \Delta T_{\text{spot}} \) and to introduce an error estimate.

We find \( T_{\text{spot}} \) and \( \Delta T_{\text{spot}} \) to be best re-preented by:

\[ T_{\text{spot}} = 3.58 \times 10^{-3} \times T_{\text{eff}}^2 + 0.754 \times T_{\text{eff}} + 0.816 \]

\[ \Delta T_{\text{spot}} = 3.58 \times 10^{-3} \times T_{\text{eff}}^2 + 0.0118 \times T_{\text{eff}} - 0.0063. \]

As can be seen from Fig. 1, the newly-derived relations are able to represent the entire cool star sample including, for the first time, the well-known solar spot temperature variations (orange squares). To test the validity of the latter equation, we use the new 3D aster model simulations is performed (lower panel). Shown are the results of the Doppler Imaging of V1338 Ori, a young G-type star (purple line), Kriskovic et al. (2019), the K-giants HD208472 (magenta diamond), Özdamar et al. (2016), and K2 Peg (green diamond, Kövar et al. 2016), the active K5 subgiant II Peg (blue diamond; Strassmeier et al. 2019), and the new 3D aster model results by Panja et al. (2020; colored triangles).

However, \( \Delta T_{\text{spot}} \) 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).

From Starspot Temperatures to the Estimation of the Star Size

Assuming the existence of a few large starspot groups on the stellar surface and that lifetimes exceeding the rotational period of the starspot can be detected, the starspot normalized to the area of the solar hemisphere (A/sun) further can be expressed as:

\[ A_{\text{sun}} = \frac{A_{\text{spot}}}{4 \times \pi \times R_{\text{sun}}^2}. \]

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 (Tsun= 5100-6900 K) by Notsu et al. (2015), black crosses), and the 3D aster values based on the data of Bizzaro et al. (2006) (blue squares). The inset below shows the previously derived relation by Berdyugina (2005) and newly derived relation discussed in this study is in the order of 30% 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 size of starspot groups on the stellar surface and that previous studies most likely underestimated the size of starspot groups on the stellar surface.

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

From Starspot Sizes to Coronal Mass Ejections

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 coronal mass ejection (CME) is constrained as constant fraction of the total non-potential (magnetised) magnetic field energy of the active region (see Emile et al. 2012). Thus, as a rather simple scaling law in the form of

\[ \frac{E_{\text{CM}}}{{\eta} \times \frac{L}{M}} = \frac{L}{M} \times \frac{B^2}{8\pi} \times \frac{R_{\text{sun}}}{2} \times \beta \]

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 spotfields 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 Shibata 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 limits of 50% (see Schrijver et al. 2012) or even higher (see Ashwood et al. 2014) have been reported. The resulting enclosing envelop around the B = 1000G level is shown in Fig. 4.

Summary and Conclusions

1. The total flare energy can further be scaled with the energy released in an associated CME. It is found that fast and energetic CMEs induce shocks in the low corona that serve as sites of coronal 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. (2018) the CME mass (MCE), the CME speed (vCME), and the corresponding released energetic peak flux proton (P) are related to $E_{\text{CME}}$ based on simple power-law relations:

\[ E_{\text{CME}} = \frac{1}{2} M_{\text{CME}} \frac{v_{\text{CME}}}{2} E_{\text{p}} \]

and

\[ E_{\text{p}} = \frac{4 \times 42.7 \times 10^{14}}{F_{\text{e}}} \times \left( \frac{v_{\text{CME}}}{10^3} \right)^{1.9} \]

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%.

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